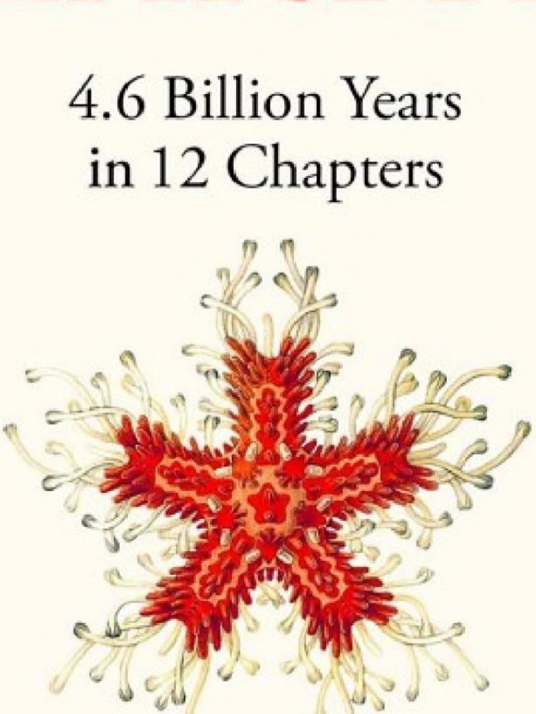
‘Who will enjoy reading this book? – Everybody!’
JARED DIAMOND

A (VERY) SHORT HISTORY OF LIFE ON EARTH

4.6 Billion Years in 12 Chapters



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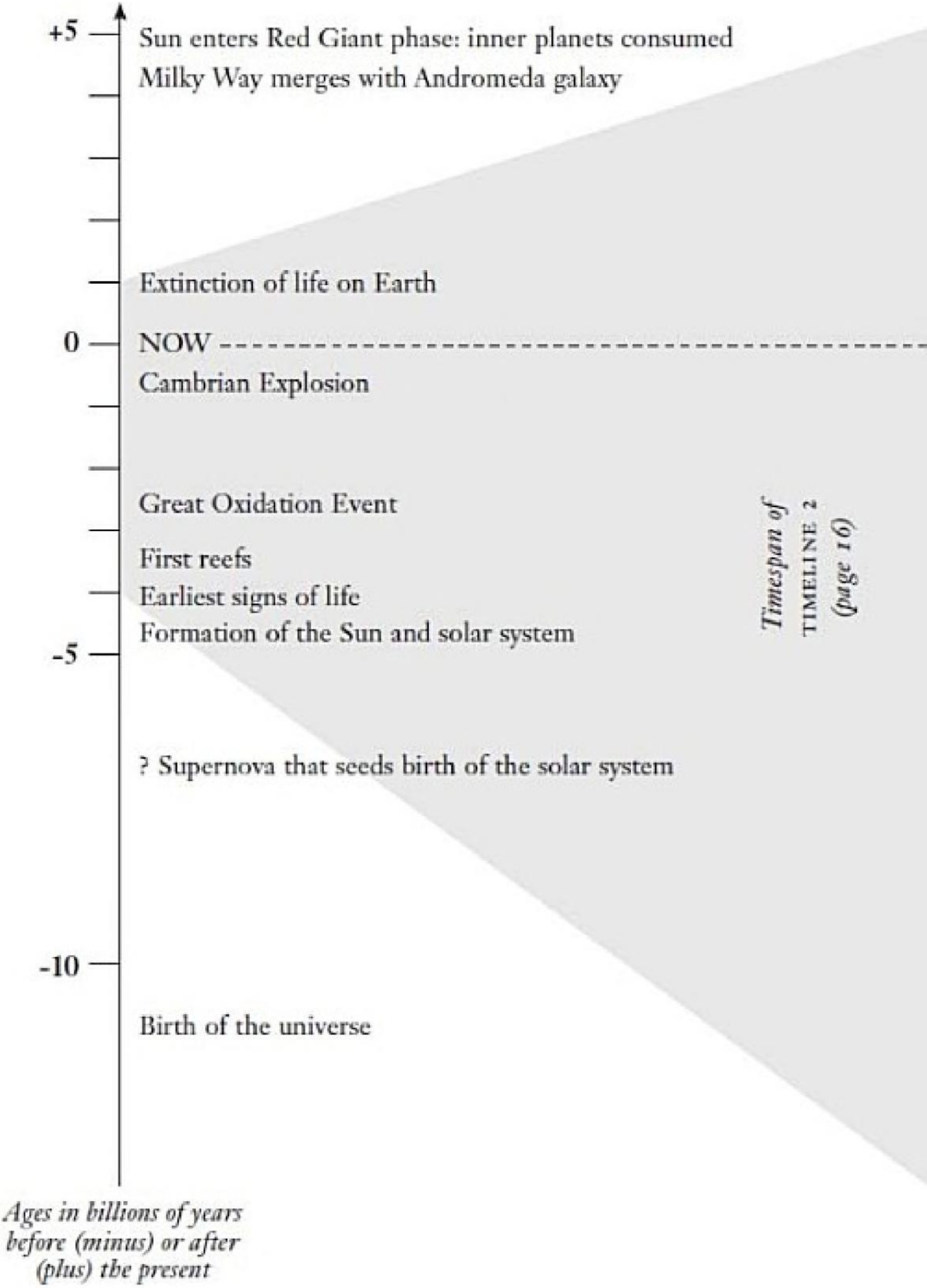

1

A SONG *of*
FIRE *and* ICE

Once upon a time, a giant star was dying. It had been burning for millions of years; now the fusion furnace at its core had no more fuel to burn. The star created the energy it needed to shine by fusing hydrogen atoms to make helium. The energy produced by the fusion did more than make the star shine. It was vital to counteract the inward pull of the star's own gravity. When the supply of available hydrogen began to run low, the star began to fuse helium into atoms of heavier elements such as carbon and oxygen. By then, though, the star was running out of things to burn.

The day came when the fuel ran out completely. Gravity won the battle: the star imploded. After the millions of years of burning, the collapse took a split second. It prompted a rebound so explosive that it lit up the universe – a supernova. Any life that might have existed in the star's own planetary system would have been obliterated. But in the cataclysm of its death were born the seeds of something new. Even heavier chemical elements, forged in the final moments of the star's life – silicon, nickel, sulphur and iron – were spread far and wide by the explosion.

Millions of years later, the gravitational shock wave of the supernova explosion passed through a cloud of gas, dust and ice. The stretch and squeeze of the gravitational wave made the cloud fall in on itself. As it contracted, it started to rotate. The pull of gravity squeezed the gas at the cloud's centre so much that atoms began to fuse together. Hydrogen atoms were pressed together, forming helium, creating light and heat. The circle of stellar life was complete. From the death of an ancient star emerged another, fresh and new – our Sun.

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The cloud of gas, dust and ice was enriched with the elements created in the supernova. Swirling around the new Sun, it also coagulated into a system of planets. One of them was our Earth. The infant Earth was very different from the one we know today. The atmosphere would have been to us an unbreathable fog of methane, carbon dioxide, water vapour and hydrogen. The surface was an ocean of molten lava, perpetually stirred up by the impacts of asteroids, comets and even other planets. One of these was Theia, a planet about the same size as today's Mars.[1] Theia struck the Earth a glancing blow, and disintegrated. The collision blasted much of the Earth's surface into space. For a few million years, our planet had rings, like Saturn. Eventually the rings coalesced to create another new world – the Moon.[2] All this happened approximately 4,600,000,000 (4.6 billion) years ago.

Millions more years passed. The day came when the Earth had cooled enough for the water vapour in the atmosphere to condense and fall as rain. It rained for millions of years, long enough to create the first oceans. And oceans were all there were – there was no land. The Earth, once a ball of fire, had become a world of water. Not that things were any calmer. In those days the Earth spun faster on its axis than it does today. The new Moon loomed close above the black horizon. Each incoming tide was a tsunami.

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A planet is more than a jumble of rocks. Any planet more than a few hundred kilometres in diameter settles out into layers over time. Less dense materials such as aluminium, silicon and oxygen combine into a light froth of rocks near the surface. Denser materials such as nickel and iron sink to the core. Today, the Earth's core is a rotating ball of liquid metal. The core is kept hot by gravity, and the decay of heavy radioactive elements such as uranium, forged in the final moments of the ancient supernova. Because the Earth spins, a magnetic field is generated in the core. The tendrils of this magnetic field reach right through the Earth and stretch far out into space. The magnetic field shields the Earth from the solar wind, a constant storm of energetic particles streaming from the Sun. These particles are electrically charged, and, repelled by the Earth's magnetic field, bounce off, or flow around the Earth and into space.

The Earth's heat, radiating outwards from the molten core, keeps the planet forever on the boil, just like a pan of water simmering on a stove. Heat rising to the surface softens the overlying layers, breaking up the less dense but more solid crust into pieces, and, forcing them apart, creates new oceans between. These pieces, the tectonic plates, are forever in motion. They bump against, slide past or burrow beneath one another. This movement carves deep trenches in the ocean floor and raises mountains high above it. It causes earthquakes and volcanic eruptions. It builds new land.

As the bare mountains were thrust skywards, vast quantities of the crust were sucked back into the depths of the Earth in deep ocean trenches, at the edges of the tectonic plates. Laden with sediment and water, this crust was drawn deep into the Earth's interior – only to return to the surface, changed into new forms. The ocean-floor sludge at the fringes of vanished continents might, after hundreds of millions of years, re-emerge in volcanic eruptions,[3] or be transformed into diamonds.

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Amid all this tumult and disaster, life began. It was the tumult and disaster that fed it, nurtured it, made it develop and grow. Life evolved in the deepest depths of the ocean, where the edges of tectonic plates plunged into the crust; and where boiling hot jets of water, rich in minerals and under extreme pressure, gushed out from cracks in the ocean floor.

The earliest living things were no more than scummy membranes across microscopic gaps in rocks. They formed when the rising currents became turbulent and diverted into eddies, and, losing energy, dumped their cargo of mineral-rich debris[4] into gaps and pores in the rock. These membranes were imperfect, sieve-like, and, like sieves, allowed some substances to cross but not others. Even though they were porous, the environment inside the membranes became different from the raging maelstrom beyond, calmer, more ordered. A log cabin with a roof and walls is still a haven from the arctic blast outside, even if its door bangs and its windows rattle. The membranes made a virtue of their leakiness, using holes as gateways for energy and nutrients, and as exit points for wastes.[5]

Protected from the chemical clamour of the outside world, these tiny pools were havens of order. Slowly, they refined the generation of energy, using it to bud off small bubbles, each encased in its own portion of the parent membrane. This was haphazard at first, but gradually became more predictable, as a result of the development of an internal chemical template that could be copied and passed down to new generations of membrane-bound bubbles. This ensured that new generations of bubbles were, more or less, faithful copies of their parents. The more efficient bubbles began to thrive at the expense of those less well-ordered.

These simple bubbles found themselves at the very gates of life, in that they found a way to halt – if temporarily, and with great effort – the otherwise inexorable increase in entropy, the net amount of disorder in the Universe. Such is an essential property of life. These foamy lathers of soap-bubble cells stood as tiny clenched fists, defiant against the lifeless world.[6]

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Perhaps the most amazing thing about life – apart from its very existence – is how quickly it began. It stirred itself into existence a mere 100 million years after the planet itself formed, in volcanic depths when the young Earth was still being bombarded from space by bodies large enough to create the major impact craters on the Moon.[7] By 3.7 billion years ago, life had spread from the permanent dark of the ocean depths to the sunlit surface waters.[8] By 3.4 billion years ago, living things had started to throng together in their trillions to create reefs, structures visible from space.[9] Life on Earth had fully arrived.

These reefs were not composed of corals, however – they still lay almost 3 billion years into the Earth's future. They consisted of greenish, hair-thin threads and scuts of slime made from microscopic organisms called cyanobacteria – the same creatures that form the bluish-green scum on ponds today. They spread in sheets over rocks and lawns on the seabed, only to be buried by sand in the next storm: but conquering again, and being buried once again, building cushion-like mounds of layered slime and sediment. These mound-shaped masses, known as stromatolites, were to become the most successful and enduring form of life ever to have existed on this planet, the undisputed rulers of the world for 3 billion years.[10]

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Life began in a world that was warm[11] but soundless apart from the wind and the sea. The wind stirred an air almost entirely free from oxygen. With no protective ozone layer in the upper atmosphere, the Sun's ultraviolet rays sterilized everything above the surface of the sea, or anything less than a few centimetres beneath the surface. As a means of defence, the cyanobacterial colonies evolved pigments to absorb these harmful rays. Once their energy had been absorbed, it could be put to work. The cyanobacteria used it to drive chemical reactions. Some of these fused carbon, hydrogen and oxygen atoms together to create sugars and starch. This is the process we call 'photosynthesis'. Harm had become harvest.

In plants today, the energy-harvesting pigment is called chlorophyll. Solar energy is used to split water into its constituent hydrogen and oxygen, releasing more energy to drive further chemical reactions. In the earliest days of the Earth, however, the raw materials were just as likely to have been minerals containing iron or sulphur. The best, however, was and remains the most abundant – water. But there was a catch. The photosynthesis of water produces as a waste product a colourless, odourless gas that burns anything it touches. This gas is one of the deadliest substances in the universe. Its name? Free oxygen, or O_2.

To the earliest life, which had evolved in an ocean and beneath an atmosphere essentially without free oxygen, it spelled environmental catastrophe. To set the matter into perspective, however, when cyanobacteria were making their first essays into oxygenic photosynthesis – 3 billion years ago, or more – there was rarely enough free oxygen at any time to count as more than a minor trace pollutant. But oxygen is so potent a force that even a trace spelled disaster to life that had evolved in its absence. These whiffs of oxygen caused the first of many mass extinctions in the Earth's history, as generation upon generation of living things were burned alive.

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Free oxygen became more abundant during the Great Oxidation Event, a turbulent period between about 2.4 and 2.1 billion years ago, when, for reasons still unclear, the concentration of oxygen in the atmosphere at first rose sharply, to greater than today's value of 21 per cent, before settling down to a little below 2 per cent. Although still unbreathably tiny by modern standards, this had an immense effect on the ecosystem.[12]

An upsurge in tectonic activity buried vast quantities of carbon-rich organic detritus – the corpses of generation on generation of living things – beneath the ocean floor. This kept it away from oxygen's reach. The result was a surplus of free oxygen that could react with anything it touched. Oxygen etched the very rocks, turning iron to rust, and carbon to limestone.

At the same time, gases such as methane and carbon dioxide were scrubbed from the air, absorbed by the abundance of newly formed rock. Methane and carbon dioxide are two of the gases in the downy filling of the insulating blanket that keeps the Earth warm. They promote what we call the 'greenhouse effect'. Without them, the Earth plunged into the first and greatest of its many ice ages. Glaciers spread from pole to pole, covering the entire planet in ice for 300 million years. And yet the Great Oxidation Event and subsequent 'Snowball Earth' episode were the kinds of apocalyptic disasters in which life on Earth has always thrived. Many living things died, but life was spurred on to undergo its next revolution.

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For the first 2 billion years in the Earth's story, the most sophisticated form of life was built on the bacterial cell. Bacterial cells are very simple, whether single, or glued together in sheets across the ocean floor, or in the long, angel-hair filaments of cyanobacteria. Each one, on its own, is tiny. As many bacteria could fit on the head of a pin as there were revellers who went to Woodstock, and with room to spare.[13]

Under a microscope, bacterial cells appear simple and featureless. This simplicity is deceptive. In terms of their habits and habitats, bacteria are highly adaptable. They can live almost anywhere. The number of bacterial cells in (and on) a human body is very much greater than the number of human cells in that same body. Despite the fact that some bacteria cause serious disease, we could not survive without the help of the bacteria that live in our guts and enable us to digest our food.

And the human interior, despite its wide variation in acidity and temperature, is, in bacterial terms, a gentle place. There are bacteria for which the temperature of a boiling kettle is as a balmy spring day. There are bacteria that thrive on crude oil; on solvents that cause cancer in humans; or even in nuclear waste. There are bacteria that can survive the vacuum of space; violent extremes of temperature or pressure; and entombment inside grains of salt – and do so for millions of years.[14]

Bacterial cells may be small, but they are famously gregarious. Different species of bacteria swarm together to trade chemicals. The waste products of one species might make a meal for another. Stromatolites – as we have seen, the first visible signs of life on Earth – were colonies of different kinds of bacteria. Bacteria can even swap portions of their own genes with one another. It is this easy trade that means, today, that bacteria can evolve resistance to antibiotics. If a bacterium doesn't have a resistance gene for a particular antibiotic, it can pick it up from the genetic free-for-all of other species with which it shares its environment.

It was the tendency of bacteria to form communities of different species that led to the next great evolutionary innovation. Bacteria took group living to the next level – the nucleated cell.

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At some point before 2 billion years ago, small colonies of bacteria began to adopt the habit of living inside a common membrane.[15] It began when a small bacterial cell, called an archaeon,[16] found itself dependent on some of the cells around it for vital nutrients. This tiny cell extended tendrils towards its neighbours so they could swap genes and materials more easily. The participants in what had been a freewheeling commune of cells became more and more interdependent.

Each member concentrated only on one particular aspect of life.

Cyanobacteria specialized in harvesting sunlight, and became chloroplasts – the bright green specks now found in plant cells. Other kinds of bacteria devoted themselves to releasing energy from food, and became the tiny pink power-packs called mitochondria which are found in almost all cells that have nuclei, whether plant or animal.[17] Whatever their specialism, they all pooled their genetic resources in the central archaeon. This became the nucleus of the cell – the cell's library, repository of genetic information, its memory, and its heritage.[18]

This division of labour made life for the colony much more efficient and streamlined. What was once a loose colony became an integrated entity, a new order of life – the nucleated or 'eukaryotic' cell. Organisms made of eukaryotic cells – whether singly – unicellular – or lots together – multicellular – are called 'eukaryotes'.[19]

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The evolution of the nucleus allowed for a more organized system of reproduction. Bacterial cells generally reproduce by dividing in half to create two identical copies of the parent cell. Variation from the addition of extra genetic material is piecemeal and haphazard.

In eukaryotes, by contrast, each parent produces specialized reproductive cells as vehicles for a highly choreographed exchange of genetic material. Genes from both parents are mixed together to create the blueprint for a new and distinct individual, different from either parent. We call this elegant exchange of genetic material 'sex'.[20] The increase in genetic variation as a consequence of sex drove an uptick in diversity. The result was the evolution of a wealth of different kinds of eukaryotes, and, over time, the emergence of gatherings of eukaryote cells to make multicellular organisms.[21]

Eukaryotes emerged, quietly and modestly, between around 1,850 and 850 million years ago.[22] They started to diversify around 1,200 million years ago, into forms recognizable as early single-celled relatives of algae and fungi, and unicellular protists, or what we used to call 'protozoa'.[23] For the first time, they ventured away from the sea and colonized freshwater ponds and streams inland.[24] Crusts of algae, fungi and lichens[25] began to adorn seashores once bare of life.

Some even experimented with multicellular life, such as the 1,200-million-year-old seaweed *Bangiomorpha*,[26] and the approximately 900-million-year-old fungus *Ourasphaira*.[27] But there were stranger things. The earliest known signs of multicellular life are 2,100 million years old. Some of these creatures are as large as 12 centimetres across, so hardly microscopic, but they are so strange in form, to our modern eyes, that their relationship with algae, fungi or other organisms is obscure.[28] They could have been some form of colonial bacteria, but we cannot discount the possibility that there once lived entire categories of living organism – bacterial, eukaryote or something entirely other – that died out without leaving any descendants, and which we should therefore find hard to comprehend.

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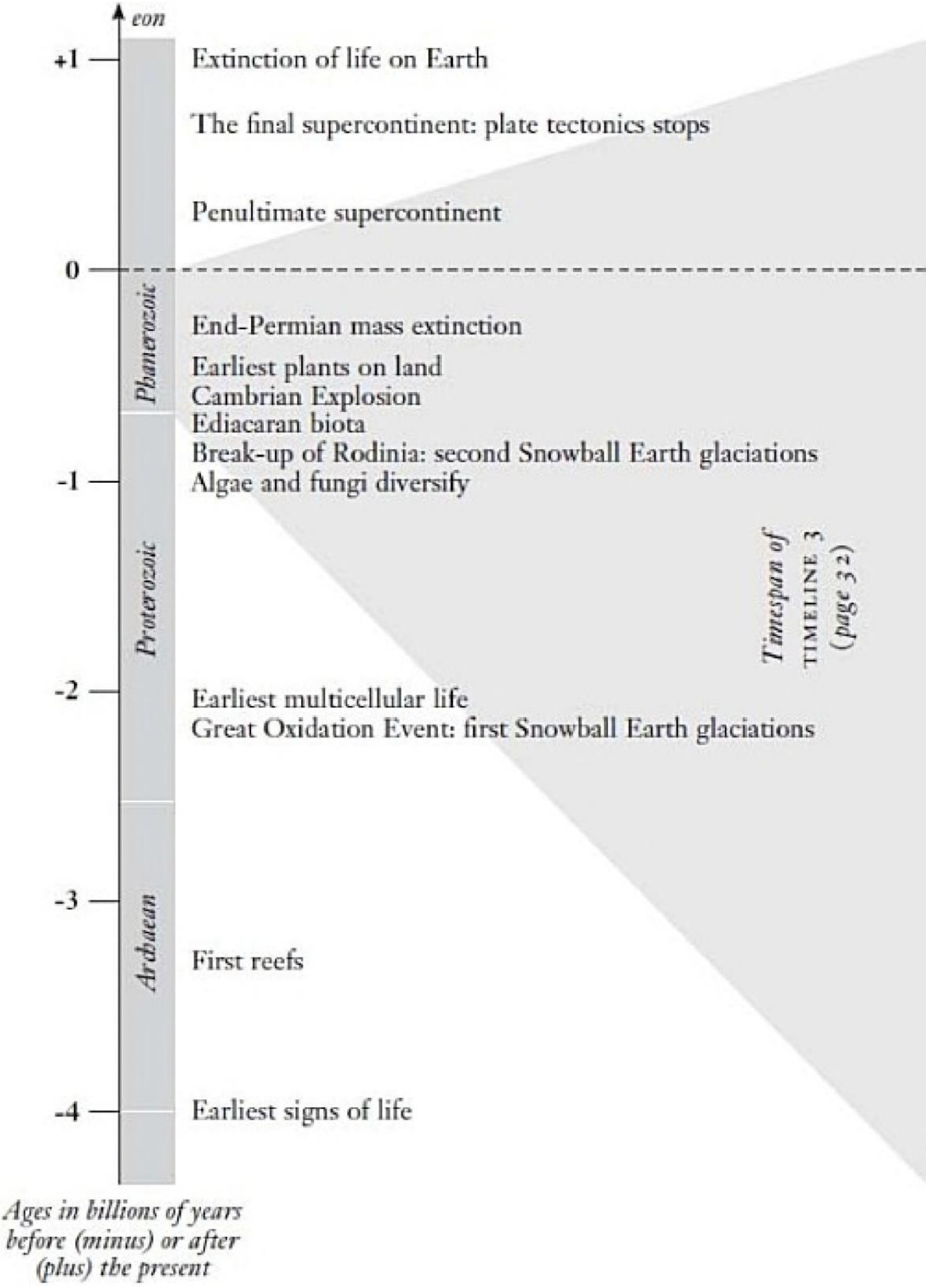
The first rumbles of an oncoming storm came from the rifting and break-up of a supercontinent, Rodinia. This included every significant landmass at the time.[29] One consequence of the break-up was a series of ice ages the like of which had not been seen since the Great Oxidation Event. They lasted 80 million years, and, like the earlier episode, covered the entire globe. But life responded once again by rising to the challenge.

Life entered the lists as a range of peaceable seaweeds, algae, fungi and lichens.

It emerged tough, mobile, and looking for trouble.

For if life on Earth was forged in fire, it was hardened in ice.

Timeline 2. Life on Earth



2

ANIMALS ASSEMBLE

The break-up of the supercontinent Rodinia began around 825 million years ago. It continued for almost 100 million years, leaving a ring of continents around the Equator. The break-up was accompanied by massive volcanic eruptions that brought vast amounts of volcanic rock to the surface, much of it the igneous rock called basalt. Basalt is easily weathered by rain and storm and many of the newly rifted landmasses were in the tropics, where greater heat and humidity makes weathering especially intense.

Wind and weather not only sloughed basalt into the oceans. They also tipped immense amounts of carbon-containing sediment into the depths, out of reach of oxygen. When carbon can be oxidized to form carbon dioxide, the Earth is warmed by the greenhouse effect. But with carbon removed from the atmosphere, the greenhouse effect stalls, and the Earth cools down. This dance of carbon, oxygen and carbon dioxide was to tap out a rhythm in the subsequent history of the Earth and the life that crawled on its face.

The result of the weathering of the fragments of Rodinia was that from around 715 million years ago, the Earth was pitched into a series of world-spanning ice ages that lasted around 80 million years.

As during the episode that followed the Great Oxidation Event more than a billion years earlier, these ice ages were spurs to evolution. They set the stage for the emergence of a new, more active kind of eukaryote – the animals.[1]

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The carbon that washed into the sea entered an ocean which, apart from a thin layer close to the surface in contact with the atmosphere, contained almost no oxygen. Even so, the concentration of oxygen in the atmosphere was no more than a tenth of the present-day value, and even less in the sunlit ocean surface. This was too small to sustain any animal much larger than the full stop at the end of this sentence.

There were some animals, however, that managed to subsist on minute quantities of oxygen. These were the sponges. Sponges first appeared around 800 million years ago,[2] as Rodinia was starting to be torn apart.

Sponges were and are very simple animals. Although sponge larvae are small and mobile, adult sponges remain in one place their whole lives. An adult sponge is simply made, being no more than a shapeless mass of cells perforated by thousands of tiny holes, channels and spaces. The cells that line these spaces draw currents of water through them by beating hair-like extensions called cilia. Other cells absorb detritus from the water current. Sponges have no distinct organs or tissues. A live sponge pushed through a sieve and back into the water will pull itself together into a different shape, but one just as alive, just as functional. It is a simple life that requires little energy – and little oxygen.

But there is no reason to disparage that which is simple. After the earliest sponges were settled, they changed the world.

Sponges living among the carpets of slime that draped the sea floor sieved particles of matter from the water. The volume of water pulled through one sponge in a day was small, but billions of sponges over tens of millions of years had an immense impact. The slow, steady work of sponges led to an even greater accumulation of sea-floor carbon, unavailable for reaction with oxygen. Sponges also cleared the water around them of detritus that would otherwise have been digested by oxygen-sucking decay bacteria. The result was a slow increase in the amount of oxygen dissolved in the sea, and in the air immediately above it.[3]

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Far above the sponges, jellyfishes and small worm-like animals consumed smaller eukaryotes and bacteria in the plankton – the sunny region of the sea closest to the surface.[4] There was more oxygen in the surface waters to start with, but the carbon-rich bodies of creatures in the plankton, once dead, sank more quickly to the bottom, rather than remaining suspended in the water, removing more carbon from the reach of molecular oxygen. Which in turn left more oxygen to accumulate in the ocean and the atmosphere.

Although large enough that some would have been visible to human eyes without a microscope, many of the creatures that made up the plankton were small enough that nutrients and wastes could simply diffuse in and out of their bodies. Those that were a little larger evolved a particular place for nutrients to enter, and for waste to diffuse out again. That place was the mouth, although it also served double duty as an anus.

The development of a distinct anus in some species of otherwise undistinguished worms led to a revolution in the biosphere. For the first time, waste was concentrated into solid pellets, rather than being a general wash of dissolved excrement. These faeces sank quickly to the sea floor rather than diffusing slowly, and this led to a literal race to the bottom. Oxygen-sucking agents of decay began to concentrate their efforts near the sea floor, rather than throughout the water column. The seas, once turbid and stagnant, became clearer, and still richer in oxygen – enough to enable the evolution of larger life forms.[5]

The development of the anus had another consequence. Animals with a mouth at one end and an anus at the other have a distinct direction of travel – a 'head' in front and 'tail' behind. At first these animals lived by picking scraps off the thick carpet of slime that had lain on the ocean floor for more than 2 billion years.

Then they began to burrow beneath the slime. And then they ate the slime itself. The unchallenged reign of the stromatolites was over.

And when the animals had eaten all the slime, they started to eat one another.

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There was still the small matter of worldwide glaciation to contend with. But evolutionary change thrives on adversity. Seaweeds flourished, providing more nourishing fare for early animals than bacteria.[6]

And it could have been that animal life was pushed in the direction of increasing complexity by the very severity of the Snowball Earth glaciations. Following the maxim that what doesn't kill you makes you stronger, animal life had, at its dawn, to be resilient to survive the most demanding period of adversity in its history. Once the glaciations receded – as all glaciations in the history of the Earth eventually have – they left animal life leaner, meaner and ready to take whatever the Earth could throw at it.

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Animal life burst into visibility sometime around 635 million years ago, in what is known as the Ediacaran period. This first flush of complex animal life was a flourish of beautiful, frondlike forms, many of which defy categorization.[7] Although some were animals, others may have been lichens, or fungi, or colonial creatures of uncertain affinity – or something so entirely foreign that we lack any means of comparison.

One of these, a strikingly beautiful creature called *Dickinsonia*, was broad but pancake-flat and segmented. It's easy to imagine one gliding gracefully over the sediment, much as flatworms or sea slugs do today.[8] Another fossil called *Kimberella* might have been a very early relative of molluscs.[9] Others, the rangeomorphs, are even harder to categorize. They resembled plaited loaves and probably remained in one place throughout their lives, although – like strawberry plants – they budded off new colonies round about the parent.[10] The world of these strangely beautiful, alien creatures was placid and quiet. They lived in shallow seas and dotted the shoreline amid the seaweed.[11]

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The earlier Ediacaran creatures tended to be of this soft-bodied, frondlike sort. Creatures that looked more definitely animal-like, and which could have moved about, appeared somewhat later, after about 560 million years ago – alongside a widespread appearance of what are known as trace fossils. Trace fossils aren't impressions of creatures themselves, but signs of their activities. They include track marks and burrows. Trace fossils are as intriguing as the footprints of criminals that have just left the scene of the crime. We can say something of the criminal's build from a footprint, and even of their intent. But we can't say anything much about, say, the clothes they were wearing, or the weapons they were carrying. To do that you'd have to catch the criminal in the act. Rarely, very rarely, can we do the same for trace fossils. One such is a fossil called *Yilingia spiciformis*, which lived at the very end of the Ediacaran. Specimens are occasionally found at the end of their own trails, and they appear to look like the kind of segmented worms fishermen today use as bait.[12]

These traces are of incalculable importance. They are an echo, or an after-image, of a moment in evolution when animals first began to move around. Until that point, creatures were usually rooted to one spot, for at least some part of their life cycle. Tracks and traces are almost always left by animals accustomed to directed, muscular motion. If one's sources of food are all around, there is no need to go looking for it in one place rather than another. However, if an animal has a single direction of travel, with a mouth at one end, it is usually looking for something, and that something is food. At some time in the middle of the Ediacaran, animals actively started to eat one another. And once that was happening, they also started to find ways to avoid being eaten.

An animal burrowing in mud needs to have a dense, resilient body to enable it to penetrate the sediment. There are various ways of achieving this. The body of a burrowing animal could be braced by an internal skeleton, like, say, a Jack Russell terrier; or an external skeleton, like, say, a crab. External skeletons tend to start off soft and flexible (as in a shrimp) but may become hard and mineralized (as in a lobster). Another way is to organize one's body as a series of repeated segments, each full of fluid, and separated from the segments fore and aft by a kind of bulkhead. If the segments are contained in a tough external tube of muscle, you can essentially force yourself into the soil by exerting pressure on it. And if you move around like that, then you are an earthworm.

The marine relatives of earthworms do much the same, but many have flexible limb-like outgrowths on each segment that help them burrow, or row through the water, or crawl along the surface. Some of the earliest fossilized animal trails, such as those of *Yilingia spiciformis*, could have been made by worms like that.

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a sudden detonation than a slow rumble. It began with the break-up of Rodinia and the evolution and eclipse of the weirdly beautiful Ediacaran fauna, and continued until around 480 million years ago.[23]

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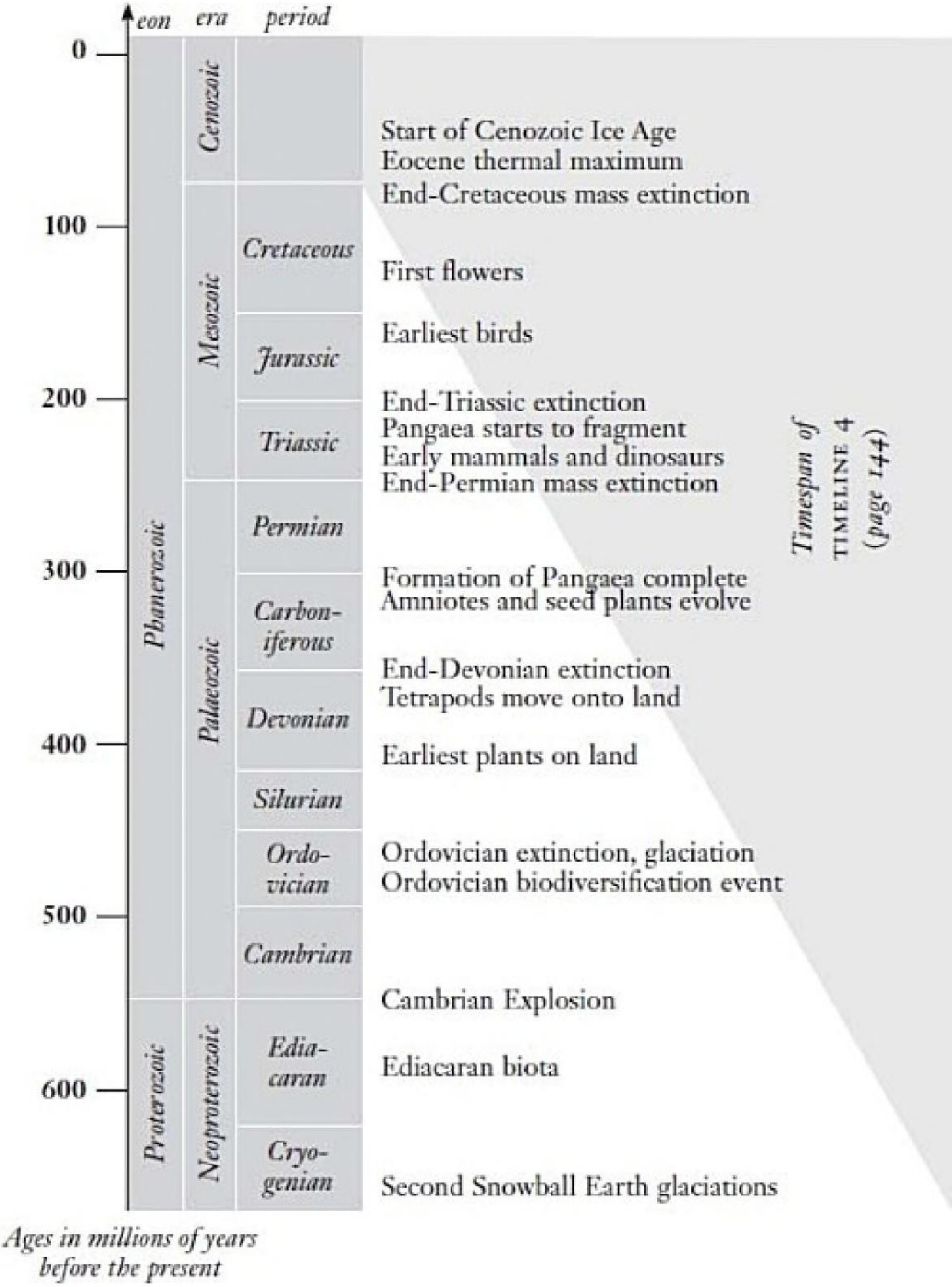
By the end of the Cambrian period, all the major groups of animals still around today had made their first appearance in the fossil record.[24] Not just arthropods and various kinds of worms, but echinoderms (spiny-skinned animals such as sea urchins) and vertebrates (the backboned animals, which includes ourselves). One of the very earliest was the fishlike *Metaspriggina*, found in the Burgess Shale. Rather than having external calcite armour, it had an internal, flexible backbone, to which powerful muscles were anchored. All the better for swimming – and fast, to avoid the nightmarish pursuit of giant arthropods such as *Anomalocaris*.

Metaspriggina was one of the very first fish to have made an entry in the fossil record. And its story belongs to the next chapter.

Timeline 3. Complex Life



3

THE BACKBONE BEGINS

As the warm, shallow oceans of the early Cambrian were filled with the spiky clatter of arthropod pincers, events were afoot in the sandy slough of mineral grains below. A small creature called *Saccorhytus*, no bigger than a pinprick, was making a modest living filtering detritus from the water between the grains.[1] Filter-feeding was nothing new – sponges had been doing it for 300 million years – and many other creatures, such as clams, were reinventing it. Panning the sediment for edible morsels is a cheap and efficient means of making a living, especially for small animals with few metabolic demands. *Saccorhytus* was just such an animal.

Shaped like a potato, albeit very much smaller, *Saccorhytus* had a large, circular mouth at one end, ready to welcome in a current of water, drawn in, sponge-fashion, by ranks of waving cilia. Along each side was ranged a line of pores, like portholes on each side of a ship, through which the filtered water exited. Inside, nets of sticky mucus trapped particles of detritus from the water current. Most of *Saccorhytus*' insides were given over to this mouth-and-portholes arrangement, known as the pharynx. The mucus was rolled up into a rope and swallowed by an internal gut. This, with all the rest of the animal's viscera, was packed in a relatively small space at the back. The anus was internal, and faeces were swept out through the portholes, along with sperm or egg cells, expelled by the parent to take their chances in the outside world.

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But *Saccorhytus* was otherwise helpless, as prey to the whims of its environment as the mineral grains between which it lived. Countless animals were doubtless swallowed by undiscriminating filter-feeders such as sponges or clams, even if they were beneath the notice of larger predators. Some of *Saccorhytus*' descendants evolved their way out by becoming larger, more mobile, armoured, fierce – or combinations of all four.

Being bigger means that an animal is less likely to be swallowed whole – although it might run the risk of being pecked at, piecemeal. To avoid this fate, some animals evolved

elephants and rhinos. Few invertebrates can match them in size. We humans, too, are uncommonly large for animals.[15] It is true that some vertebrates can be very small, weighing a matter of a few grams: but *all* vertebrates are visible to the naked human eye. Many invertebrates, on the other hand, are hardly visible without a hand lens or microscope.[16]

Insects are the most numerous invertebrates, and support themselves with an external skeleton made of a flexible protein called chitin. When the insect needs to grow, it sheds its entire external skeleton, inflates itself, and waits for the newly made one, still rather soft, to harden, before it can move. This is one reason insects are small. More than a certain size, and an insect without an exoskeleton would be crushed under its own unsupported weight. The close cousins of the insects, the crustaceans, also moult, but they live mainly in water, which supports their weight. This means that crustaceans can grow somewhat larger than insects. Think, for example, of crabs or lobsters, which can grow much larger than any insect. Nonetheless, even the largest lobster is a tiddler compared to many vertebrates.

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The most primitive vertebrates alive today are lampreys and hagfish. These have no external armour, and have probably been that way since they first evolved. Like *Metaspriggina* and other extremely early fishes, they also lack jaws and paired fins. Other vertebrates, though, adopted thick coats of armour plating. Armoured fishes appeared later in the Cambrian. Although they still lacked jaws, and were supported internally by a notochord, most early fishes were clothed in a suit of armour.[17] This was often a set of solid plates around the head and pharynx, but loose and scalier at the back end, to allow the tail to move. The armour was not made of calcite, or calcium carbonate, but a different mineral, hydroxyapatite, a form of calcium phosphate. Calcium phosphate armour is unique to vertebrates in the animal kingdom.[18]

The armour of the earliest fishes was usually a variant of a thick layer-cake of hydroxyapatite done three ways. At the base was a spongy layer. In the middle was a somewhat denser

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