CONTENTS

1 Discovering the Conversation 1
2 The Nature of the Conversation: Starting with C 16
3 Expanding the Alphabet: N and P 31
4 Completing Life's Alphabet: S and Trace Elements 47
5 Water and Oxygen 60
6 Trimming the Tree of Life 69
7 Living on a Dynamic Planet 88
8 The Conversation Begins 99
9 The Story of O, Part 1 112
10 The Story of O, Part 2 125
11 The Story of O, Part 3 138
12 The Minerals of Life 151
13 Plants Enter the Conversation 169
14 Climate and Habitability 182
15 Close Calls? 196
16 The Conversation in the Twenty-First Century 209
17 Other Conversations? Mars 225
18 Other Conversations? Everywhere Else 241

Acknowledgments 257
References and Further Reading 261
Illustration Credits 285
Index 287
COLOR PLATES *(following page 158)*

CHAPTER 1

Discovering the Conversation

In the fall of 1973, I set out for college with high hopes and some trepidation, a bag of socks and underwear, and no idea what I wanted to do in life. In the small Pennsylvania Dutch town where I grew up, only a limited array of professions impinged on daily life, notably medicine, law, and engineering. I knew I didn't want to become a doctor or lawyer, and I was good at math, so I decided to study engineering. By the end of freshman year, I had one additional insight: I wasn't cut out for engineering, either.

At home, it was clear that "I don't know" wasn't a popular answer to the question of what I was doing in college, so when I returned to campus, I enrolled in five math and science courses and audited another, hoping that at least one of them might rub off. By some minor miracle, it worked. In fact, I was inspired by two courses, one in geology and the other in biology. As taught in those days, these courses seemed to describe separate universes, but sitting in my room one evening, it struck me that maybe they could be seen as two sides of a single coin. Maybe knowing something about biology would make me a better geologist, and, equally, knowledge of the Earth might help me to understand the life it supports. Fossils provided an obvious point where Earth and life intersect, but even as a sophomore, I could dimly see that questions of how the Earth works—how, for example, carbon cycles through the biosphere—involve both physical and biological processes. I'm not sure that my teachers shared this nascent vision, but they were supportive and probably smiled inwardly when this naïve geology student showed up in a microbiology course. I, on the other hand, was hooked; the conversation between Earth and life would become the lodestar for my career in science.

I didn't know it at the time, but the way of thinking that took root in my undergraduate mind has a name: geobiology. Unlike physics and chemistry, which are fundamental approaches to matter and energy, geology is the study of an object: the Earth. When I was a student in the 1970s, applications of physics and chemistry to the study of our planet, called geophysics and geochemistry, respectively, were in the ascendancy, rapidly changing how scientists view the Earth and its history. In contrast, geobiology had yet to flower.

In the decades since then, geobiology—the study of how Earth and life interact and have done so through time—has expanded from a fledgling enterprise to a thriving discipline at the intersection of physical and biological sciences. Paleontology has benefitted enormously from geobiological insights, but so have studies of the environment—past, present, and future. Geobiology permeates discussions of life's great radiations and mass extinctions. It underpins research on Earth's environmental history. It illuminates many aspects of ecology and evolution and is critical to understanding twenty-first-century global change. Moreover, it informs astrobiological efforts to understand how life might be distributed throughout the universe. Disciplinary silos are so twentieth century; integrative approaches now fuel much of our most exciting and transformative science, including how Earth and life talk.

Despite its recent flowering, geobiology has deep roots. Snippets of geobiological thinking might be recognized retrospectively in the writings of da Vinci, Steno, and other Renaissance luminaries, but it was really in the eighteenth century that modern views of Earth and life began to take shape. For many centuries, Judeo-Christian tradition had held that our planet's history was short: An essentially modern-day Earth was formed during the first four days of Creation, to be populated with life on Day 5 and, on Day 6, Adam and Eve. James Ussher's 1650 calculation that it all began around nightfall on October 22, 4004 BC is famous for its precision, but in truth, others, from the Venerable Bede to Isaac Newton, had made similar estimates of the Earth's antiquity, all based on New Testament elaboration of the generations from Adam to Jesus.

Cracks in this young Earth chronology began to develop in the mid-eighteenth century, with the proposal by the great French naturalist Georges-Louis Leclerc, Comte de Buffon, that our planet must be much older than conventionally accepted; he estimated about 75,000 years based on experiments with the cooling of molten iron, which he envisioned to be important in Earth's development through time. Buffon also argued that this long planetary history is recorded in the rocks observed in cliffs and mountainsides.

By the century's end, the cracks had widened into emerging new views of the Earth. In a series of popular lectures and publications, a pioneering German mineralogist named Abraham Gottlob Werner hypothesized that the rock layers observable in nature reflect the sequential precipitation of different materials from an originally global ocean, beginning with granite and concluding with unconsolidated sediments. Called neptunism, after the primacy of precipitation from seawater, Werner's worldview envisioned a relatively old Earth (he reckoned a million years or so), with a discernible, deterministic history recorded in the rocks. The Earth around us took shape as minerals precipitated and the waters receded.

At about the same time, a Scottish naturalist named James Hutton was developing a different view of the Earth. A keen observer, Hutton recognized that our modern world is not invariant; hills and mountains are continually sculpted by erosion, while the sediments they generate inexorably fill in lakes and embayments. This understanding, however, laid bare a biological conundrum: If the environments that support life on land and in the sea are in a continual state of change, how can plants and animals, so clearly designed to fit their environs, persist in time? Hutton's solution was ingenious: As erosion wears down summits in one place, heat lifts new mountains upward somewhere else, maintaining the environments that species need to survive. Moreover, uplift and erosion, burial and lithification, continually cycle the materials of the Earth from mountain to sediments and back again. In a now famous 1788 essay, Hutton repeatedly used the term "habitability," and his view that life is sustained through time by planetary processes anticipates modern astrobiology by two centuries. Like Werner, then, Hutton saw history in rocks, but unlike Werner, he had no need to invoke processes no longer in play. In Hutton's "uniformitarian" view (from the hypothesized uniformity of process throughout Earth's history), our planet has been shaped and reshaped through time by processes we can observe today, leaving, in Hutton's famous phrase, "no vestige of a beginning, no prospect of an end."

Two centuries after the publication of Hutton's *Theory of the Earth* (1788), James Lovelock, who waits in the wings to enter this pocket history, reminded Earth scientists that Hutton actually likened the Earth to a superorganism and recommended what he called geophysiology as the proper approach to its investigation.

> *We are thus led to see a circulation of the matter in this globe, and a system of beautiful economy in the works of nature. This earth, like a body of an animal, is wasted at the same time that it is repaired. It has a state of growth and augmentation; it has another state, which is that of diminution and decay. This world is thus destroyed in one part, but it is renewed in another; and the operations by which this world is thus constantly renewed, are as evident to the scientific eye, as are those in which it is necessarily destroyed. (Hutton, 1788)*

Just as physiology regulates the properties of cells and tissues, keeping them within closely constrained limits (what biologists call homeostasis), the Earth is a self-regulating, geophysiological system, its endless changes maintaining the broad environmental constancy needed for life to persist. Organisms, however, really served only as a metaphor for Hutton. Life benefitted from this planetary regulation but played no major role in its maintenance. For several decades, the acolytes of Werner and Hutton debated the nature of Earth history, but in time, notably with the publication of Charles Lyell's influential *Principles of Geology* (1830–1833), the uniformitarian view carried the day.

One more crack in the view of an unchanging planet opened widely as the eighteenth century drew toward its close. Working at the Natural History Museum in Paris, the eminent anatomist Georges Cuvier established the fact of extinction—like the physical landscape, life was not constant in time. Many naturalists had observed fossils unlike any known living animals, but in an age of exploration, it seemed likely that while extant counterparts of those fossils might not reside in Europe, they would be discovered in the vast lands still to be explored. Moreover, to many contemporary thinkers, the very idea of extinction suggested flaws in the Creation, discouraging its consideration. Studying the bones of mammoths and mastodons, however, Cuvier recognized that while these remains were similar to the skeletons of elephants, they belonged to distinct species, species unknown in the modern world. As elephants were large and conspicuous, Cuvier rejected the idea that mammoths and mastodons would turn up in some territory yet to be explored, and so, in a pathbreaking 1796 paper, he argued that these cousins of living elephants are extinct.

In the years that followed, geologists established that not only did many fossils record extinct species, but fossil faunas appeared to change systematically through time. To Cuvier, this reflected catastrophes that episodically exterminated life, followed by renewed Creation to repopulate the world. Catastrophism provided one explanation for the emerging fossil record, but another, sharply different view was percolating among early-nineteenth-century thinkers: evolution.

Charles Darwin's *On the Origin of Species,* published in 1859, is generally regarded as the foundational document in evolutionary biology. Darwin proposed a compelling mechanism for evolutionary change, called natural selection, and so placed evolution at the center of debates about life and its history. He was not, however, the first to espouse evolutionary ideas. Beginning, once again, in the late eighteenth century, dozens of people had earlier argued the case. Many of these theses gained few adherents, requiring modern historians of science to achieve even minor recognition. But while evolutionary thinking was not widely embraced, it was fairly broadly known. For example, in his picaresque novel *Martin Chuzzlewit,* published 15 years before Darwin's magnum opus, Charles Dickens mentioned the idea that humans are descended from monkeys. His note has something of a "How 'bout them talking dogs" flavor to it, but Dickens clearly expected readers to know the reference. With Darwin and the subsequent birth of genetics, not only did evolution become biology's most important theory, it also opened new ways to consider how Earth and life talk.

Hutton, Werner, Lyell, and others established that Earth is a dynamic planet, its immensely long history recorded in rocks. In turn, Darwin and others argued that life is equally dynamic, with a long history recorded by fossils and explained by evolution. But it took one more visionary to introduce the idea that Earth and life interact in time and space. That person was Friedrich Wilhelm Heinrich Alexander von Humboldt. In the twenty-first century, Humboldt's is arguably not a household name, persisting in no small part through the distant echoes of place-names, from Humboldt, South Dakota ("A small town with a big heart," according to its website) and Humboldt County, California, with its eponymous university, to the Humboldt Glacier in Greenland and Berlin's Humboldt University. Two hundred years ago, however, Humboldt was among the most famous people in the world, a friend of Goethe and houseguest of Thomas Jefferson. Napoleon was cool toward his fellow Parisian, perhaps, it is said, out of jealousy for Humboldt's fame.

Humboldt was an intrepid explorer, as well as a deep thinker who excelled at seeing the connections among his various observations. From 1799 to 1804, he and his research partner Aimé Bonpland undertook the first scientific exploration of South America's interior, paddling along the Orinoco River and scaling volcanoes in the Andes. Prominent among Humboldt's many discoveries was the geographic distribution of plant species—in South America, the flora changed with altitude much as it did with latitude in Humboldt's European experience. From this, he concluded that the structure of plants and their geographic distribution are governed by their physical environment—

temperature, water, and soil. Importantly, and way ahead of his time, Humboldt reasoned that one couldn't, or at least shouldn't, study the flora and the environment in isolation. To understand either, one had to consider both together as a unified system. "Everything," he wrote, "is interrelated."

This integrated view of Earth and life shines through the great work of Humboldt's maturity, *Kosmos* (1845), but it eventually faded into the background as science grew more disciplinary and intellectual silos came to demarcate (and isolate) different fields. In her superb biography of Humboldt, Andrea Wulf captures its fate well: "Unlike Christopher Columbus or Isaac Newton, Humboldt did not discover a continent or a new law of physics. Humboldt was not known for a single fact or a discovery but for his worldview. His vision of nature has passed into our consciousness as if by osmosis. It is almost as though his ideas have become so manifest that the man behind them has disappeared." Humboldt, it is worth noting, also recognized that in time human activities might harm the natural world. "The most dangerous worldview is the worldview of those who have not viewed the world," he wrote, a thought worth taking to heart today.

So when did the outlines of modern geobiology begin to coalesce? The holistic perspective necessary to integrate Earth and life sciences began to (re)emerge early in the twentieth century, notably through the writings of the Russian mineralogist and geochemist Vladimir Ivanovich Vernadsky. His 1926 volume *The Biosphere* is commonly recognized as the opening salvo of modern geobiological thought, although it says something about the field's development that *The Biosphere* was not translated into English, even in abbreviated form, until 1986. Vernadsky's language is flowery, more metaphorical than analytical. He proclaims more than argues, and readers may find one bit nonsensical and another visionary, sometimes in the same paragraph. Without question, however, Vernadsky appreciated the interconnectedness of Earth and life, and his mineralogist's knowledge of chemical reactions helped him to recognize chemistry—what we now call geochemistry—as a primary basis for the connection.

In 1875, the Austrian geologist Eduard Suess coined the term *biosphere* as the envelope at the Earth's surface that contains and sustains life. In adapting this term, Vernadsky reframed it as the zone in which life and Earth interact. In particular, Vernadsky appreciated the role of metabolism in the conversation between our planet and the life it supports. Metabolism encompasses the ways in which organisms take in food and energy from their environment and use it for growth, reproduction, and work. Photosynthesis, for example, converts carbon from the environment into organic molecules, and respiration reverses the process, establishing a cycle that connects the physical and biological worlds. Indeed, Vernadsky voiced some specific appreciation for the role of bacteria (his student Sergei Winogradsky—he of the famous column found in many biology classrooms—would become one of the great pioneers of microbial ecology), but plants and animals dominate his discussion.

Vernadsky believed that the physical Earth has not changed appreciably through time and that life has always been a part of it. He accepted evolution but didn't consider it an important process in shaping the physical environment. He did, however, recognize that humans have changed the game, building on Pierre Teilhard de Chardin's slightly earlier concept of the noosphere (the biosphere in the age of reason). Anticipating the current concept of the Anthropocene (chapter 16), Vernadsky argued that much as the biosphere had transformed the geosphere, the noosphere was now transforming the biosphere.

The penultimate personality in this history is the Dutch scientist Lourens Baas Becking, whose 1934 book *Geobiology* not only gave the emerging discipline its name but clearly set out a modern view of how Earth and life talk. (Similar to Vernadsky's book, *Geobiology* was published in English translation only in 2016.)

Baas Becking was fortunate to study at Delft University during the golden age of microbiology that flowered there. He recognized that bacterial metabolism lay at the functional heart of geobiology, with microbes cycling nitrogen, sulfur, and other elements, as well as carbon. Establishing a lab at Stanford University, Baas Becking turned his attention to saline lakes, working out how microorganisms thrive in, and indeed help to regulate, these salty ecosystems. Although Bass Becking would return to the Netherlands and then move on to Australia, his early research on saline lakes gave him the experience and perspective needed to undertake his extended essay.

"This discourse is about this life, of and by the Earth," wrote Baas Becking, ". . . an attempt to describe the relationship between organisms and the Earth. The name 'geobiology' simply expresses this relationship. This new word does not attempt to describe a new field. It rather tries to unite phenomena that have thus far been known to the different areas of biology as much as possible under one viewpoint." He was too modest.

What followed was a detailed description of environmental factors that influence life and biological processes that help to shape the environment—sleeves-rolled-up empiricism in contrast to the philosophical musings of Vernadsky. Baas Becking's book contains what may be the first graphical depiction of a biogeochemical cycle, outlining how carbon moves through the biosphere. Baas Becking was more concerned with process than history, so a geobiological view of Earth and life through time was left for another generation. But his picture of how elements cycle through environments, and therefore how organisms and environments influence each other, is strikingly modern.

In the 1950s and 1960s, as geochemistry flowered as a way of examining the Earth, increasing attention started to be paid to element cycling, as advanced in seminal works by Robert Garrels, Robert Berner, Wallace Broecker, and others. At the same time, geobiology as an emerging field developed a time dimension, reorienting research on the history of life and environments. Dick Holland, one of my mentors in graduate school, pioneered geochemical research into our planet's environmental history, arguing that for the first two billion years of Earth history, the atmosphere and oceans contained little, if any, oxygen gas. At the same time, in a neighboring building, my principal thesis advisor, Elso Barghoorn, discovered fossils of ancient microorganisms which demonstrated that Earth has been a biological planet—a microbial planet—for most of its history. It was Preston Cloud, however, who linked long-term trends in environmental and biological history, effectively founding the subdiscipline of historical geobiology. A paleontologist by training, Pres recognized that Earth's tripartite oxygen history—none, a bit, and then a lot—coincided in time with a fossil record marked by bacteria, then bacteria plus protozoans and algae, and finally microbes plus plants and animals. Earth and life, Pres maintained, changed through time in coordinated fashion, with evolution both influencing and being influenced by the physical environment.

A central figure in this intellectual coming of age is James Lovelock, father of the Gaia Hypothesis. An independent inventor, notably of the electron capture detector, which allows scientists to measure exceedingly small amounts of chemical compounds in a sample, Lovelock was a frequent visitor to NASA's Jet Propulsion Laboratory at the time when Mars exploration was moving from aspiration to reality. Discussions at JPL inspired him to think about how one might detect the presence of life on another planet. While his colleagues focused on potential chemical signatures in Martian soils, Lovelock looked more broadly, his attention captured by the atmosphere. The thin atmosphere of Mars is decidedly distinct from that of Earth, and as Lovelock and his JPL colleague Dian Hitchcock discussed the problem, they came to the conclusion that the air we breathe on Earth must reflect life, and not simply the physical workings of the planet. Martian air, in contrast, showed no evidence of such biological influence. From this kernel, Lovelock developed a broader, more radical idea, which he christened the Gaia Hypothesis, after the personification of Earth and mother of all life in Greek mythology.

In Lovelock's view, Gaia is a complex entity involving Earth's biosphere, atmosphere, oceans, and soil, the totality constituting a feedback or cybernetic system that seeks and maintains an optimal physical and chemical environment for life on this planet. The maintenance of relatively constant conditions by active control may conveniently be described by the term borrowed from biology: homeostasis, already introduced as the physiological maintenance of stable conditions within cells or larger organisms. Here, then, is the essence of Gaia: Like Hutton's concept of geophysiology, Gaia envisioned a world kept habitable by interacting processes, but now with life, rather than Earth, in the driver's seat.

One day in the early 1970s, I happened to sit in on a fascinating conversation. Six people crowded around a small table in Harvard's Earth science building, as Jim Lovelock, not yet a household name, held forth on the relationship between life and environment. Organisms, Lovelock argued, were the architects of the physical world around them, actively maintaining Earth as a habitable planet. Dick Holland, already introduced as a game-changing geochemist, was having none of it. To Dick, at least at the time, life was more or less an epiphenomenon on a planet regulated by physical processes. As the only student at the table, I kept my mouth shut, but the discussion stayed with me.

Today, the end-member perspectives of Lovelock and Holland have largely been abandoned, replaced by a gamut of hypotheses from the broad intellectual space between them. It is far from clear what “optimal conditions for life” entail, as optimal conditions for sulfate-reducing bacteria lie far from those best suited for rabbits. Nor is it necessarily clear that natural selection will favor mutations that benefit the biosphere as a whole, rather than individual populations. And increasingly sophisticated research into our planet’s history strongly implicates the physical Earth in redox history, climate change, and mass extinctions. Yet Lovelock’s provocation unquestionably moved the dial. Life is not and never has been simply a passive presence on an active planet. Life influences the physical environment in ways both large and small, and with equal certainty, events in the physical Earth have shaped both ecology and evolution through time. It is not the predominance of biological and physical processes that matters, but, rather, their interactions. In a nutshell—geobiology.

INDEX

Page numbers in italics refer to figures and tables.

adenosine triphosphate (ATP), 32, 39, 54

aerobic respiration, 22–24, 34, 67–68, 84–86, 130–132, 152, 172, 200

air quality concerns, 209–210

algae, 24, 36, 55–56, 213

Altman, Sidney, 104–105

Amazon, 60, 194, 210, 224

amino acids, 50, 74, 77, 101–105, 247

ammonia (NH_3), 32–35, 100–101, 213–214, 247

ammonification, 32

ammonium ion (NH_4^+), 32

amoebae, 70, 179, 203

amorphous silica. *See* silica (SiO_2)

amphibians, 179

anaerobic ammonia oxidation (anammox), 34

anaerobic respiration, 116, 131, 152, *153,* 161

anhydrite, 51

animalcules, 76

animals/animal life: amphibians, 179; arthropods, 144, 178–179, 206; brachiopods, 144, 155–157, 206; carnivores, 139–141, 144; choanoflagellates, 58, 140–141; dinosaurs, 108, 181, 204, 206; in early fossil record, 138–151, *142,* 165, 178, 204, *205*; influences on habitability, 194–195; invertebrate, 139; *Kimberella,* 143, 149; mollusks, 144, 156, 159, 179, 206; oxygen and, 138–150; placozoans, 76, 143; seawater and, 139–140; vertebrates, 144, 157, 178–181

anoxic environments, 24, 50–51, 55, 67, 126–129, *127*, *147*, 199–200, 256

anoxygenic photosynthetic bacteria, 121–122, 200–201

Antarctica, 61, 89, 143, 186–188, 215, 227

Anthropocene Epoch, 11, 222–223

aquatic fungi, 181

aquatic metabolism, 169

archaea: Asgard, 83–84, 132; carbon dioxide and, 24; gene transfers, 199; internal membranes of, 133; metabolism and, 131–132; nitrogen and, 35, 213; origination before glacial events, 201; phylogeny, 79–83

archaeocyathids, 165

Archean Eon, 93, 96–97, 120–121

Arctic, 83, 187, 258

arthropods, 144, 178–179, 206

Arvidson, Ray, 229–230
Asgard archaea, 83–84, 132
astrobiology, 3, 5, 229, 240–254, *244*
Atlantic Ocean, 28, 44, 56, 89, 90–91
atmospheric oxygen, 68, *147*, 172

Baas Becking, Lourens, 11–12
bacteria: anoxygenic photosynthetic bacteria, 121–122, 200–201; branching order, 80; carbon dioxide and, 24; discovery of, 77; extinction threats, 198–199; free-living, 84–85; gene transfers, 199; internal membranes of, 133; metabolism and, 11, 25, 131; minerals and, 152; nitrogen and, 32–33, 35, 38, 213; organic compound respiration, 173; origination before glacial events, 201; photosynthesis by, 24; proteobacteria, 85; Tree of Life and, 79–87; water needs, 234. *See also* cyanobacteria
Baldwin, James, 224
Barghoorn, Elso, 12–13
barite ($BaSO^4$), 160
Bastin, Jean-François, 217
Benner, Steve, 101, 105–106
Benzerara, Karim, 156–157
Berner, Robert, 12, 173
bicarbonate ions (HCO_3^-), 18, 26, 152, 184
biogeochemical, 12, 203, 213, 220, 223
biomass, 20, *20*, 38, 169–171, 180
biomineralization, 154–160, *158,* 163, *164,* 167–168
biominerals, 151, 159
biosphere: astrobiological forces and, 243; carbon cycles through, 2, 12, 57, 86, 197; defined, 10–11; Gaia Hypothesis and, 14; natural selection and, 15; nitrogen fixation and, 35; oxygen cycles and, 65, 123; silicon in, 58, 65; sulfur removal from, 51; water cycles and, 64
The Biosphere (Vernadsky), 9–10
biosynthesis, 33, 107
bivalves, 206
Blättler, Clara, 125
Bloch, Konrad, 136
Bonpland, Aimé, 8
Bosch, Carl, 214
Braarudosphaera bigelowii, 36, 213
brachiopods, 144, 155–157, 206
Brocks, Jochen, 136–137
Broecker, Wallace, 12, 61

cadmium, 57
calcium (Ca), 53
calcium carbonate ($CaCO_3$), 21, 26, 53, 151–159, *153*, 161, *164*, 165–168, 212
calcium dolomite $CaMg(CaCO_3)$, 21
calcium oxalate, 160
calcium phosphate, 39, 53, 146, 157–158, 163
Cambrian Period, 144, *149*, 163–168, 178
Campbell, Ian, 146
Canfield, Don, 125–126, 130–131, 138
carbonate ion (CO_3^{2-}), 18
carbonate skeletons, 154, 155–157, 161–166, *166*
carbon (C): as diamonds, 28–29; estimates of amounts, 19–20; overview of, 17–30, *18*; photosynthesis and, 21–24, 31–33, 40, 45–46, 108; in plants, 170–171; in seawater samples, 45–46
carbon cycle, *21*; bacterial metabolisms in, 25; biological, 25–30, 40, 52, 57, 85; carbon dioxide and, 171,

184; geological, 29; metabolism and, 30, 46; movement through biosphere, 2, 12, 57, 86, 197; nitrogen and, 36–38; oxygen and, 66, 85–86; photosynthesis and, 31; processes involved, 2, *21,* 46, 66, 199, 211; reservoir of organic matter, *21,* 23; water and, 66

carbon dioxide (CO_2): aerobic respiration and, 152; availability of, 46, 208; habitability and, 184–185, 188, 192, 197; human generation of, 212–213, 218–220; overview, 17–30; photosynthesis and, 64, 67, 81, 113, 169; plate tectonics and, 27–29; removal by weathering, 27; role in regulating climate, 20–22; Tree of Life and, 107

carbon fixation, 31, 51, 82, 122, 169, 171

carbonic acid (H_2CO_3), 26

Carboniferous Period, 172–173, 179

carbon isotopes, 61, 116

carnivores, 139–141, 144

Cassini spacecraft, 182, 245–247

catastrophism, 7, 27, 204, 207–208

Cech, Thomas, 104–105

celestite ($SrSO_4$), 160

cellulose, 171

cerium, 129, 172

Chardin, Pierre Teilhard de, 11

Chatton, Édouard, 77

chemical weathering, 26, 39, 54, 68, 166, 173–177, 185, 188, 191–192, 212

chemoautotrophy, 33–34, 81, 86

chemosynthesis, 24–25, 51, 131

chlorine, 53

chlorophyll, 43, *43*, 54, 169

chloroplasts, 36, 84–85, 113, 133

choanoflagellates, 58, 140–141

Christidis, Nikolaos, 217

chromium, 57

clams/clam shells, 151, 154–155

climate: El Niño state, 214–216; glaciation and, 190–191; global warming and, 188, 209–217, 220, 224; greenhouse gases and, 33, 172–173, 183–188, 192, 197, 211, *212,* 214–215, 220–221, 239; heat waves, 210; importance to habitability, 185–195; Snowball refrigeration, 191–192

climate change, 15, 215–218

Cloud, Preston, 13

Cloudina, 164, 165

cnidarians, 206

coal, 172–173

cobalt, 42, 49, 57

Coleridge, Samuel Taylor, 233–234

collagen protein, 55, 157

comparative biology, 102, 203

continental crust, 92, 97

continental drift, 89–90

copper, 54, 57

coral, 53, 155–156, 206

Coriolis effect, 63

Creationism, 3

Crutzen, Paul, 223

Curiosity rover, 236, 238

cuticle in plants, 64, 178

Cuvier, Georges, 6–7

cyanobacteria: ancestors of chloroplasts, 85; evolution of, 179–180; iron and, 55–56; in origin of life, 120–123, 125, 145; photosynthesis and, 43–44, 113; precipitation and, 156–157; water use, 24

Dales Gorge, Australia, 113–115, *114*

“Darkness” (Gordon), 207

Darwin, Charles, 7–8, 70–71, *71,* 99–100

decapods, 206
deep-water environments, 23, 126–128, 147
denitrification, 34–35, 86, 213–214
Devonian Period, 172, 175, 178, 193, *205*
diamonds, 28–29
diatoms, 44, 58, 158–159, 167–168, 179
Dickens, Charles, 7
dimethylsulfoniopropionate (DMSP), 52
dinosaurs, 108, 181, 204, 206
DNA, 17, 32, 65, 85, 102–107
Doushantuo Formation, 147
Du Toit, Alex, 89–90
dynamic topography, 174, 188

Earth (planet): continental crust, 92, 97; continental drift, 89–90; habitability of, 182–186, 241–242; mass extinctions, 2, 15, 30, 204–208, *205,* 259; meteorites and, 93–94, 102–103, 111, 117, 204–208, *210,* 238–239, 245; physical processes on, 256; relationship to Sun, 29, 183, 186–187, 195, 198, 208, 225. *See also* plate tectonics
eclipses of Sun, 250
ecosystems, 11, 25, 38–41, 47, 57, 89, 109, 131, 177, 180–181, 194, 206
Ediacaran Period, *142,* 143–148, *164*, 165
Edmund, John, 173–174
electrolytes, 52–54
electron capture detector, 13
El Niño state, 214–216
Enceladus (moon), 182, 245–248, *246*
endosymbioses, 84–85
Epsom salt ($MgSO_4 \cdot 7H_2O$), 50
erosion, 4–5, 92, 161
eukaryotes: aerobic respiration, 84; Asgard archaea and, 83–84; complexity of, 81; eukaryotic cells and, 141; formation of, 83–84; genomes, 133; origination before glacial events, 201; photosynthesis and, 85; Tree of Life and, 79, 131–132
eukaryotic microorganisms: amoeba, 70, 179, 203; carbon and, 24; discovery of, 76; fossils of, 133–136, *135,* 145, 203; nitrogen and, 35, 38; Radiolaria, 58, 158, *158,* 167; respiration of, 22
Europa (moon), 242–245, *244*, 247
European Space Agency, 237, 248
evaporation, 49, 51, 62–64, 161, 166, 170, 235
Everything Must Go: The Stories We Tell About the End of the World (Lynskey), 207
extrasolar planets, 249–255

Faint Young Sun Paradox, 183–184
Falkowski, Paul, 123–124
Farquhar, James, 117
fatty acids, 103–104
fault systems, 28, 88, 91
Fermi, Enrico, 255
Fermi Paradox, 255–256
ferric iron (Fe^{3+}), 24, 55, 233
fertilizer, 31
first eukaryotic common ancestor (FECA), 132
flowering plants, 181, 194
forest life, 16
fossil fuels, 212, 220
fossils: of ancient microorganisms,

12–13, 133–137, 199, 203; of animals, 138–151, 165, 178, 204, *205*; of aquatic ancestors, 179–180; to calibrate evolutionary divergences, 72–73, 119, 154, 159; of coastal microbes, 167; in distinctive land biota, 89; of eukaryotic organisms, 133–136, *135,* 145, 203; of extinct species, 6–8, 108; intersection of Earth and life, 1; on meteorites, 228; microfossils, 134, 136, 199, 203, 228; plate tectonics and, 92; trace tracks, *149*
Fournier, Greg, 199
Fox, George, 79
fractionation, 116–118
free-living bacteria, 84–85
fresh water, 18, 60–66, 95, 137, 159, 186
Frost, Robert, 207
fungi: aquatic, 181; carbon dioxide and, 24; mushrooms, 84, 180; nitrogen and, 32; organic compound respiration, 173; in soil, 176, 180–181; toadstools, 180; *Xeromyces bisporus,* 234

Gaia Hypothesis, 13–14, 52
Garrels, Robert, 12
gastropods, 206
geobiology, 2–3, 9–15, 156–157
Geobiology (Becking), 11
geochemistry, 2, 10, 12
geoengineering, 216, 220–221
geophysics, 2, 90–91
geosphere, 11
germ theory, 76
glacial ice, 60, 186–188, 204, 223
glaciation, 190–191
global warming, 188, 209–217, 220–224
Glossopteris tree, 89, 92
Gondwana supercontinent, 146, 173
Gordon, George (Lord Byron), 207
Great Oxygenation Event (GOE), 118–125, *119,* 128–134, *147,* 192–193, 200–201
Green, Jaime, 226
Green, Nathaniel, 226
green algae, 44, 85, 136, 145, 149, 177, 179–180, 203
greenhouse gases, 33, 172–173, 183–188, 192, 197, 211, *212*, 214–215, 220–221, 239. *See also* carbon dioxide; methane
Greenland, 8, 186, 215, 258
groundwater, 60, 130, 176, *231*
gypsum ($CaSO_4 \cdot 2H_2O$), 49, 51–52, 115

Haber, Fritz, 214
habitability, 182; animal influences on, 194–195; carbon dioxide and, 184–185, 188, 192, 197; climate importance to, 185–195; of Earth, 182–186; global warming and, 188, 209–217, 220, 224; Great Oxygenation Event (GOE), 118–125, *119,* 128–134, *147,* 192–193, 200–201; greenhouse gases and, 33, 172–173, 183–188, 192, 197, 211, *212,* 214–215, 220–221, 239; of Mars, 227–236; organisms and, 14; planetary processes and, 4–5; plant influences on, 193–194; pollutants and, 215, 224; questions surrounding, 197; renewable resources and, 218–220; solar luminosity and, 184, 196–198, 208; woodland habitat, 16

Hadean Eon, 93, 96
Haldane, J. B. S., 100
Harland, W. Brian, 191
Hayes, Paul, 184
heat waves, 210
Heezen, Bruce, 90
Hess, Harry, 90
Hitchcock, Dian, 13
Hoffman, Paul, 201
Holland, Dick, 12, 14
Holmes, Arthur, 91
homeostasis, 6, 14, 53
Hooke, Robert, 76
Hooker, Joseph, 99–100
horizontal gene transfer, 80, 82
human induced global change, 209–224; global warming, 209–216, *210*; habitat alteration, 220–221; human mitigation, 218–224; sea-level rise, 215–216
Humboldt, Friedrich Wilhelm Heinrich Alexander von, 8–9
Hutton, James, 4–6
hydrocarbons, 228–229, 248
hydrogen gas (H_2), 24, 86, 101, 119, 183–184, 219, 247
hydrogen (H), 47, 107
hydrogen peroxide (H_2O_2), 66
hydrogen sulfide (H_2S), 24, 49–51, 56, 67, 86, 119, 122–123, 128–130
hydrological cycle, 63–64, 95
hydrothermal systems, 49, 56, 68, 83, 107, 110–111, 118, 122, 161, 166
hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), 157

ice sheets, 186–190, 201. *See also* glacial ice
Intergovernmental Panel on Climate Change (UN), 216
Io, 243
iodine, 49, 129
iron (Fe): in human bodies, 49, 54–56; on Mars, 112, 231, 233; metabolism and, 54, 56–57, 106, 199; in origin of life, 113–115, 128; photosynthesis and, 42, 46, 199–200; reactive iron, *127*, 128; in sea water, 55–57
iron oxide, 112–115, 121, 128, 228, 230
Is Mars Habitable? (Wallace), 227
isotopes, 29, 61, 67, 92, 94, 108, 116–118, 129, 172

James Webb Space Telescope, 254
jarosite, 231–232, 235
Javaux, Emmanuelle, 133
Jet Propulsion Laboratory (NASA), 13
Johnston, Dave, 148
Judeo-Christian tradition, 3
Jupiter (planet), 182, 242–245, *244*, 249, 251–252

Kasting, Jim, 184
Kepler-1606 b (planet), 254
Kimberella, 143, 149
King, Nicole, 140–141
Kirschvink, Joe, 191
Kosmos (Humboldt), 9

Laakso, Tom, 148
Lahr, Dan, 141
last eukaryotic common ancestor (LECA), 132–133, 136–137
Leclerc, Georges-Louis, 3
Leeuwenhoek, Antonie van, 76
Liebig, Justus von, 41
Liebig's Law of the Minimum, 41
life, origin of. *See* origin of life
lignin, 170–171

limestone ($CaCO_3$), 21, 26–27, 92, 152, 161–162, 165–166, *166*, 168, 184
Linnaeus, Carl, 151
lipids, 17–18, 81, 103, 105, 136, 153
Lovelock, James, 5, 13–14, 52
Lowell, Percival, 226–227
Lyell, Charles, 6
Lynskey, Dorian, 207
Lyons, Tim, 128–129, 254

magma ocean, 94
magnesium, 53–54
magnetism, 92, 159–160, 191, 197–198, 242–243
magnetite (Fe_3O_4), 159–160, 191, 228–229
magnetotaxis, 160
Maldonado, Manuel, 167
Malick, Terrence, 69
mammoths, 6
manganese, 57
Margulis, Lynn, 84, 200
Mars Exploration Rover (MER) mission, 177, 235
Mars (planet): early observation of, 226–227; exploration/studies, 13, 229–241; geological features, 176–177; habitability of, 227–236; iron samples, 112, 231, 233; meteorites and, 227–229; overview of, 225–240; water and, 233–236
Martin, Bill, 107
Martin Chuzzlewit (Dickens), 7
mass extinctions, 2, 15, 30, 204–208, *205*, 259
mastodons, 6
metabolism: aquatic, 169; archaeal, 131–132; bacterial, 11, 25, 131; carbon cycle and, 30, 46; defined, 10; in eukaryotic cells, 132–133; iron and, 54, 56–57, 106, 199; microbial, 49, *51,* 76, 203, 228; nitrogen and, 33, 35, 38, 213; in origin of life, 102–111; overview of, 81–83, 100, 104; oxygen and, 120, 201; planetary life and, 10, 105
metals, 53–54, 57, 106, 130
meteorites, 93–94, 102–103, 111, 117, 204–208, *210,* 227–229, 238–239, 245
methane (CH_4), 78, 101, 184–185, 192, 213, 247–248, 253–254
microbes/microbiology: anaerobic heterotrophic microbes, 201; gene transfers, 199; innovations in, 79–80; metabolism and, 49, *51,* 76, 203, 228; nitrogen and, 32–34, 38
microfossils, 134, 136, 199, 203, 228
Micrographia (Hooke), 76
microorganisms, 11, 20, 24, 33–35, 67, 76, 78–79, 108, 133, 176, 180, 240, 245. *See also* eukaryotic microorganisms
Milankovitch, Milutin, 186–187
Miller, Stanley, 100–102
Mills, Dan, 138–139
Milo, Ron, 222–223
minerals, 151, 154–160, *158,* 163, *164,* 167–168. *See also* specific minerals
mitochondria, 36, 72, 84–85, 132–133, 214
mollusks, 144, 156, 159, 179, 206
molybdenum (Mo), 57, 124, 129, 172
moons, planetary, 110, 182, 185, 225, 242–254, *244*, *246*
Morell, Virginia, 78–79
Morrison, Shaunna, 17
Mössbauer spectrometer, 233

mushrooms, 84, 180. *See also* fungi
myoglobin, 54

natural selection, 7, 15, 70, 99, 105, 108, 227
Neoproterozoic Era, 190–192
neptunism, 4
Newton, Isaac, 3, 242
New York Times, The, 218–219, 224
Niel, C. B. van, 77
nitrate (NO_3^-), 24, 32–34, 86, 121, 131, 148
nitrification, 33–35, 86, 213–214
nitrite ion (NO_2^-), 33
nitrogenase, 50
nitrogen fixation, 35, 38, 50, 86, 123–124, 213
nitrogen gas (N_2), 32–38, 213–214, 247–248
nitrogen (N): bioavailability of, 34–36; biogeochemical cycling of, 213; habitability and, 197; metabolism and, 33, 35, 38, 213; microbes and, 34; in origin of life, 123–124, 148–149; overview of, 31–38, *37*; photosynthesis and, 31–33, 38, 41–42, 45–46; in seawater samples, 45–46
nitrous oxide (N_2O), 33, 214
noosphere, 11
nuclear holocaust, 207–208
nuclear power, 219
nucleic acids, 79, 81, 102, 104–106
nucleotides, 74, 78, 102–103, 105–106
Nursall, J. R., 138–139

On the Origin of Species (Darwin), 7, 70–71
Oparin, Alexander, 100
Opportunity rover, 230–231, 233, 235–236, 238–240
optimal conditions for life, 15
Ordovician Period, 166, *166*, 177–178, *205*
organelles, 36, 77, 84–85, 213
organisms: complex molecules in, 102; Lovelock, James on, 14; in origin of life, 102–108; single-cell, 134, 141, 153, 156, 158, 171
origin of life: beginnings of, 99–111; cyanobacteria in, 120–123, 125, 145; iron in, 113–115, 128; metabolism in, 102–111; nitrogen in, 123–124, 148–149; organisms in, 102–108; oxygen in, 103, 112–137; phosphorus in, 121–123, 146; proteins in, 102, 105; seawater, 126–129; sulfate in, 115
The Origins of Continents and Oceans (Wegener), 89
oxidized iron (Fe^{3+}), 24, 113, 115–116, *116*, 152
oxygen gas (O_2): carbon and, 23; on early Earth, 81; in origin of life, 103, 112–137; overview of, 64–68; photosynthesis and, 82
oxygen (O): aerobic respiration, 22–24, 34, 67–68, 84–86, 130–132, 152, 172, 200; anaerobic respiration, 116, 131, 152, *153,* 161; animal life and, 138–150; anoxygenic photosynthetic bacteria, 121–122, 200–201; atmospheric, 68, *147,* 172; Great Oxygenation Event, 118–125, *119,* 128–134, *147,* 192–193, 200–201; in human bodies, 47; metabolism and, 120, 201; overview of, 64–68, 112–124; in photosynthesis, 22–23, 66–68, 119–121, 171; plant life and, 150, 172; whiffs of oxygen, 120, 122
ozone (O_3), 65

Pace, Norman, 79

Pacific Ocean, 60, 90, 214

paleontology, 2, 13, 92, 126, 133, 144

Paleozoic Era, 145, 173, 179, 181, 188, 193

Pangaea supercontinent, 97

Pasteur, Louis, 76, 99

Permian Period, 89

Perseverance rover, 236, 238–239

petroleum resources, 21, 213, 220

phagocytosis, 85

Phanerozoic Eon, 91, *205*

Philosophiæ Naturalis Principia Mathematica (Newton), 242

phosphate ions (PO_4^{3-}), 39, 39–40, 103, 103, 121, 146, 157, 160

phosphine (PH_3), 241

phosphorus (P): biomineralization and, *163*; habitability and, 197; in origin of life, 121–123, 146; overview, 38–40, *41*; photosynthesis and, 31–33, 41, 45–46, 122; in seawater samples, 45–46

photic zone, 122–123, *158*, 167

photosynthesis: anoxygenic photosynthetic bacteria, 121–122, 200–201; carbon and, 21–24, 31–33, 40, 45–46, 108; carbon dioxide and, 64, 67, 81, 113, 169; cobalt and, 42, 46; cyanobacteria and, 43–44, 113; evolution of, 82–83; fractionation, 116–118; hydrogen sulfide in, 67; iron and, 42, 46, 199–200; nitrogen and, 31–33, 38, 41–42, 45–46; overview of, 31–33; oxygen in, 22–23, 66–68, 119–121, 171; phosphorus and, 31–33, 41, 45–46, 122; rates of, 40–44

phylogenics, 72–78, *73*, 80, 102, 119, 140, 143, 158, 203

physical processes, 14–15, 25–26, 29–30, 41, 44, 68, 86, 98, 100, 107, *109,* 111, 124, 174, 193, 229, 254–256

phytoliths, 159

phytoplankton, 39–46, 145, 170–171

placozoans, 76, 143

plankton, 36, 145, 159, 168, 213. *See also* phytoplankton

plants/plant life: carbon in, 170–172; chlorophyll in, 43, *43,* 54, 169; cuticle in, 64, 178; flowering, 181, 194; green algae, 44, 85, 136, 145, 149, 177, 179–180, 203; influences on habitability, 193–194; overview, 169–181; oxygen and, 150, 172; phytoliths on, 159; stabilization of soils by, 174–177; stomata in, 64, 169; transpiration, 64; vascular, 170–171, 178–181; water and, 63–65. *See also* photosynthesis; phytoplankton

plate tectonics: carbon and, 27–29; climate and, 185, 187; in fault systems, 88; Harland, W. Brian on, 191; overview, 88–89, 91–96, 197–198, 256; volcanoes and, 27

pollutants, 215, 224

polycyclic aromatic hydrocarbons (PAHs), 228–229

porewaters, 124, 152, 162

The Possibility of Life (Green), 226

potassium, 53

precipitation, 4, 42, 52, 62–64, 152–156, *153*, 161–162, 165–166, 229. *See also* rain/rainfall

primates, 72–74, *73*

Principles of Geology (Lyell), 6

prokaryotes, 77–79

proteins: amino acids and, 50, 74, 77, 101–105, 247; cofactors in, 53; collagen, 55, 157; in origins of life, 102, 105
proteobacteria, 85
Proterozoic Eon, 92–93, *127*, 128–130, 136, 143–147, *147*, 161, 188–190, 193–194, 201, 204
protists, 40, 58, 140–141, 156–160, 163, *163*, 168, 176, 179–180, 203
protozoans, 13, 24, 156, 158, 203
Proxima Centauri (star), 252–253
pyrite (FeS_2), 52, 54, 56, 68, 104–106, 115–117, *127*, 128, 148, 152

radioactive carbon (^{14}C), 61
radioisotopes, 94, 116
radiolarians, 58, 158, *158*, 167
rain/rainfall, 26, 50, 56, 61–63, 194, 206, 210–211, 221, 238, 248. *See also* precipitation
Rasmussen, Birger, 123, 124
Raymo, Maureen, 188
reactive iron, *127*, 128
Redfield, Alfred, 44–45
Red Mars (Robinson), 240
renewable resources, 218–220
"The Rime of the Ancient Mariner" (Coleridge), 233–234
Río Tinto, 231, 233
river channels, 174–176, *175*
RNA, 32, 78, 102–107
Robinson, Kim Stanley, 240
Ruddiman, William, 188

saline lakes, 11
salinity, 62, 233
San Andreas Fault, 28, 88, 91
Saturn (planet), 182, 243, 245, *246*, 248–249, 252
Saxe, John Godfrey, 95–96
Schiaparelli, Giovanni, 226
sea-level changes, 215–216, 221
seawater: animal life and, 139–140; gravitational pull of Moon, 243; human intolerance of, 234; molybdenum in, 129; motion of, 61; origin of life, 126–129; Pacific Ocean, 60, 90, 214; phosphate in, 147–148; salinity and, 62, 233; temperature and, 61–62, 210–211
selenium, 57
Sepkoski, Jack, 204
SETI Institute, 255
shallow-water environments, 126–127, 130, 205
Shen, Yanan, 126
siderite ($FeCO_3$), 116
silica (SiO_2), 58, 94, 152, *158*, 158–159, 165–168, 235
silica skeletons, 58, 165–167
silicon (Si), 19, 58, 65
Silurian Period, 178
single-cell organisms, 134, 141, 153, 156, 158, 171
skeletons: archaeocyathids, 165; carbonate, 154, 155–157, 161–166, *166*; *Cloudina, 164,* 165; minerals in, 159–168; phosphorus, *163*; silica, 58, 165–167
Snowball Earth, *189,* 192–193, 201–204
snowpack, 60
sodium, 53
sodium chloride (NaCl), 49, 244
soil, 176–177
solar luminosity, 184, 196–198, 208
Spencer, Chris, 93
Sperling, Erik, 139
Spirit rover, 230, 235–236, 238–240

Squyres, Steve, 229
Stanier, R. Y., 77
sterols, 136–137
Stevenson, David, 254
Stoermer, Eugene, 223
stomata, 64, 169
strontium, 92
subduction, 91, 95–97
Suess, Eduard, 10
sulfate (SO_4^{2-}): anoxic water and, 24; in microbial metabolism, 49; in origin of life, 115; in seawater, 50–51
sulfate (SO_4^{2+}), 24
sulfur dioxide (SO_2), 27, 50, 117
sulfur isotopes, 116–118
sulfur (S): as aerosols, 221; in human bodies, 50; hydrogen sulfide (H_2S), 24, 49–51, 56, 67, 86, 119, 122–123, 128–130; overview of, 49–54, *51*
Sun (star): Earth's relationship to, 29, 183, 186–187, 195, 198, 208, 225; eclipses of, 250; energy from, 21, 218; Faint Young Sun Paradox, 183–184; planetary impact of, 242–243; ultraviolet radiation from, 66
supercontinents, 93, 97–98, 146, 173, 196
superorganism, 5
surface water, 39–43, *43*, 60, 129, 200, 214, 247

Tamre, Erik, 199
teeth/tooth material, 157, 159, 160–162, *162*
Tharp, Marie, 90
Theory of the Earth (Hutton), 5
Thiemens, Mark, 117
tin, 57
Titan (moon), 245, *248*, 248–249
toadstools, 180. *See also* fungi
Tosca, Nick, 234–235
transpiration, 64
Tree of Life, 69–98, 107, 131–132, 160, 199
The Tree of Life (Malick), 69

uniformitarian view, 4–6
universal phylogeny, 74, *75*
uraninite (UO_2), 116
uranium, 94, 129
Urey, Harold, 100–101
Ussher, James, 3

vanadium, 57, 129
vascular plants, 170–171, 178–181
Venus (planet), 241, 249
Vernadsky, Vladimir Ivanovich, 9–10
vertebrates, 144, 157, 178–181
Vickers, Peter, 249
viruses, 39–40, 44, 80, 159
volcanoes, 8, 26–30, 49–50, 68, 90, 94, 110, 117, 119, 207–208, 211, 243, 256
Vosseberg, Julian, 133

Walker, Jim, 184
Wallace, Alfred Russel, 227
The War of the Worlds (Welles), 227
water (H_2O): carbon and, 23; deep-water environments, 23, 126–128, 147; on Earth's surface, 39–43, *43,* 60, 129, 200, 214, 247; on Enceladus (moon), 182, 245–248, *246*; on Europa (moon), 242–245, *244,* 247; evaporation, 49, 51, 62–64, 161, 166, 170, 235; floods/flooding, 174–176; fresh, 18, 60–66, 95, 137, 159, 186; groundwater, 60, 130, 176, *231*; in human bodies, 47;

water (H_2O) (*cont*)
  hydrological cycle, 63–64, 95; irrigation use, 222; Mars and, 233–236; overview of, 60–64; porewaters, 124, 152, 162; precipitation, 4, 42, 52, 62–64, 152–156, *153,* 161–162, 165–166, 229; rain/rainfall, 26, 50, 56, 61–63, 194, 206, 210–211, 221, 238, 248; seawater, 60–62; shallow-water environments, 126–127, 130, 205; snowpack, 60; vapor, 27, 33, 52, 60–64, 66, 111, 169–170, 183, 194. *See also* seawater
Wegener, Alfred, 89
Welles, Orson, 227
Wells, H. G., 227, 255
Werner, Abraham Gottlob, 4
whiffs of oxygen, 120, 122
Widdel, Fritz, 57
wildfires, 209–210
Woese, Carl, 77–79
Wolfe, Ralph, 78
woodland habitat, 16, 89
Wordsworth, Robin, 239
Wulf, Andrea, 9

Xeromyces bisporus, 234

zinc, 49, 57
zircon, 94–95, 108
zirconium, 94