A BRIEF HISTORY OF EARTH

Four Billion Years in Eight Chapters

ANDREW H. KNOLL

ch.
CUSTOM HOUSE

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ELEMENTAL COMPOSITION OF THE EARTH AND LIFE
(percent, by weight)

Earth	
Iron	33
Oxygen	31
Silicon	19
Magnesium	13
Nickel	1.9
Calcium	0.9
Aluminum	0.9
Everything else	0.3
Cells in the human body:	
Oxygen	65
Carbon	18
Hydrogen	10
Nitrogen	3
Calcium	1.5
Phosphorous	1
Everything else	1.5

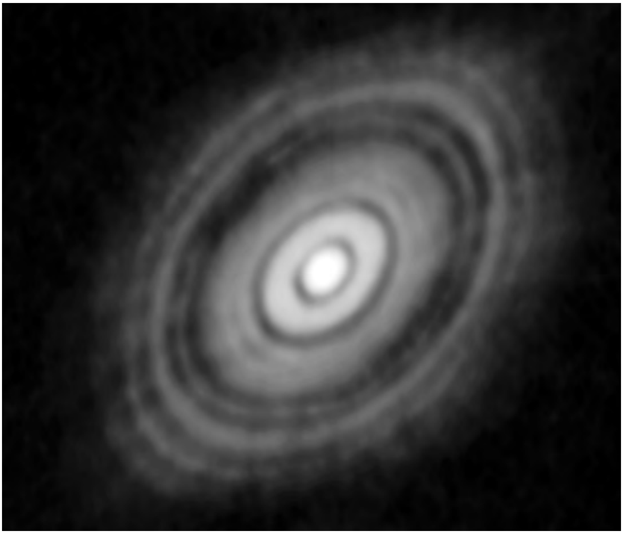


FIGURE 1. This remarkable image, taken by the Atacama Large Millimeter Array, shows HL Tauri, a young Sun-like star, and its protoplanetary disk. The rings and gaps evident in the image record emerging planets as they sweep their orbits clear of dust and gas. Our own solar system may have looked much like this 4.54 billion years ago. *ALMA (ESO/NAOJ/NRAO)/NASA/ESA*

FIGURE 2. The Allende meteorite, a carbonaceous chondrite that fell to Earth in 1969. Rounded grains inside are chondrules, rocky spheroids that formed early in our solar system's history and aggregated into larger bodies, eventually to form the inner planets of our solar system, including Earth. Carbonaceous chondrites contain both water and organic molecules, furnishing materials that would eventually end up in our atmosphere, oceans, and life. The accompanying block is 1 centimeter on each side. *Matteo Chinellato (via Wiki, Creative Commons)*

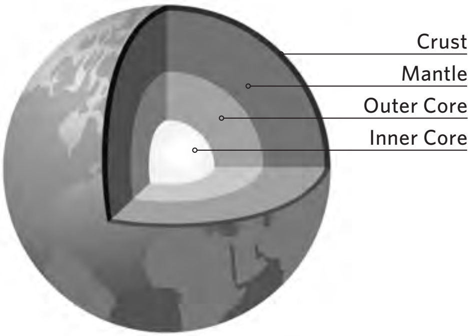
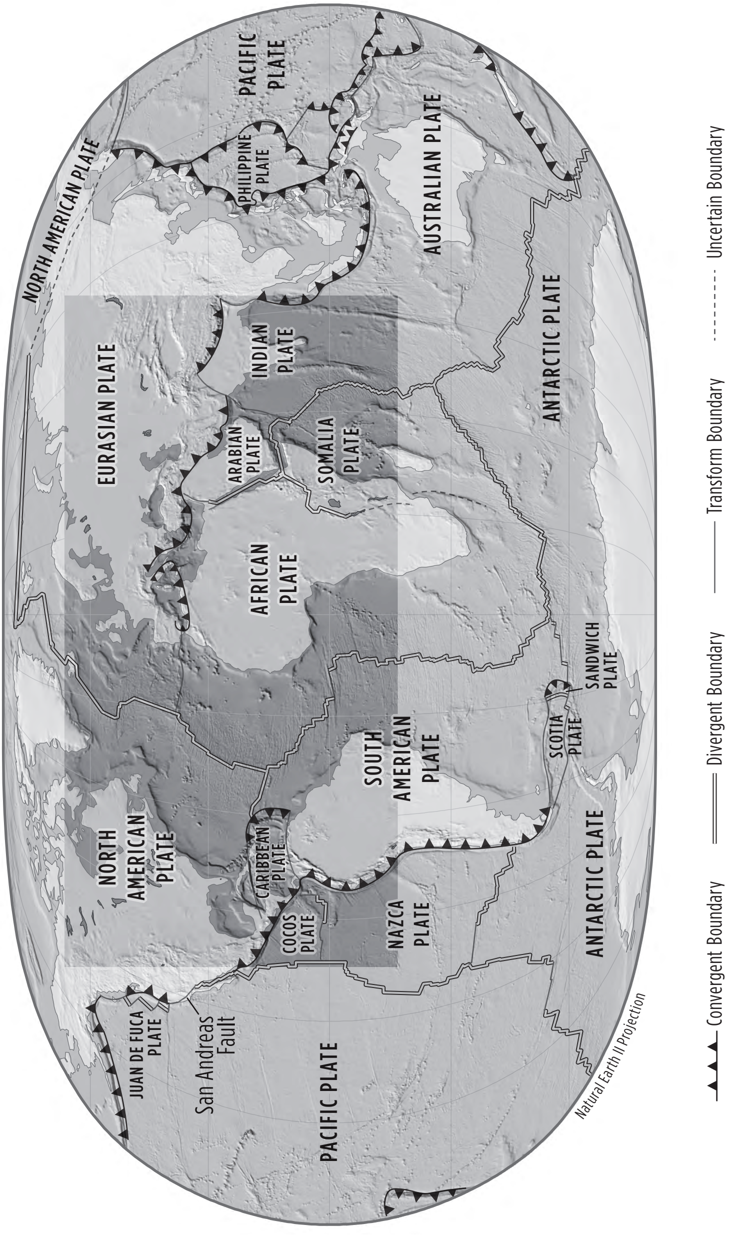


FIGURE 3. A cross section of the Earth, showing our planet's internal zonation. The crust on which we tread is only a thin surficial veneer, and the atmosphere and oceans are even thinner.

FIGURE 4. Siccar Point, in Scotland, where James Hutton grasped the dynamism of the Earth and the immensity of time. *Andrew H. Knoll*

FIGURE 5. The revolutionary map of the Earth produced by Bruce Heezen and Marie Tharp in 1977. Long, fault-scarred mountain chains rise from the deep sea floor. *World Ocean Floor Panorama, Bruce C. Heezen and Marie Tharp, 1977. Copyright by Marie Tharp 1977/2003. Reproduced by permission of Marie Tharp Maps LLC and Lamont-Doherty Earth Observatory*.

FIGURE 6. The Earth's surface consists of interlocking plates. Plates are pulled apart, and new ocean crust forms along oceanic ridge systems (shown as double lines); this causes continents to diverge from one another. Plates glide past each other along transform faults (single lines), but at convergent margins (toothed lines) they collide, with one plate subducting beneath the other. Volcanoes, earthquakes, and actively growing mountain belts are concentrated along convergent plate boundaries. *Map illustration by Nick Springer/Springer Cartographics, LLC*


NORTH AMERICAN PLATE
PACIFIC PLATE
PHILIPPINE PLATE
AUSTRALIAN PLATE
EURASIAN PLATE
INDIAN PLATE
ARABIAN PLATE
SOMALIA PLATE
AFRICAN PLATE
ANTARCTIC PLATE
SANDWICH PLATE
SCOTIA PLATE
SOUTH AMERICAN PLATE
NORTH AMERICAN PLATE
CARIBBEAN PLATE
COCOS PLATE
NAZCA PLATE
ANTARCTIC PLATE
JUAN DE FUCA PLATE
San Andreas Fault
PACIFIC PLATE
Natural Earth II Projection
Convergent Boundary
Divergent Boundary
Transform Boundary
Uncertain Boundary

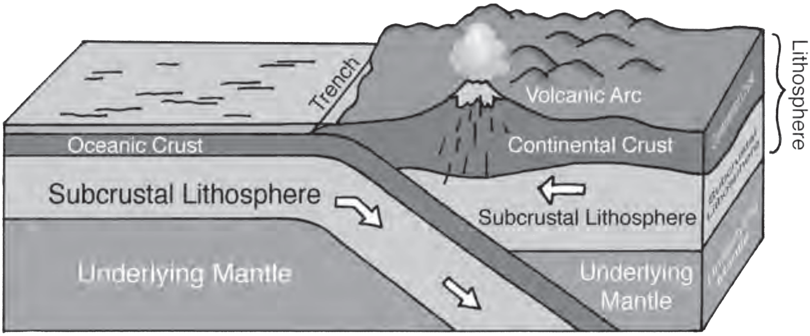


FIGURE 7. Mountains form where continents collide (e.g., the Appalachians) or oceanic crust subducts beneath a continent, as shown here (the Andes), all driven by convection in the mantle below. Trenches, linear depressions in the deep seafloor, form a surface expression of convergent plate boundaries. *Source: U.S. Geological Survey*

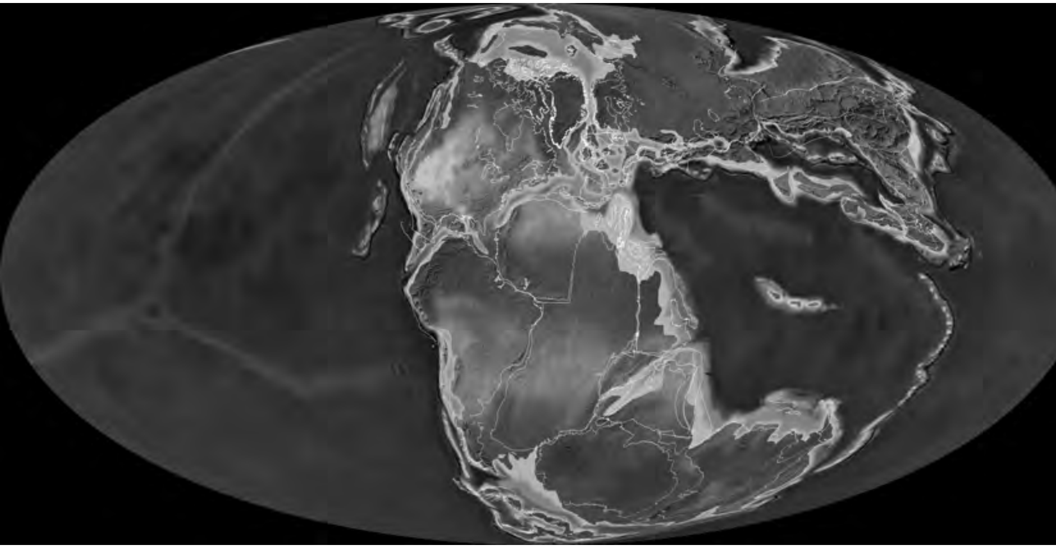


FIGURE 8. A reconstruction of Earth's surface as it existed circa 180 million years ago. The continents, which aggregated earlier, largely remain clustered. The Atlantic Ocean has just begun to open. In contrast, Tethys (the large sea south of Asia and north of the Gondwana continents) will soon close as Africa, India, and Australia separate and move northward. Eventually they will collide with Europe and Asia, producing the long mountain chain that runs from the Alps to the Himalaya, and on to New Guinea. *2016 Colorado Plateau Geosystems, Inc.*

FIGURE 9. A cliff made of 800- to 750-million-year-old sedimentary rocks, exposed in the glaciated highlands of Spitsbergen. These rocks, and rocks like them found globally, preserve evidence of a rich microbial biota that existed long before the evolution of plants and animals. *Andrew H. Knoll*

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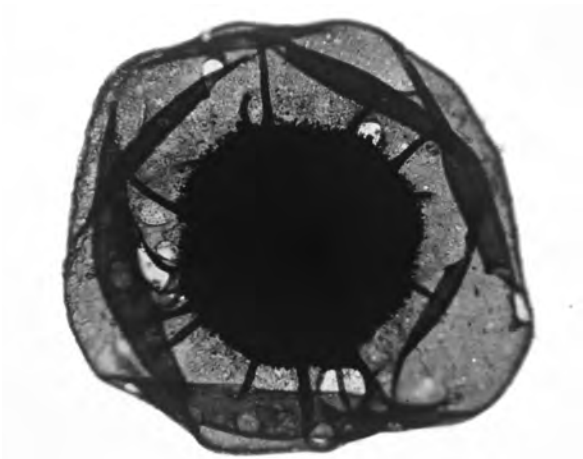

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FIGURES 10–13. Nodules of black chert occur within limestones in the Spitsbergen succession (Figure 10). These contain abundant and diverse microfossils of cyanobacteria (Figures 11 and 12) and other microorganisms. Mudstones in the same succession preserve beautiful fossils of single-celled eukaryotic microorganisms (Figure 13). *Andrew H. Knoll*

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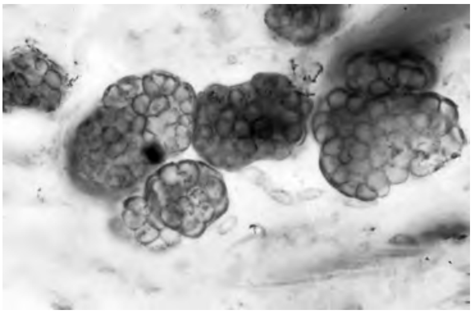

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FIGURE 14. Stromatolites, laminated structures that formed when microbial communities trapped fine-grained sediments and bound them in place. Microbial communities colonized the firm surfaces of cobbles and then accreted upward as sediments accumulated, their growth recorded by the fine layering seen in the picture. The columns on the right are about 5 centimeters (2 inches) across. *Andrew H. Knoll*

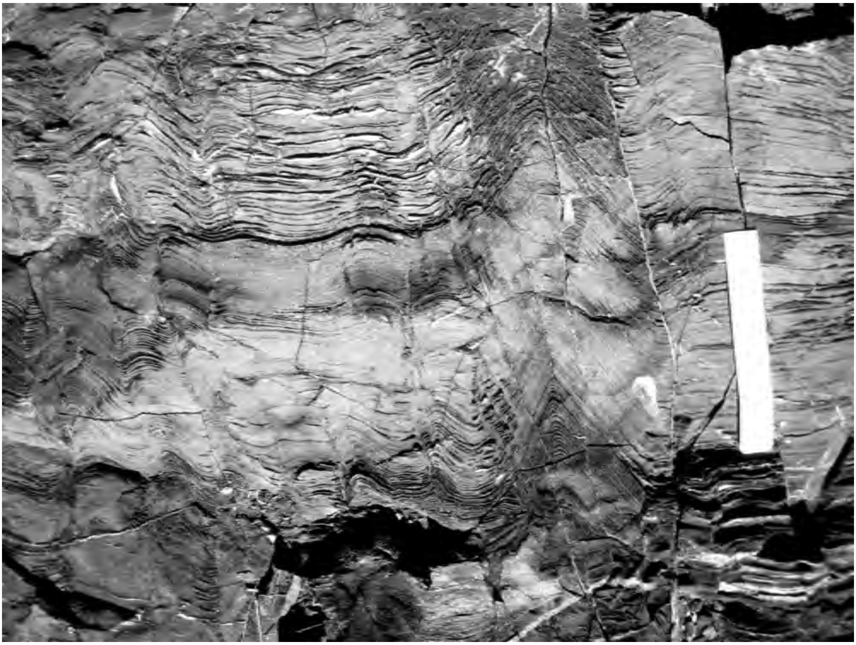


FIGURE 15. Stromatolites in 3.45-billion-year-old sedimentary rocks from Western Australia. Along with evidence from carbon and sulfur isotopes, these structures document the presence of microbial life early in Earth's history. Scale is 15 centimeters (6 inches) long. *Andrew H. Knoll*

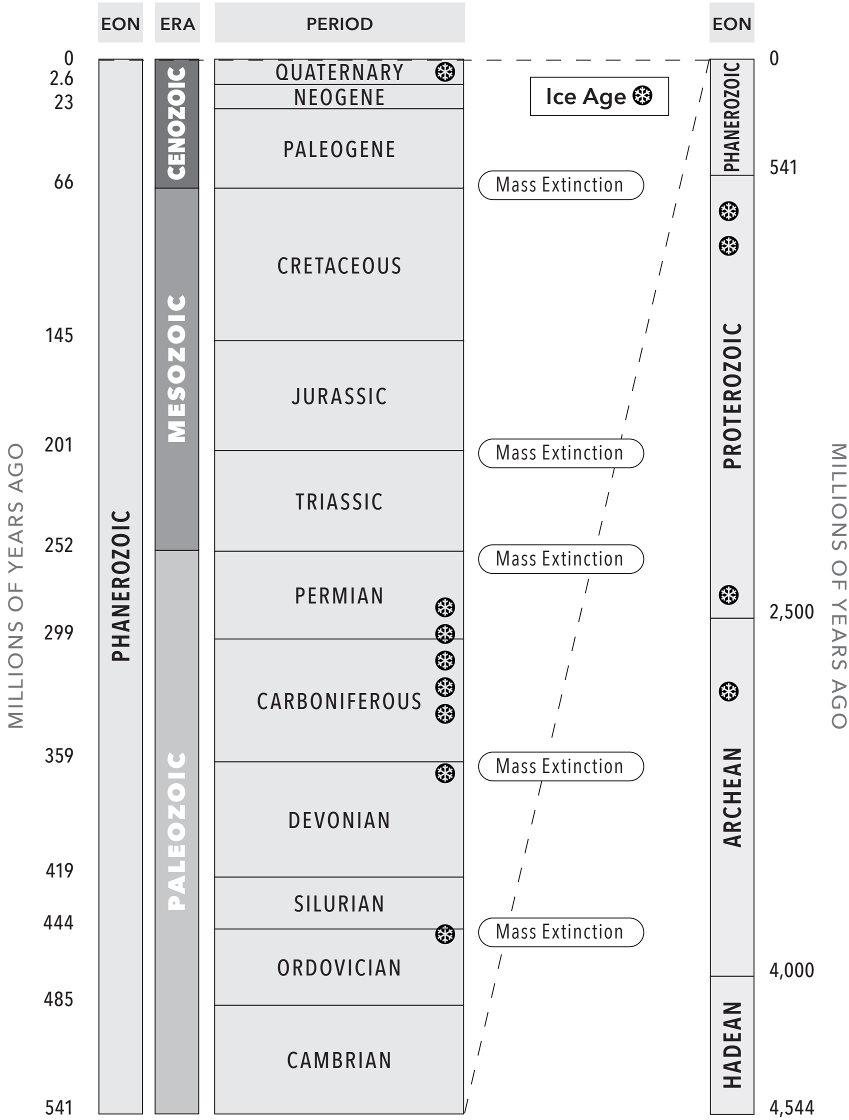


FIGURE 16. The geologic timescale. Time intervals based on the International Chronostratigraphic Chart, version 2020, produced by the International Commission on Stratigraphy.

FIGURE 17. 2.5-billion-year-old iron formation exposed in Dales Gorge, Western Australia. *Andrew H. Knoll*

The question of life without oxygen is relatively easy to address because oxygen-free environments exist today, and they teem with life. How does life persist in these forbidding (to us) habitats? In our familiar macroscopic world, plants gain energy and carbon via photosynthesis, harnessing light energy to form sugar from carbon dioxide and releasing oxygen gas as a byproduct. In simplified form, the photosynthetic equation looks like this:

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

Animals do the reverse, ingesting organic molecules as food and reacting some of it with oxygen to gain energy—what we call respiration (plants also respire):

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

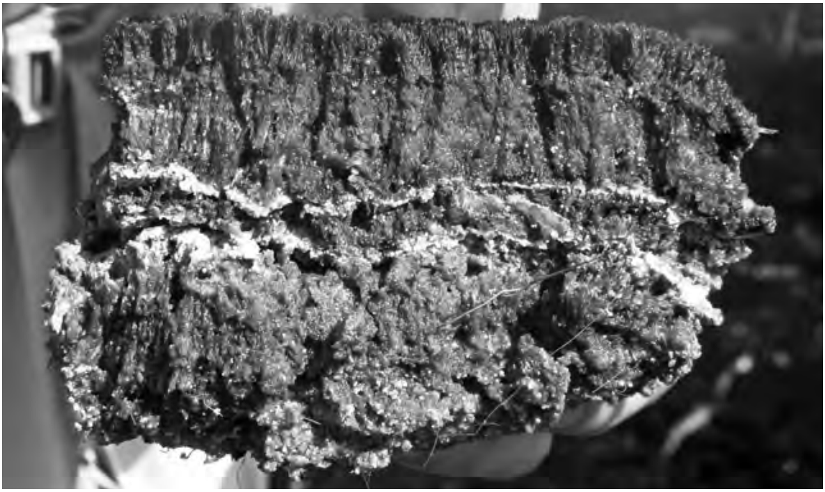
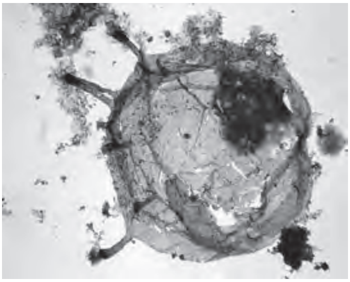


FIGURE 18. Oxygen-free habitats are common on the modern Earth. Here we see a microbial community from the Turks and Caicos Islands, in the Caribbean. The dark fibrous layer at the surface (above the upper arrow), actually pigmented deep green by cyanobacteria, is exposed to the air and so is oxygen-rich. Below this veneer (in the zone between the arrows), light still penetrates, but oxygen does not, giving rise to the slightly lighter layer rich in purple photosynthetic bacteria. These bacteria use hydrogen sulfide as a source of electrons and do not generate oxygen gas. In this layer and beneath it, aerobic respiration is impossible; some microorganisms respire using sulfate and other ions instead, and others ferment organic molecules. *Andrew H. Knoll*



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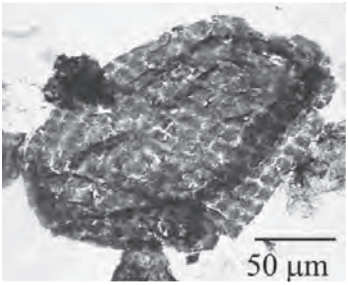

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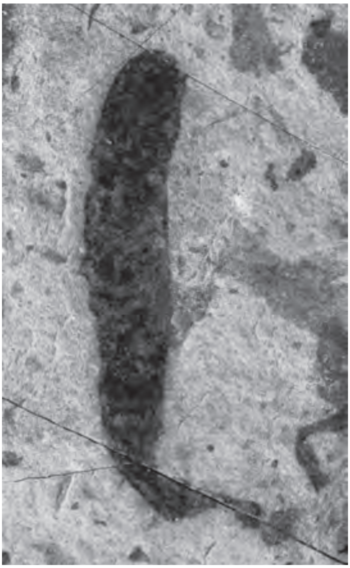

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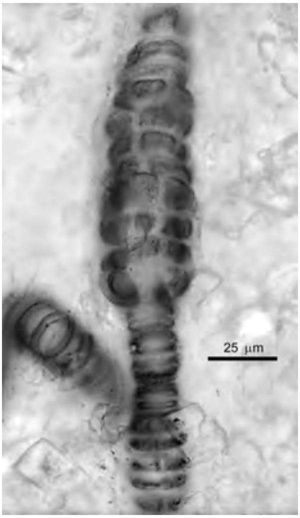
FIGURES 19–21. Fossils of early eukaryotic organisms. (Figure 19) a single-celled organism with arm-like extensions that may have functioned to absorb organic molecules for food, from 1,500- to 1,400-million-year-old rocks in northern Australia; (Figure 20) a thick, plate-like cell wall that would have protected its owner from an unfavorable environment and other organisms, also from 1,500- to 1,400-million-year-old rocks in Australia; (Figure 21) among the oldest known organisms with a simple multicellular structure, from nearly 1.6 billion-year-old rocks in China. The bar in 20 = 50 microns in 19 and 20, and = 5 millimeters in 21. *Figures 19 and 20 by Andrew H. Knoll; Figure 21 courtesy of Maoyan Zhu, Nanjing Institute of Geology and Palaeontology*



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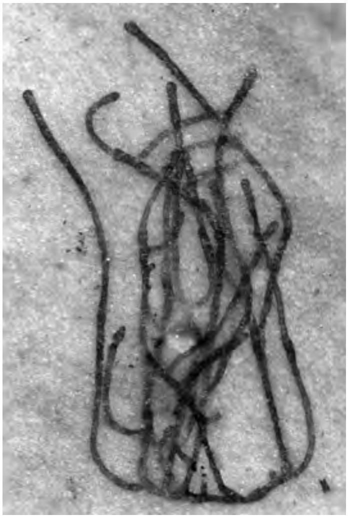

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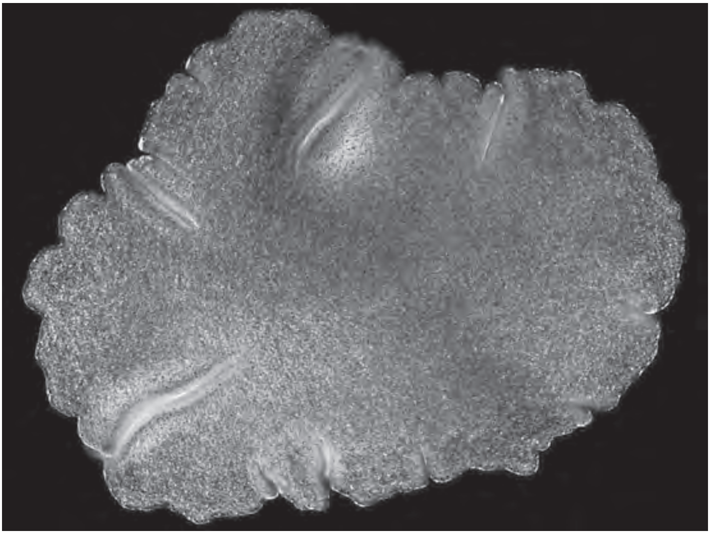
FIGURES 22 AND 23. Fossils show that diverse eukaryotes thrived before the dawn of animals. Here we see the oldest known red (Figure 22) and green (Figure 23) algae, preserved in billion-year-old rocks from arctic Canada and China, respectively. Bar in Figure 22 = 25 microns for that figure, and = 225 microns for Figure 23. *Figure 22 courtesy of Nicholas Butterfield, University of Cambridge; Figure 23 courtesy of Shuhai Xiao, Virginia Tech*

FIGURE 24. Fossils of early animals in 565-million-year-old sedimentary rocks from Mistaken Point, Newfoundland. Scale bar shows 1 centimeter units. *Courtesy of Guy Narbonne, Queen's University*



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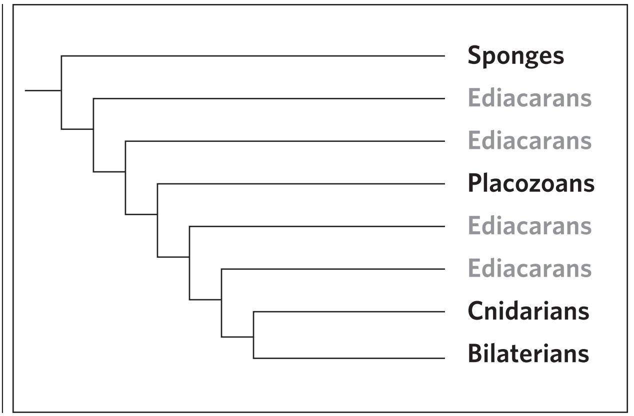
FIGURES 25 AND 26. *Trichoplax adhaerens* and its proposed evolutionary relationship to both Ediacaran and living animals. *Figure 25 courtesy of Mansi Srivastava, Harvard University*



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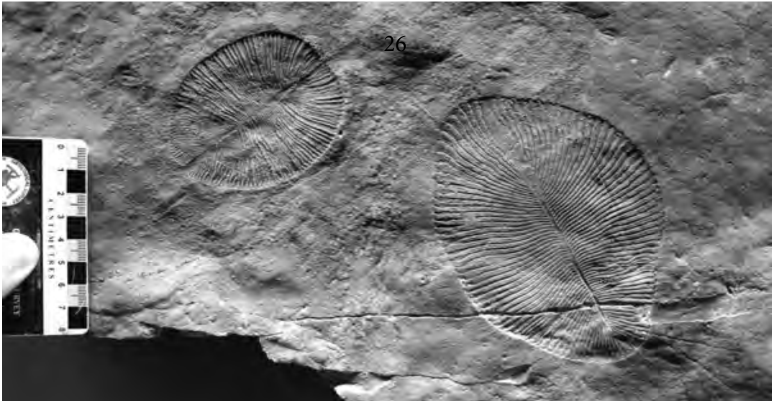

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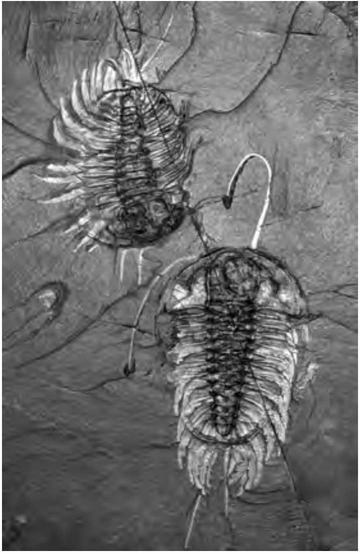
FIGURES 27–31. Fossils and trackways of animals in Ediacaran rocks, including *Dickinsonia* (Figure 27), *Arborea* (Figure 28), the earliest mineralized animal skeleton (Figure 29), *Kimberella* (Figure 30), and tracks made by an early bilaterian animal with limbs (Figure 31). *Figure 27 courtesy of Alex Liu, University of Cambridge; Figure 28 courtesy of Frankie Dunn, University of Oxford; Figures 29 and 31 courtesy of Shuhai Xiao, Virginia Tech; Figure 30 courtesy of Mikhail Fedonkin, Geological Institute, Russian Academy of Sciences*

FIGURES 32–34. Cambrian fossils from the Burgess Shale. Trilobites, showing exquisitely preserved limbs and antennae (Figure 32); *Opabinia*, an extinct relative of arthropods (Figure 33); and a polychaete worm with conspicuous bristles (Figure 34). *Copyright Smithsonian Institution—National Museum of Natural History. Photographs by Jean-Bernard Caron.*



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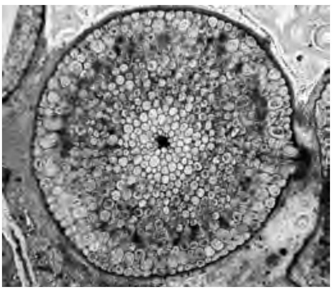
FIGURES 35–37. The Rhynie Chert, 407 million years old, Scotland. Rhynie rocks provide one of our earliest glimpses of terrestrial ecosystems, including simple plants (Figure 35, anatomically preserved cross section in Figure 36), animals, fungi (Figure 37, arrows point to fungi living on the tissues of Rhynie plants), algae, protozoans, and bacteria, all living on land or in shallow pools. *Figure 35 courtesy of Alex Brasier, University of Aberdeen; Figure 36 courtesy of Hans Steur; Figure 37 courtesy of Paleobotany Group, University of Münster*



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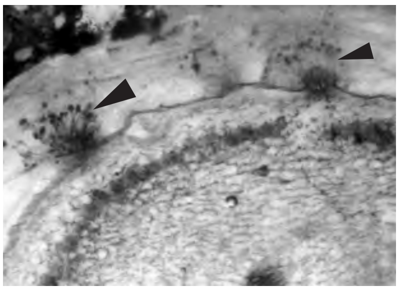

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FIGURE 38. *Tiktaalik,* a 375-million-year-old fossil (reconstructed on left) that exhibits features intermediate between those of fish and land vertebrate animals. *Courtesy of Neil Shubin, University of Chicago*

FIGURE 39. *Patagotitan mayorum,* a gigantic titanosaur skeleton on display in the American Museum of Natural History, New York. From snout to tail, the skeleton is 122 feet (37 meters) long. © *American Museum of Natural History/D. Finnin*

FIGURE 40. *Archaeopteryx lithographica*, a remarkable fossil that links dinosaurs and birds. This is the original specimen displayed at the Museum für Naturkunde in Berlin. © *H. Raab* (*User: Vesta*)/*source: https://commons.wikimedia.org/wiki/File:Archaeopteryx_lithographica_(Berlin_specimen).jpg*

FIGURE 41. The Cretaceous-Paleogene boundary in Gubbio, Italy, where Walter Alvarez developed the case for mass extinction by meteorite impact. White limestones to the lower right were deposited toward the end of the Cretaceous Period; they contain diverse skeletons of tiny foraminiferans and coccolithophorid algae. The reddish limestones in the upper left formed at the beginning of the Paleogene Period; they contain only a few foram and coccolithophorid species. Separating them is a thin layer of fine mudstone, at the top of the white zone, much sampled by curious geologists. *Andrew H. Knoll*

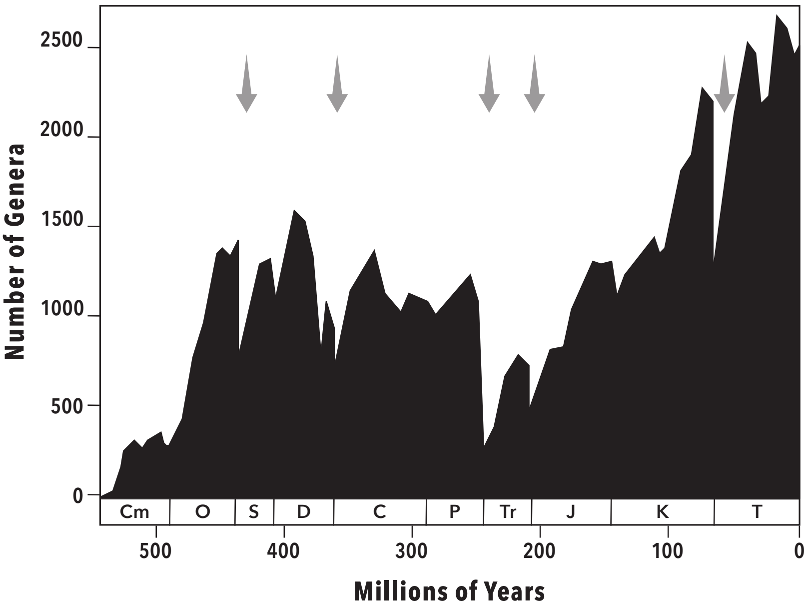

FIGURE 42. A compilation of the genus-level diversity of marine animals through time, painstakingly developed by Jack Sepkoski. Arrows point to five moments during the past 500 million years when diversity plummeted rapidly—the "Big Five" mass extinctions. *Source: Sepkoski's Online Genus Database*

FIGURE 43. The Permian-Triassic boundary exposed in Meishan, China. The massively bedded rocks in the lower right are later Permian limestones rich in fossils. Above them, the rocks turn abruptly to fine-grained limestones that contain few fossils. Some 90 percent of marine animal species went extinct at the point in time marked by the change in sedimentary rock type. *Andrew H. Knoll*

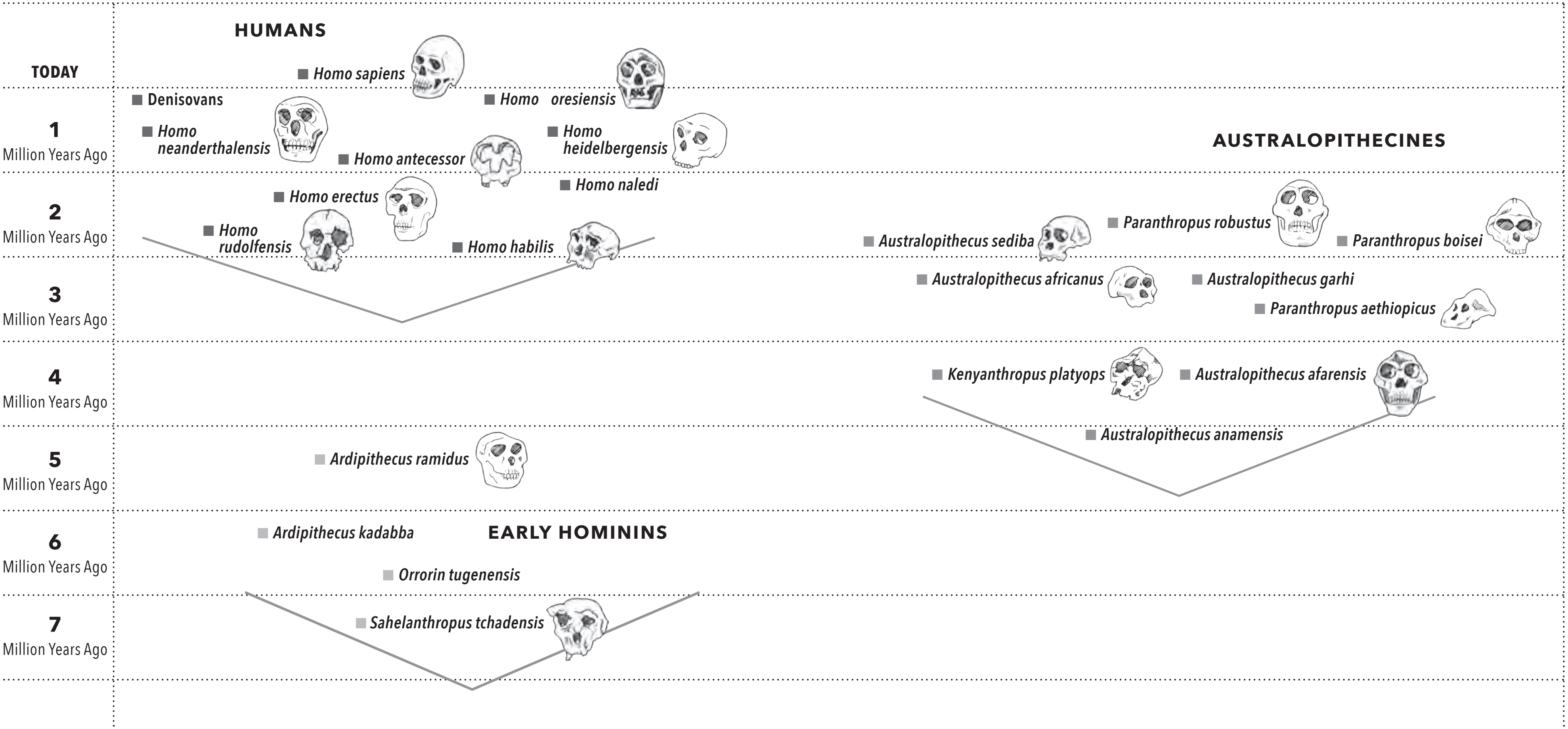

FIGURE 44. Hominin diversity over the past 7 million years; humans are the sole surviving lineage of a once diverse group.

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FIGURES 45 AND 46. Humankind's great leap forward: (Figure 45) Exquisite animals carved from mammoth ivory nearly 40,000 years ago. (Figure 46) The oldest known cave paintings, from Indonesia, dating back some 44,000 years. *Figure 45 copyright Museum der Universität Tübingen MUT, J. Lipták; Figure 46 courtesy of Adam Brumm, Griffith University, photo credit Ratno Sardi*

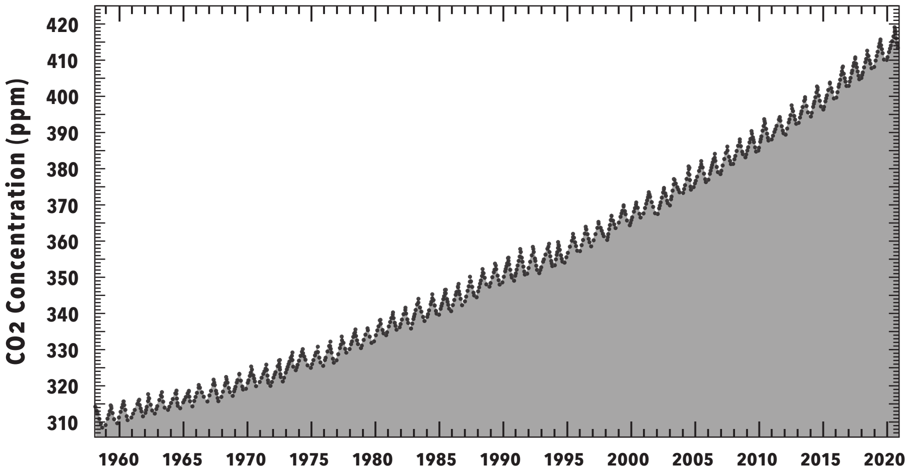

FIGURE 47. The amount of carbon dioxide in the atmosphere, measured hourly since 1958 from a station atop Mauna Loa in Hawaii. The small annual oscillations reflect the fact that there is more land in the Northern Hemisphere than below the equator, and so more photosynthesis in the northern summer, drawing down carbon dioxide levels. In the northern winter, photosynthesis slows but respiration keeps its pace, restoring carbon dioxide to the atmosphere. *Scripps Institution of Oceanography*

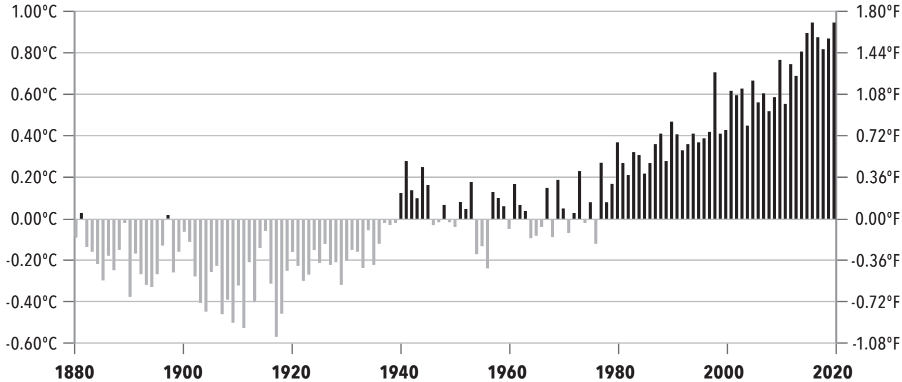

FIGURE 48. Global temperature over the past 140 years. The chart shows the deviation in May temperatures from their twentieth-century average. Before 1940, global temperatures were consistently below the twentieth-century average; since 1978, they have been consistently above the average and getting warmer by the year. *Source: NOAA Climate.gov*

Further Reading

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