

THE ATHEIST BIBLE

A 4-BILLION-YEAR STORY



THE ATHEIST BIBLE

A 4-Billion-Year Story — The History of Life on Earth

ENHANCED, VERIFIED & ILLUSTRATED EDITION

Landry Industries · 2026

Original narrative by Marie-Soleil Seshat Landry with Google Gemini. This enhanced edition was independently reviewed, fact-checked against current scientific literature, corrected, and substantially expanded; original technical figures were drawn; and front and back matter were added.

The verification pass for this edition included live confirmation of volatile and recently revised facts against primary and authoritative sources, current to June 2026. Among the substantive revisions: the missing Paleozoic and Mesozoic eras were written as two new chapters; the base of the Cambrian was corrected to 538.8 Ma and the Ordovician Period restored to the time scale, following the International Commission on Stratigraphy (ICS, 2022/2024 revisions); the portrait of the Last Universal Common Ancestor was updated to reflect Moody et al. (2024); the tree of life was redrawn to the modern two-domain model; and the status of the "Anthropocene" was corrected to note that it was formally rejected as an epoch by the IUGS in 2024. Responsibility for the selection and framing of the material rests with the author.

A NOTE ON CERTAINTY. The deep past is reconstructed, not witnessed. Where this book states an age, a name, or a number, it reflects the best current scientific consensus; where the science is genuinely unsettled, the text says so.

Reconstructions of ancient organisms such as LUCA are inferences from living evidence — portraits, not photographs.

Typeset in EB Garamond, Cinzel, and Inter. Figures produced as vector diagrams; rendered to PDF with an HTML → WeasyPrint pipeline.

LICENSE. This text may be shared under Creative Commons Attribution 4.0 (CC BY 4.0). ORCID 0009-0008-5027-3337.

THE ATHEIST BIBLE

A 4-BILLION-YEAR STORY

*The history of life on Earth — from a molten world
and the first spark in the dark, to the age of humans*

WRITTEN BY

MARIE-SOLEIL SESHAT LANDRY

ENHANCED • VERIFIED • ILLUSTRATED EDITION

LANDRY INDUSTRIES • 2026

ABSTRACT

This book chronicles the roughly four-billion-year history of life on Earth, from the planet's cosmic and geological origins to the present day.

Beginning with the assembly of a habitable world from the solar nebula, it surveys the leading scientific accounts of abiogenesis — the emergence of life from non-living chemistry — weighing settings from Darwin's "warm little pond" to the alkaline hydrothermal vents of the deep sea. The narrative then follows the great innovations that reshaped the biosphere: the first cells; the invention of oxygenic photosynthesis, which terraformed the atmosphere; and the symbiotic origin of the complex eukaryotic cell, now understood to have arisen from *within* the archaea rather than alongside them.

From there the book recounts the explosive diversification of animal life in the Cambrian, the colonization of the land by plants and then vertebrates, and the rise and fall of dominant groups across the Paleozoic, Mesozoic, and Cenozoic eras. It examines the five great mass extinctions that punctuated this history — above all the end-Permian "Great Dying," the most severe biotic crisis in the fossil record — and the evolutionary opportunities each catastrophe created. Finally it traces the rise of mammals after the fall of the non-avian dinosaurs, the emergence of *Homo sapiens* in Africa some three hundred thousand years ago, and the planet-altering impact of a single species, placing today's biodiversity crisis in the long perspective of deep time.

This enhanced edition revises the original throughout against current evidence, distinguishes settled fact from active debate, adds two chapters covering the previously omitted Paleozoic and Mesozoic eras, and supplies original figures, an expanded bibliography, and a corrected geologic time scale.

PREFACE

The story of life on Earth is the greatest story ever told. It is a narrative of unimaginable scope, spanning billions of years and featuring a cast of characters stranger and more wonderful than any fiction. It is a story of cataclysm and recovery, of quiet revolutions and explosive change, of intricate connections and blind chance. It is our story.

To understand who we are, we must understand where we come from — not just from our parents or our recent ancestors, but from the first self-replicating molecule, the first cell, the first creature to crawl from the sea. Our bodies are living museums, carrying the genetic legacy of a four-billion-year-old lineage. Our DNA contains the blueprints of ancient bacteria, the bone structure of a lobe-finned fish, and the brain architecture of a small mammal that survived the asteroid.

The goal of this book is to make this immense story accessible. By weaving together insights from geology, chemistry, paleontology, and biology, it aims to provide a coherent narrative of our shared history. We will journey back to a time when our planet was a molten ball of rock, witness the first spark of life in a primordial ocean, hide from the giant reptiles of the Mesozoic, and walk across the ice-age plains with our earliest human ancestors. It is a humbling and awe-inspiring journey. To grasp the sheer depth of geological time and the relentless, branching path of evolution is to gain a profound perspective on our own fleeting but powerful existence in the latest chapter of this epic tale.

A NOTE ON THIS EDITION

The first version of this book was generated by a large language model and, like much that such systems produce, it was eloquent, broadly accurate, and wrong in specific and revealing ways. It promised, in its own abstract, to recount “the rise and fall of dominant groups through the Paleozoic, Mesozoic, and Cenozoic eras” — and then skipped directly from the Cambrian to the age of mammals, leaving out the trilobites, the first forests, the conquest of the land, and the entire reign of the dinosaurs. It dated the base of the Cambrian to a figure the world’s stratigraphers had already revised. It drew the tree of life in a shape that two decades of genomics have overturned. And it described the “Anthropocene” as an all-but-official chapter of geological time, months after that very proposal had been formally voted down.

None of this makes the original worthless; much of its prose was genuinely good, and it is preserved here. But it does illustrate why a story about evidence must itself be held to the standard of evidence. For this edition, every volatile claim — every date, every name, every superlative — was checked against current scientific sources, and the gaps were filled. The two missing eras are now restored as Chapters Four and Five. Several figures and the time scale have been corrected. Where the science remains in honest dispute, this edition tells you so, rather than papering over the uncertainty with confidence. That, after all, is the difference between a scripture and a science: the willingness to be revised.

CONTENTS

FRONT MATTER

Abstract	7
Preface	9
A Note on This Edition	11

THE NARRATIVE

I	The Origin of a Habitable Planet	17
II	The Spark of Life — Abiogenesis	21
III	The First Revolutions — Cells and Metabolism	25
IV	Explosion and Invasion — The Paleozoic	31
V	The Age of Reptiles — The Mesozoic	37
VI	The Age of Mammals — The Cenozoic	41
VII	Deep Time, Extinction, and the Anthropocene	47

BACK MATTER

Epilogue — A Story of Connection	51
Bibliography	53
Appendix A — Geologic Time Scale	57
Appendix B — A Two-Domain Tree of Life	61
Further Reading	63

FIGURES

- 1 The four eons of deep time, on a single linear scale
- 2 The rise of atmospheric oxygen through Earth's history
- 3 The five great mass extinctions, and the sixth now under way
- 4 A simplified two-domain tree of life

CHAPTER ONE

THE ORIGIN OF A HABITABLE PLANET

CIRCA 4.6 – 4.0 BILLION YEARS AGO · THE HADEAN & EARLY ARCHEAN

Approximately 4.6 billion years ago, in a quiet spiral arm of the Milky Way, a vast, cold cloud of interstellar gas and dust began to collapse under its own gravity. This solar nebula — enriched with heavy elements forged in the hearts of long-dead stars — was the crucible of our solar system. As it contracted, it spun faster, flattening into a rotating protoplanetary disk. At the dense, hot centre, pressures and temperatures grew so extreme that hydrogen nuclei began to fuse into helium. A star, our Sun, was born.

In the cooler regions of the disk, the remaining matter began to clump. Microscopic grains stuck together, growing into pebbles, then boulders, then kilometre-sized planetesimals. Through a chaotic process of collision and accretion, these grew ever larger. In the warm inner solar system, where volatile compounds like water ice could not condense, rocky bodies formed and slowly coalesced into the four terrestrial planets: Mercury, Venus, Earth, and Mars. Our planet had been born — but its formative years would be violent and inhospitable.

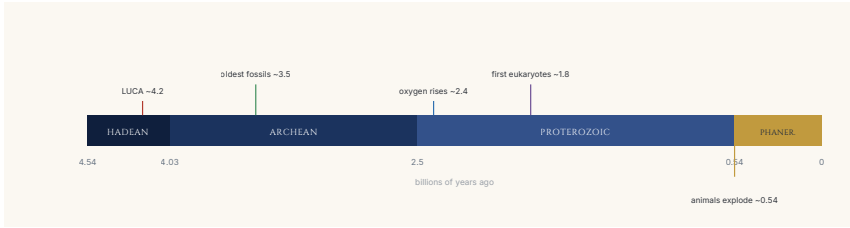


FIGURE 1. The four eons of deep time on a single linear scale. Note how little of Earth's history the Phanerozoic — the entire age of visible, complex life — actually occupies: a thin gold sliver at the right-hand edge. For nearly nine-tenths of the planet's existence, life was microscopic.

1.1 THE HADEAN EON: A WORLD IN FLAMES

The first 500 million years of Earth's history are known as the Hadean Eon, named after Hades, the Greek underworld. It was a hellish time. The young Earth was a ball of molten and semi-molten rock, its surface heated by the decay of radioactive elements and the relentless bombardment of leftover debris.

The most consequential of these impacts came when a Mars-sized protoplanet, dubbed Theia, struck the early Earth a glancing blow. The collision was so immense that it melted the outer layers of both bodies and flung a tremendous quantity of molten rock into orbit, where it quickly coalesced into the Moon. This was no mere cosmic accident of scenery: the Moon's gravitational pull would go on to stabilize Earth's axial tilt, damping the wild climatic swings that might otherwise have made the evolution of complex life far more difficult.

As the heaviest bombardment subsided, the Earth began to cool. A solid crust formed, and dense elements such as iron and nickel sank to the centre, creating the planet's core. This process of differentiation was itself vital to life: the churning of the molten outer core generates Earth's magnetic field, a protective shield that deflects the solar wind and prevents it from stripping away our atmosphere and boiling off our oceans.

OLDER THAN THE OLDEST ROCK

Earth's surface has been so thoroughly recycled that almost nothing survives from the Hadean. Yet a handful of mineral grains do. Tiny crystals of zircon from the Jack Hills of Western Australia have been dated to about 4.4 billion years ago (Wilde et al., 2001), and their chemistry hints that liquid water — and perhaps a cool crust — existed startlingly early. One such grain has even yielded a flake of carbon whose isotopic signature some read as a faint chemical whisper of life by 4.1 billion years ago (Bell et al., 2015), though that claim remains debated.

1.2 OCEANS, ATMOSPHERE, AND THE FAINT YOUNG SUN

Following the Hadean came the Archean Eon, beginning around 4 billion years ago. The planet had cooled enough for liquid water to persist. Volcanoes erupting across the young world released vast quantities of gas from the interior — a process of outgassing that built a primordial atmosphere nothing like today's: a toxic, oxygen-free mix of water vapour, carbon dioxide, nitrogen, and perhaps methane and ammonia. As the planet cooled, the water vapour condensed and fell in a planet-wide deluge that may have lasted for ages, filling the first global oceans. Evidence for these ancient seas survives in some of the oldest known sediments on Earth — roughly 3.8-billion-year-old metamorphosed rocks in Greenland that bear the marks of having been laid down in water (Mojzsis et al., 1996).

This early world presented a paradox. The young Sun was perhaps a quarter to a third dimmer than it is today, and by the simplest calculation Earth's oceans should have frozen solid. That they did not is the “faint young Sun paradox.” The most widely accepted resolution is that the early atmosphere was rich in greenhouse gases — carbon dioxide and methane above all — which trapped enough of the Sun's faint warmth to keep water liquid.

The stage on which life would appear was kept warm by the same kind of atmospheric chemistry that governs our climate today.

1.3 THE INGREDIENTS FOR LIFE

By the dawn of the Archean, the Earth possessed the key ingredients for life. It had a steady supply of energy, from sunlight above and geothermal heat below. It had abundant liquid water, the universal solvent in which life's chemistry unfolds. And it had the essential chemical building blocks: the elements that form the backbone of all biology — carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulphur — were present in the air, the seas, and the rocks.

The final piece was the supply of more complex organic molecules. Some surely formed on Earth itself, but a significant quantity was probably delivered from space. Comets and carbon-rich asteroids, relics of the outer solar system, rained down on the young planet, seeding it with amino acids — the building blocks of proteins — and the nucleobases from which genetic molecules are built (Chyba & Sagan, 1992). The planet was habitable, the oceans were formed, and the raw materials were in place. All that was missing was the spark.

CHAPTER TWO

THE SPARK OF LIFE — ABIOGENESIS

THE BLURRY FRONTIER WHERE CHEMISTRY BECAME
BIOLOGY

Somewhere on the sterile, primordial Earth, a profound transformation occurred. Non-living chemical matter, obeying only the ordinary laws of physics and chemistry, organized itself into a system that could metabolize, grow, and replicate. This transition — abiogenesis — is among the most significant and mysterious events in our planet's history. We may never recover its precise sequence, but decades of research have sketched several compelling pathways from a collection of simple molecules to the first living cell. This chapter explores that critical juncture, the blurry line where chemistry became biology.

2.1 DEFINING LIFE: A FUZZY BOUNDARY

Before we can ask how life began, we must ask what life is. At first glance the answer seems obvious — a bacterium is alive, a rock is not — but the boundary is surprisingly blurry. Viruses carry genes and evolve, yet are inert without a host cell to replicate them. Prions are mere misfolded proteins, lacking any genetic material, and yet they propagate by forcing other proteins to misfold.

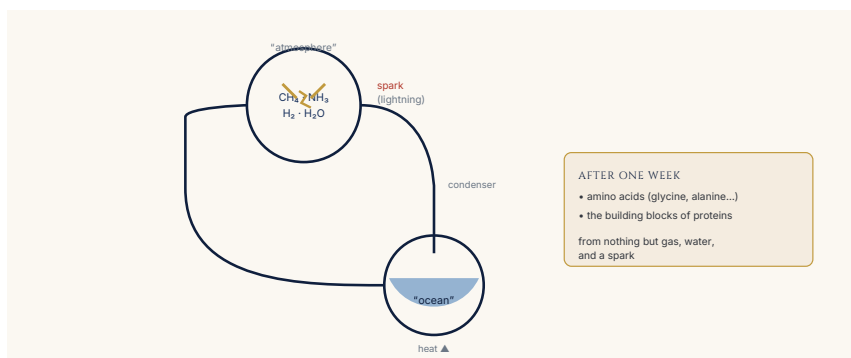
For our purposes we can define life by a cluster of functional properties. A living system is chemically distinct from its surroundings and enclosed by a boundary, such as a cell membrane. It harnesses energy and raw materials from its environment to maintain itself — a process we call metabolism. And, most

importantly, it can replicate, passing its characteristics to the next generation. Evolution by natural selection, the engine of all biological complexity, can begin only once such imperfect replication is in place. The central question of abiogenesis, then, is how a system with these properties could arise on its own.

2.2 THE PRIMORDIAL SOUP

The oldest and most famous idea is the “primordial soup.” First articulated by Alexander Oparin and J. B. S. Haldane in the 1920s, it envisions a primitive ocean rich in dissolved organic compounds, energized by lightning and solar ultraviolet light, in which simple molecules react to build more complex ones — amino acids, nucleotides, and the like.

The idea gained dramatic experimental support in 1953, in the landmark Miller–Urey experiment. Stanley Miller, a graduate student working with Harold Urey, built a closed glass apparatus containing heated water (the ocean) and a mixture of gases then thought to represent the early atmosphere — methane, ammonia, and hydrogen. He subjected this miniature world to electrical sparks, simulating lightning. After only a week, the water had turned a murky brown and was found to contain several amino acids, the building blocks of proteins (Miller, 1953). Later experiments, under a range of conditions, have produced all twenty of life’s amino acids, along with nucleobases and sugars. They proved that the step from simple inorganic chemistry to the building blocks of biology is not a fantastical leap but an expected outcome under plausible early-Earth conditions.



The Miller–Urey experiment of 1953. A sealed loop of gases and water, driven by electrical sparks, produced amino acids within days — the first experimental demonstration that life's building blocks form readily under early-Earth conditions. Schematic.

2.3 THE IRON–SULPHUR WORLD: LIFE AT THE VENTS

The soup model has a weakness: a planet-wide ocean would have been a very dilute solution, making it hard for molecules to find one another and react. An alternative moves the cradle of life from the sunlit surface to the dark ocean floor — to hydrothermal vents, fissures in the seabed where hot, mineral-laden water gushes from the planet's interior into the cold sea.

The “iron–sulphur world” hypothesis, championed by Günter Wächtershäuser, proposes that the surfaces of iron-sulphide minerals at these vents catalysed the first metabolic reactions, with chemical energy supplied not by lightning but by the geochemical gradient between vent fluid and seawater (Wächtershäuser, 1988). One kind of vent looks especially promising: the alkaline hydrothermal vent, which exhales warm, alkaline, hydrogen-rich fluid. The porous, honeycombed mineral chimneys of such vents could have served as natural hatcheries, their tiny compartments concentrating organic molecules and providing scaffolds for the first protocells — powered, crucially, by the natural difference in acidity between the alkaline vent fluid and the more acidic Archean ocean (Russell et al., 1994). That same proton gradient across a membrane is, remarkably, how every living cell still powers itself today.

2.4 THE RNA WORLD: A BRIDGE TO MODERN LIFE

Modern life stores its information in DNA and does its chemical work with proteins. This poses a chicken-and-egg puzzle: DNA is needed to build proteins, but proteins are needed to copy DNA. How could such an interdependent system ever start?

The RNA World hypothesis offers an elegant answer. RNA, a molecular cousin of DNA, is more versatile than either: it can store genetic information *and* catalyse chemical reactions. Catalytic RNA molecules — ribozymes — are real, and their existence suggests that the earliest life might have run on RNA alone, with the same molecules both carrying the instructions for their own replication and carrying it out. A self-copying RNA strand, arising in some protected, energy-rich pocket — within a vent's mineral pores, perhaps, or a simple lipid vesicle — would have been the first true living entity. Through imperfect copying, variation would arise; natural selection would favour the strands that were more stable or replicated faster; and over ages the system would grow in complexity, eventually learning to build proteins, the more efficient catalysts. Later still, the more chemically stable DNA molecule would take over the archive, leaving RNA in its familiar modern role as messenger and regulator. The hypothesis bridges the gap from simple prebiotic chemistry to the DNA-and-protein world of the Last Universal Common Ancestor.

CHAPTER THREE

THE FIRST REVOLUTIONS — CELLS AND METABOLISM

CIRCA 4.0 BILLION – 539 MILLION YEARS AGO · THE AGE OF
THE MICROBE

With the appearance of the first self-replicating systems, the era of biology had truly begun. For the next two billion years — nearly half of our planet's history — life would remain a purely microscopic affair. Yet this was no age of stasis. The events that unfolded in the microbial world were revolutionary, reshaping the planet's geology, atmosphere, and chemistry. Here the basic architecture of life was established: the first cells, the invention of metabolic engines such as photosynthesis, and the great leap to the complex eukaryotic cell. This was the age of the microbe, and it laid the foundations for everything that followed.

3.1 THE LAST UNIVERSAL COMMON ANCESTOR

By comparing the genetic codes and core machinery of all living things — from the simplest bacterium to the largest whale — we can infer the nature of their last shared relative: the Last Universal Common Ancestor, or LUCA. It is essential to be clear about what LUCA was and was not. It was *not* the first living thing, nor the origin of life; it was the last organism from which all life surviving today descends. Many other lineages surely lived alongside it and left no descendants.

From genetic reconstruction we can sketch a surprisingly detailed portrait. LUCA was a single-celled organism that already possessed a sophisticated operating system: a cell membrane, DNA as its genetic archive, RNA as

messenger, and ribosomes on which to build proteins. Every organism on Earth still runs on this same fundamental machinery — a profound testament to our shared ancestry. From LUCA, life branched into its two great prokaryotic domains, the Bacteria and the Archaea.

A RECONSTRUCTION, NOT A PHOTOGRAPH

A major 2024 analysis sharpened this picture considerably. By tracking genes that had already duplicated before LUCA, researchers estimated that it lived around 4.2 billion years ago — startlingly early, within perhaps a few hundred million years of Earth's formation — and that it was already a complex cell, with a genome of roughly 2,500 genes, comparable to a modern bacterium (Moody et al., 2024). They reconstruct it as an anaerobic organism that fed on hydrogen and carbon dioxide, that may have possessed a rudimentary defence against viruses, and that lived not in isolation but as one member of an already-functioning ecosystem. If so, life did not merely survive the violence of the early Earth — it was already flourishing. This portrait is an inference drawn from living evidence, and it will be revised; but it is the most detailed reconstruction we have.

3.2 THE GREAT OXYGENATION EVENT

For over a billion years, life inhabited an anoxic — oxygen-free — world, its metabolisms anaerobic, extracting energy without oxygen. Then a revolutionary trick changed everything: photosynthesis. Earlier forms existed, but a new and far more powerful version evolved in a group of bacteria called cyanobacteria. This oxygenic photosynthesis used sunlight to split water itself, capturing hydrogen to build sugars and releasing, as waste, free oxygen.

Layered mounds built by communities of such microbes — stromatolites — appear in rocks as old as about 3.5 billion years, among the oldest widely accepted traces of life. For hundreds of millions of years, the oxygen they produced was mopped up by iron dissolved in the seas, which rusted and sank

to form vast banded iron formations. But around 2.4 billion years ago these chemical sinks became saturated, and oxygen began, for the first time, to accumulate in the atmosphere.

This Great Oxygenation Event was a catastrophe for the anaerobic life that then ruled the planet, to which oxygen was a corrosive poison; it likely triggered the first great die-off in Earth's history. Yet it was also the single greatest opportunity life had ever encountered, for it opened the door to a vastly more powerful metabolism: aerobic respiration, the controlled burning of fuel with oxygen. The energy released by aerobic respiration is on the order of fifteen times greater than that from fermentation — and this enormous surplus would, in time, become the key that unlocked the door to complex life (Lyons, Reinhard & Planavsky, 2014).

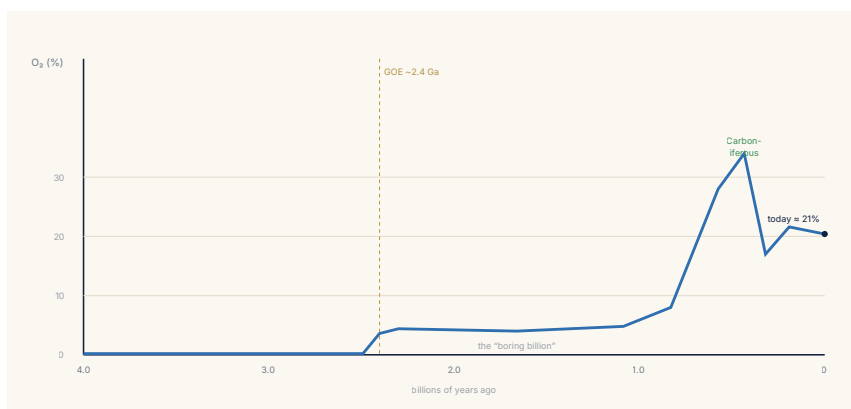


FIGURE 2. The rise of atmospheric oxygen, in schematic form. Oxygen was negligible until the Great Oxygenation Event around 2.4 billion years ago, lingered at low levels through the long mid-Proterozoic, then rose toward modern values as complex life emerged — overshooting to perhaps 30 per cent or more in the coal forests of the Carboniferous before settling near today's 21 per cent. Curve schematic; exact values remain uncertain and debated.

3.3 THE ORIGIN OF EUKARYOTIC CELLS: A SYMBIOTIC LEAP

For some two billion years, life consisted of prokaryotes — bacteria and archaea — relatively simple cells whose DNA floats freely within them. Then arose a new and far more elaborate kind of cell: the eukaryote, the lineage that would give rise to all plants, animals, fungi, and protists. Eukaryotic cells are larger and intricately organized; they keep their DNA inside a nucleus and are filled with specialized compartments called organelles. The fossil record of unambiguous eukaryotes extends back to roughly 1.6 to 1.8 billion years ago.

The origin of this complexity is explained by the theory of endosymbiosis, famously marshalled by Lynn Margulis (1967). The eukaryotic cell, on this view, arose from a partnership *between* cells. A host cell engulfed a free-living bacterium — an aerobic respirer, able to exploit the newly abundant oxygen — but did not digest it. Over generations the guest became the mitochondrion, the powerhouse of all eukaryotic cells. Much later, in the lineage leading to plants, a eukaryote took in a photosynthetic cyanobacterium, which became the chloroplast. These mergers endowed the new lineage with the prodigious energy budget and genetic raw material needed to build larger and more sophisticated life. That mitochondria and chloroplasts still carry their own small genomes, and divide like the bacteria they once were, is the lasting fingerprint of this ancient symbiosis.

But who was the host? Here the modern picture has shifted decisively. The classic textbook tree showed three coequal domains — Bacteria, Archaea, and Eukarya — branching from a common stem. Genomic evidence now favours a different, *two-domain* arrangement: the eukaryotes did not branch off beside the archaea but emerged from *within* them (Williams et al., 2013). The decisive clue came in 2015, when researchers sequencing sediment near a deep-sea vent field called Loki’s Castle identified a new group of archaea — the Lokiarchaeota, first of the “Asgard” archaea — carrying genes for features once thought uniquely eukaryotic (Spang et al., 2015). The Asgard archaea are, on

current evidence, the closest prokaryotic relatives of all complex life, ourselves included.

For years these organisms were known only from fragments of DNA. Then, after more than a decade of painstaking effort, a Japanese team grew one in the laboratory: a slow-living, hydrogen-dependent archaeon from deep marine mud, long known by its strain name MK-D1 (Imachi et al., 2020). It lives in syntrophy — a metabolic handshake — with partner microbes, and extends long, branching tendrils that reach out and entangle them. That behaviour inspired a concrete model for our own origin: a host archaeon may have gradually entangled and then engulfed the bacterium that became the mitochondrion, with the nucleus and the rest of the eukaryotic cell assembled around that founding partnership. The greatest leap in the history of the cell may have begun as two struggling microbes feeding each other in the mud.

3.4 THE RISE OF COMPLEX ORGANISMS

For another billion years, eukaryotes lived mostly as single cells — amoebae, algae, and their kin. The final revolution of this early era was the leap to true multicellularity, in which cells not only live together but cooperate, specializing into distinct types to form a single coherent organism. This transition happened independently many times, giving rise separately to plants, fungi, and animals.

The first widely accepted evidence of large, complex organisms comes from the late Proterozoic. By roughly 575 million years ago the seas held the enigmatic Ediacaran biota — strange, soft-bodied, often frond-like forms unlike anything alive today. For at least one iconic Ediacaran genus, *Dickinsonia*, the discovery of preserved cholesterol-like molecules has confirmed that it was a true animal (Bobrovskiy et al., 2018). Then, beginning around 538.8 million years ago, something spectacular unfolded. Over a geologically brief interval the fossil record erupts with an astonishing diversity of complex animals bearing shells, skeletons, limbs, and heads. This event — the Cambrian Explosion — established nearly every major animal body plan that

exists today, and at last lit the long, slow fuse of the microbial world. To that explosion, and to the conquest of the land that followed, we now turn.

CHAPTER FOUR

EXPLOSION AND INVASION — LIFE CONQUERS THE PALEOZOIC

CIRCA 539 – 252 MILLION YEARS AGO · THE PALEOZOIC ERA

For three billion years, life had been almost entirely small, soft, and confined to the water. The Paleozoic Era — the “era of ancient life” — changed all of that with bewildering speed. In its opening act, the seas filled with armoured, mobile, complex animals. In its later acts, life performed perhaps its most audacious feat of all: it crawled out of the water and colonized the bare rock of the continents. The era would end in the greatest catastrophe the biosphere has ever known.

4.1 THE CAMBRIAN EXPLOSION

Beginning around 538.8 million years ago, the fossil record undergoes a transformation so abrupt that it has been called an explosion. Within a window of a few tens of millions of years — an eye-blink against the billions that preceded it — almost every major animal body plan in existence today makes its first appearance. Arthropods, molluscs, echinoderms, and the first chordates (our own phylum) all emerge, equipped with hard shells, jointed limbs, eyes, guts, and the means to swim, burrow, and hunt.

Our most vivid window onto this world is the Burgess Shale of British Columbia, a deposit of extraordinary fossils that preserves even soft-bodied creatures in fine detail (Briggs, 2015). It reveals a Cambrian sea both familiar and deeply strange: trilobites scuttling across the floor; *Anomalocaris*, a metre-

long predator with grasping front appendages and a circular mouth; and a menagerie of experimental forms, some of which left no descendants. Crucially, the Cambrian also marks the dawn of ecological warfare — the first hard skeletons were also the first armour, evolved in an escalating arms race between predator and prey.

What lit the fuse? No single cause suffices, but several conditions converged. Rising oxygen levels could at last support the high metabolic demands of active, predatory animals. The evolution of genetic toolkits for building complex bodies — the deeply conserved *Hox* genes among them — gave evolution new architecture to work with. And once predation and active movement appeared, ecological feedback did the rest, driving runaway diversification. The result was the founding of the modern animal world.

4.2 THE GREAT ORDOVICIAN DIVERSIFICATION — AND THE FIRST CATASTROPHE

If the Cambrian built the body plans, the Ordovician Period (about 485 to 444 million years ago) populated the seas with staggering numbers of new families within them — a surge sometimes called the Great Ordovician Biodiversification Event. Reefs, brachiopods, cephalopods, early jawless fishes, and dense plankton communities filled warm, shallow oceans.

Then, around 444 million years ago, came the first of the “Big Five” mass extinctions. As the supercontinent Gondwana drifted over the South Pole, vast ice sheets formed, sea level plunged, and the shallow seas that held most marine life drained away; a second pulse struck as the ice melted again. An estimated 85 per cent of marine species vanished. Life had diversified spectacularly — and discovered, for the first time in the era of complex animals, how suddenly it could be cut down.

4.3 THE INVASION OF THE LAND

The continents of the early Paleozoic were barren — bare rock, sediment, and microbial crust, without a single plant or animal. The greening of the land

was a gradual, revolutionary process. The first simple vascular plants took hold along wet margins in the Silurian Period (about 444 to 419 million years ago), small and rootless at first. As plants spread, they began to build the first soils and to draw down atmospheric carbon dioxide. The oxygen they released thickened the protective ozone layer overhead, shielding the surface from ultraviolet radiation and making the land newly habitable. Arthropods — the ancestors of insects, spiders, and millipedes — followed the plants ashore, the first animals to live out of water.

In the Devonian Period (about 419 to 359 million years ago), the land turned green in earnest. Plants evolved roots, leaves, and wood, and by the period's later stages the first true forests rose. The seas, meanwhile, teemed with fish of every kind — armoured placoderms, sharks, and bony fishes — earning the Devonian its nickname, the Age of Fishes. It was from one group of fishes, the lobe-finned fishes with their sturdy, bony fins, that the most consequential of all land invaders would come.

A FISH WITH THE MAKINGS OF A LIMB

In 2004, on Ellesmere Island in the Canadian Arctic, paleontologists unearthed *Tiktaalik roseae*, a roughly 375-million-year-old creature beautifully intermediate between fish and four-legged animal (Daeschler, Shubin & Jenkins, 2006). It had gills and scales like a fish, but also a flattened head, a neck, and stout fin bones arranged like the beginnings of a wrist and limb — a snapshot of vertebrates on the threshold of land. Its discoverers had predicted the age and the kind of rock in which such a fossil should lie, then went looking in rocks of exactly the right age. They found it.

From such lobe-finned ancestors arose the tetrapods — the four-limbed vertebrates — and with them the lineage that includes amphibians, reptiles, birds, and mammals. The Late Devonian, however, also brought another of the Big Five: a protracted crisis around 372 million years ago, tied to

widespread ocean anoxia, that erased an estimated three-quarters of species and fell especially hard on marine life.

4.4 COAL FORESTS, GIANT INSECTS, AND THE AMNIOTE EGG

The Carboniferous Period (about 359 to 299 million years ago) takes its name from the immense coal deposits it left behind. Sprawling, swampy forests of giant club mosses, horsetails, and tree ferns blanketed the wet tropical continents. So much plant matter was buried before it could fully decay that atmospheric oxygen may have climbed to around 30 per cent — well above today's 21. In that oxygen-rich air, arthropods reached gigantic sizes: dragonfly-like insects with the wingspan of a hawk, and millipede relatives more than two metres long.

The period's most far-reaching innovation, though, was reproductive. Early land vertebrates, like today's amphibians, still had to return to water to lay their eggs. In the Carboniferous, one lineage evolved the amniote egg — a self-contained capsule with its own protective membranes and food supply, able to develop on dry land. Freed at last from dependence on standing water, the amniotes could colonize the continental interiors. From them would descend two great lines: the sauropsids, leading to reptiles, dinosaurs, and birds; and the synapsids, leading eventually to mammals.

4.5 THE GREAT DYING

Through the Permian Period (about 299 to 252 million years ago), the continents fused into a single supercontinent, Pangaea, ringed by a world ocean. On land, the synapsids — our own distant relatives — rose to dominance, in forms ranging from sail-backed predators to squat, tusked herbivores. Life had spread across the land and filled the seas. And then, 252 million years ago, it very nearly ended.

The end-Permian extinction — the “Great Dying” — was the most severe biotic crisis in the entire fossil record, far exceeding the later catastrophe that

would claim the dinosaurs. By most estimates it eliminated on the order of 80 per cent or more of marine species, and a comparable share of life on land; by some species-level metrics the toll approaches the obliteration of nine in ten species (Erwin, 2006). The trigger is now strongly tied to one of the largest volcanic events in Earth's history: the eruption of the Siberian Traps, which flooded an area the size of a continent with lava and, more lethally, injected staggering volumes of carbon dioxide and other gases into the atmosphere (Burgess, Bowring & Shen, 2014). The consequences cascaded — runaway greenhouse warming, acidifying oceans, and the spread of oxygen-starved “dead zones” through the seas. Life on Earth came as close as it has ever come to being switched off entirely. That it recovered at all set the stage for a wholly new cast of characters — and for the age of the dinosaurs.

CHAPTER FIVE

THE AGE OF REPTILES — THE MESOZOIC

CIRCA 252 – 66 MILLION YEARS AGO · THE MESOZOIC ERA

Out of the ashes of the greatest extinction the world has known, life rebuilt itself. The Mesozoic Era — the “era of middle life” — would last some 186 million years and would belong, above all, to the reptiles. It opened on a single vast supercontinent under a recovering sky, and it would close in a single afternoon of fire. Between those two catastrophes lies the most famous chapter in the history of life: the long reign of the dinosaurs.

5.1 RECOVERY AND THE DAWN OF THE DINOSAURS

The Triassic Period (about 252 to 201 million years ago) began in a depleted world. Recovery from the Great Dying was slow; for several million years the land bore an impoverished cast of survivors. But empty ecological space is opportunity, and the Triassic became a time of evolutionary experiment. Among the reptiles, one group — the archosaurs, or “ruling reptiles” — rose to prominence, splitting into two great branches: one leading toward the crocodilians, the other toward the dinosaurs and, eventually, the birds.

By the late Triassic, the first true dinosaurs had appeared — small, agile, bipedal creatures, modest beginnings for a dynasty. In the very same interval, and just as quietly, another lineage crossed a different threshold: the first mammals evolved from among the synapsids, whose forerunners had ruled the Permian. These earliest mammals were tiny, and for the next 150 million years

they would remain so, living in the margins of a world that belonged to the reptiles.

The Triassic ended, as the Permian had, in catastrophe. Around 201 million years ago the end-Triassic extinction — another of the Big Five — eliminated an estimated three-quarters of species. Its leading cause echoes the Great Dying before it and the dinosaurs' fall to come: a vast outpouring of lava and volcanic gas, this time from the Central Atlantic Magmatic Province, erupted as Pangaea began to tear itself apart and the Atlantic Ocean was born. The crisis cleared away many of the dinosaurs' rivals — and left the survivors to inherit the Earth.

5.2 THE JURASSIC: GIANTS AND THE FIRST BIRDS

In the Jurassic Period (about 201 to 145 million years ago), the dinosaurs came into their own. As Pangaea fragmented and climates grew warmer and wetter, lush forests of conifers, cycads, and ferns spread across the continents. In them evolved the largest animals ever to walk the Earth: the sauropods — long-necked, long-tailed herbivores such as *Brachiosaurus* and *Diplodocus*, some exceeding thirty metres in length and tens of tonnes in weight. Hunting among them were the great predatory theropods, including *Allosaurus*, the dominant carnivore of its day.

It was also in the Jurassic that one lineage of small, feathered theropods crossed one of the most celebrated thresholds in evolution. Around 150 million years ago lived *Archaeopteryx*, a creature the size of a raven that combined the teeth, clawed hands, and long bony tail of a dinosaur with unmistakable feathered wings. For more than a century it stood as the iconic “missing link” between dinosaurs and birds. A flood of discoveries since — many of them exquisitely preserved feathered dinosaurs — has transformed that lonely intermediate into a richly populated transition. Feathers, we now know, evolved long before flight, first as insulation and display, and were widespread among theropods. The conclusion is striking in its simplicity: birds are not merely the descendants of dinosaurs; they *are* dinosaurs, the one branch of that great family to survive to the present day.

THE DINOSAURS ARE NOT ALL GONE

Every sparrow at a window feeder and every gull over a harbour is a living theropod dinosaur — a direct descendant of the same lineage that produced *Tyrannosaurus*. The roughly ten thousand species of birds alive today make dinosaurs, by that measure, one of the great ongoing success stories of vertebrate life. When we say the dinosaurs went extinct, we mean only the non-avian dinosaurs. The rest are still very much with us.

5.3 THE CRETACEOUS: FLOWERS AND TYRANTS

The Cretaceous Period (about 145 to 66 million years ago) was the longest of the Mesozoic and, in many ways, its climax. The continents drifted toward their modern configurations; sea levels rose so high that shallow seaways split landmasses in two, including a great inland sea that divided North America down the middle. Dinosaurs reached their greatest diversity. In the north roamed the horned *Triceratops*, the armoured ankylosaurs, the duck-billed hadrosaurs in vast herds — and, near the period's end, *Tyrannosaurus rex*, among the largest land predators that has ever lived.

But the Cretaceous's most consequential revolution was botanical. Early in the period, the flowering plants — the angiosperms — first appeared, and then radiated with extraordinary speed. By co-evolving with insect pollinators, flowering plants spread into nearly every habitat and reshaped terrestrial ecosystems from the ground up. The world began, at last, to take on a recognizably modern aspect: flowers, broad-leaved trees, and the intricate web of relationships between plants and the insects that fed on and fertilized them. The stage was set for the world we know — and then, in an instant, the curtain fell.

5.4 THE DAY THE MESOZOIC ENDED

Sixty-six million years ago, an asteroid roughly ten kilometres across struck the shallow sea off what is now the Yucatán Peninsula of Mexico. The impact released energy beyond meaningful comparison — many billions of times the yield of the bombs that ended the Second World War. It blasted out a crater more than 150 kilometres wide, now buried beneath the surface and known by the name of a nearby town: Chicxulub.

The case for this impact was first assembled not from the crater, which was identified later, but from a thin, worldwide layer of clay laid down precisely at the boundary between the Cretaceous and the period that followed. That layer is enriched in iridium — an element rare in Earth's crust but abundant in asteroids — a chemical signature of impact that the geologist Walter Alvarez and his physicist father Luis Alvarez recognized for what it was (Alvarez et al., 1980). The immediate aftermath was apocalyptic: a pulse of searing heat as ejected debris rained back through the atmosphere, then wildfires, tsunamis, and a prolonged darkness as dust and soot veiled the Sun, collapsing the photosynthesis on which nearly all food chains depend. Many scientists hold that the catastrophe was compounded by an unrelated convulsion already under way on the far side of the planet — the eruption of the Deccan Traps in what is now India, one more of the great volcanic outpourings whose lethal fingerprints recur throughout this book.

When the darkness lifted, the non-avian dinosaurs were gone, along with the flying pterosaurs, the great marine reptiles, and the ammonites that had filled the seas. An estimated three-quarters of all species had vanished. The end-Cretaceous extinction — the most famous of the Big Five, though far from the most severe — closed the Age of Reptiles in a single geological instant. And it opened, for the small, warm-blooded survivors that had waited 150 million years in the undergrowth, a world swept suddenly and utterly clear.

CHAPTER SIX

THE AGE OF MAMMALS — THE CENOZOIC AND THE RISE OF HUMANITY

CIRCA 66 MILLION YEARS AGO – THE PRESENT · THE CENOZOIC ERA

The Chicxulub impact drew a fiery line across geologic time. The world that emerged from the long darkness was emptied of its giant reptilian overlords and eerily quiet. This new era — the Cenozoic, which began 66 million years ago and continues to this day — is the story of the meek inheriting the Earth. For 150 million years the mammals had lived in the shadows, small and nocturnal, scurrying beneath the feet of dinosaurs. With their masters suddenly gone, they stepped into the daylight, and into an empty world of boundless opportunity.

6.1 THE WORLD AFTER DINOSAURS: THE PALEOGENE

The Paleogene Period (about 66 to 23 million years ago) dawned on a broken world. The first signs of recovery are written in the rocks as a “fern spike” — a layer dominated by fern spores, the mark of hardy, fast-growing plants recolonizing a scorched and simplified landscape (Vajda, Raine & Hollis, 2001). For hundreds of thousands of years, life struggled to find its footing.

For the surviving mammals, however, the empty world was an invitation. Freed from the long tyranny of the dinosaurs, they underwent a spectacular adaptive radiation, diversifying with great speed to fill the countless ecological roles left vacant (Alroy, 1999). Within roughly ten million years of the

extinction, the major lineages of modern mammals had appeared: small generalists gave rise to the first rodents; the first primates took to the trees; the first hoofed herbivores browsed the recovering forests; and the first dedicated carnivores evolved to hunt them. No longer confined to the undergrowth, mammals became the dominant vertebrates of the land.

Their ascent was not entirely uncontested. The birds — the surviving dinosaurs — seized the moment too. In South America and Europe, giant flightless “terror birds” stood up to three metres tall, armed with massive hooked beaks, and for a time rivalled the mammalian carnivores as apex predators. Meanwhile the backdrop to this drama was a restless climate. The early Paleogene was intensely warm, a greenhouse world with palm trees near the poles. That warmth peaked around 56 million years ago in a brief, extreme episode of global heating — the Paleocene–Eocene Thermal Maximum — driven by a massive release of carbon into the atmosphere and ocean (Zachos, Dickens & Zeebe, 2008). It is studied closely today, for it is the closest analogue the deep past offers to the carbon-driven warming of our own age. After this thermal peak, the planet began a long, erratic slide toward cooler conditions.

6.2 A COOLING WORLD: THE NEOGENE

Through the Neogene Period (about 23 to 2.6 million years ago), the long cooling and drying continued, and it remade the living world. The warm, globe-spanning forests of the Eocene gave way to open woodlands and, for the first time, to vast grasslands. Grasses are tough, abrasive plants, and in response to them mammals evolved high-crowned, hard-wearing teeth and, in many lineages, longer legs built for running across open country. The great grazing herds — horses, antelope, and their kin — spread across the new savannas, pursued by fleet predators. It was a world increasingly like our own.

In Africa, this opening of the landscape set the scene for our own origins. Among the apes of the late Neogene, one lineage began to spend more time on the ground, and eventually to walk upright on two legs. By around six to seven million years ago, the earliest members of the human family — the hominins — had diverged from the lineage leading to chimpanzees. Bipedalism came

first, long before large brains; our ancestors walked across the savanna on two legs for millions of years while their skulls still held an ape-sized brain.

6.3 THE QUATERNARY AND THE ICE AGES

The last 2.6 million years — the Quaternary Period — have been defined by dramatic, cyclical climate instability: the great Ice Ages. Through the Pleistocene epoch, the planet swung between long, cold glacial periods, when ice sheets more than a kilometre thick buried much of North America and Eurasia, and shorter, warmer interglacials — such as the Holocene, the present interval. These repeated swings reshaped continents, opened and closed land bridges, and placed life under relentless selective pressure.

The Pleistocene was an age of giants. Woolly mammoths, mastodons, and woolly rhinoceroses roamed the cold steppe-tundra alongside giant ground sloths, towering camels, and colossal bison. They were hunted by an equally formidable array of predators: the sabre-toothed cat *Smilodon* with its knife-like canines, the powerful dire wolf, and the immense short-faced bear (Koch & Barnosky, 2006). This was the world that our own ancestors would have to learn to navigate — and, in time, to dominate.

6.4 THE HUMAN STORY

The very instability that drove the Ice Ages is thought to have been a crucial engine of our evolution. In Africa, the global rhythm of glaciation translated into shifting cycles of wet and dry, forcing early hominins to cope with rapidly changing environments — conditions that favoured intelligence, social cooperation, and technological ingenuity. Within the genus *Homo*, the fossil record shows a clear trend of increasing brain size and tool-making skill: from *Homo habilis* with its simple stone choppers, to *Homo erectus*, the first homin-in to master fire and to walk out of Africa entirely. That long journey produced several large-brained human species, among them the Neanderthals, superbly adapted to the cold of Ice Age Europe, and the more recently recognized Denisovans of Asia.

THE OLDEST OF OUR KIND

For decades, the earliest fossils of *Homo sapiens* were dated to about 200,000 years ago and came from East Africa, suggesting a single cradle for our species. In 2017, that picture changed. Fossils from Jebel Irhoud in Morocco — at the opposite corner of the continent — were re-dated to roughly 300,000 years ago and identified as early *Homo sapiens* (Hublin et al., 2017). The finding pushed back the origin of our species by 100,000 years and argued that we emerged not from one small region but gradually, across the whole of Africa — a pan-African origin for a pan-global species.

Possessing a singular combination of cognitive gifts — complex language, symbolic thought, and relentless innovation — *Homo sapiens* began to spread out of Africa in earnest around 60,000 to 70,000 years ago, after earlier and more limited dispersals. As our ancestors moved into new lands, they met the other human species already there, and sometimes interbred with them: the DNA of Neanderthals and Denisovans survives today in the genomes of billions of living people, a faint genetic echo of those ancient encounters. Yet wherever *Homo sapiens* went, the other hominins ultimately vanished, until ours was the only human species left on Earth.

As the last glacial period drew to a close, around 11,700 years ago, a great extinction swept the large animals of the world. Across the globe — most severely in the Americas and Australia — the megafauna disappeared: the mammoths, the giant sloths, the great marsupials. The cause is still debated. One view emphasizes the abrupt climate change at the close of the Ice Age, which reorganized ecosystems faster than specialized giants could adapt. The other, the “overkill” hypothesis, holds that the arrival of skilled human hunters in lands whose animals had no inherited fear of people drove them to extinction (Martin, 1973). Most likely the two pressures acted together. Either way, the lesson is sobering: for the first time, a single species had become a

geological force, capable of reshaping the living world on a global scale — a prelude to the age that was to come.

CHAPTER SEVEN

DEEP TIME, MASS EXTINCTION, AND THE ANTHROPOCENE

THE LONG PERSPECTIVE · AND THE PRESENT MOMENT

We have followed life's story across four billion years, and a pattern has emerged from the narrative — a rhythm of slow building and sudden collapse. Again and again, the biosphere has been struck down and has risen anew, each catastrophe clearing the ground for the next great experiment. This closing chapter steps back from the chronicle to consider that rhythm directly: the great mass extinctions of the past, what they share, and why the present moment may be writing a sixth such chapter — this time in a single species' hand.

7.1 THE BIG FIVE

In 1982, the paleontologists David Raup and Jack Sepkoski analysed the marine fossil record and found that, above the constant background hum of ordinary extinction, five episodes stood out as catastrophic spikes (Raup & Sepkoski, 1982). These became known as the “Big Five” mass extinctions, and we have met each of them in the course of this book.

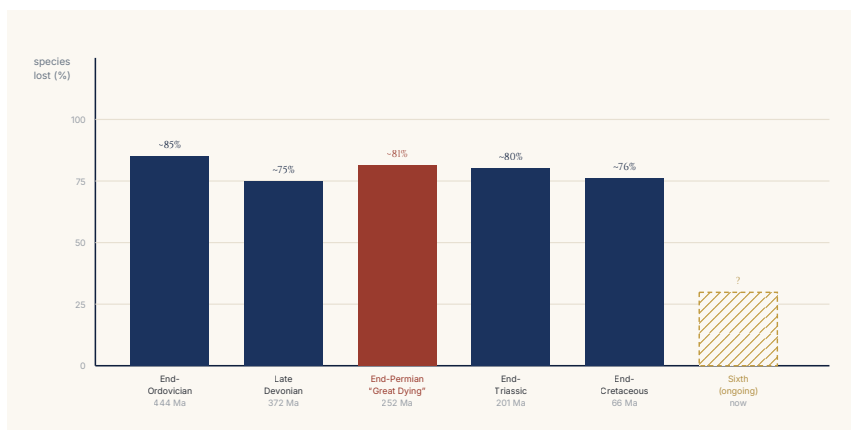


FIGURE 3. The five great mass extinctions of the geological past, by approximate share of species lost, with the present human-driven biodiversity crisis — the proposed “sixth extinction” — shown for comparison. The end-Permian “Great Dying” was the most severe (estimates of marine species loss range from about 81 to over 90 per cent); the famous end-Cretaceous event that ended the dinosaurs was, in proportional terms, the smallest of the five. The sixth bar is hatched because it is unfinished, and its eventual magnitude is not yet determined.

Set side by side, the five reveal both their variety and their common threads. The end-Ordovician crisis (about 444 million years ago) was driven by a sudden glaciation that drained the shallow seas. The Late Devonian (about 372 million years ago) was a protracted decline tied to ocean anoxia. The end-Permian “Great Dying” (about 252 million years ago) — the worst of all — and the end-Triassic (about 201 million years ago) were both triggered by colossal volcanic outpourings and the runaway greenhouse warming they unleashed. And the end-Cretaceous (66 million years ago), uniquely, was set off by an asteroid from space. Different triggers, yet strikingly similar killing mechanisms recur: rapid change in climate and in the chemistry of the air and oceans, faster than ecosystems could absorb. Continent-scale volcanic eruptions — large igneous provinces — and the carbon they vented stand behind most of the worst crises in the record. The common denominator of

mass extinction is not any single kind of catastrophe, but the *speed* of the change it imposes.

7.2 THE SIXTH EXTINCTION

That observation lends a particular weight to the present. Having chronicled the five great extinctions of the past, we now find ourselves the cause of what many scientists argue is a sixth (Barnosky et al., 2011). Current rates of species loss are estimated to run hundreds, even thousands, of times above the natural background rate recorded in the fossil record (Ceballos et al., 2015). The drivers are by now familiar: destruction of habitat, a rapidly changing climate, pollution, the overexploitation of wild populations, and the wholesale transport of species around the world. This event, if it proves to be one, would be unique in the entire history of life — the only mass extinction caused by the deliberate and accidental actions of a single living species.

7.3 THE ANTHROPOCENE

The Holocene — the warm interglacial that began with the retreat of the glaciers — saw the rise of agriculture and of human civilization. But over the last few centuries the scale of human influence has grown so vast that many researchers argue we have pushed the Earth into a new interval of geological time: the Anthropocene, the age of humans (Crutzen & Stoermer, 2000). Humanity has cleared forests and reshaped landscapes on a planetary scale; through the burning of fossil fuels it has released, in a geological instant, carbon that took hundreds of millions of years to bury, altering the climate and the chemistry of the oceans (Steffen, Crutzen & McNeill, 2007). We have manufactured novel materials — plastics, concrete, pure aluminium — that will leave a permanent signature in the rock record, and we have shuffled the planet's species across every ocean and continent.

A DEBATE NOT YET SETTLED — AND A VOTE ALREADY CAST

The term “Anthropocene” now runs through public discussion, but precision matters: it has not been adopted as a formal unit of the geological time scale. In March 2024, after fifteen years of study, the relevant body of stratigraphers voted down a proposal to define the Anthropocene as an epoch beginning around 1950, and that decision was ratified by the International Union of Geological Sciences. By the formal conventions of geology, then, we still live in the Holocene. What is not in scientific dispute is the reality the word points to: that human activity has become a dominant force shaping the planet’s surface, climate, and life. The disagreement is about bookkeeping, not about the magnitude of what we are doing.

7.4 THE MOST UNCERTAIN CHAPTER

The four-billion-year story of life has reached its most uncertain passage. The evolutionary pressures we are now applying will shape the future of life on Earth for millions of years to come. Some organisms are adapting to the world we are making, thriving in our cities and our fields; countless others are vanishing forever. The history we have traced is, throughout, a tale of resilience, adaptation, and chance — of catastrophic endings and unlooked-for beginnings. It has now produced a species that is, for the first time, aware of its own impact upon the whole.

And so the story arrives at a question it cannot yet answer. Will this new geological force — humanity — prove a brief and destructive episode, culminating in just one more extinction layer in the rock, indistinguishable in the long run from the asteroid and the volcanic floods? Or will we become the first species in the history of the Earth to grasp the story it belongs to, and to take conscious responsibility for the stewardship of the planet and the future of life itself? Four billion years of ancestry have handed us that choice. What we do with it is the one part of this story that remains unwritten.

EPILOGUE — A STORY OF CONNECTION

The four-billion-year story of life is, in the end, a story of connection. It binds us to the stardust from which our planet was made, and to the first tenacious microbe clinging to a rock in a primordial sea. It connects the oxygen in every breath we take to the ancient cyanobacteria that first poisoned, and then enriched, the air. It joins the bones of our hands to the fins of a Devonian fish, and the architecture of our brains to the small, frightened mammal that lived through the fall of the dinosaurs.

This unbroken thread of ancestry — stretching back through countless generations across an almost unimaginable expanse of time — is our planet's greatest legacy. We are not separate from the story; we are its latest, most consequential, and most self-aware product. To understand this history is not merely an academic exercise. It is an act of understanding ourselves, and our place in the universe. It instills a profound humility before the sheer improbability of our existence, and a sense of urgent responsibility for the future of the single, precious lineage of life to which every one of us belongs.

• • •

BIBLIOGRAPHY

Works cited in the text, together with the principal sources consulted for this edition's revisions. Where a claim rests on recent or revised science, the relevant source is listed here.

- Alroy, J. (1999). The fossil record of North American mammals: evidence for a Paleocene evolutionary radiation. *Systematic Biology*, 48(1), 107–118.
- Alvarez, L. W., Alvarez, W., Asaro, F., & Michel, H. V. (1980). Extraterrestrial cause for the Cretaceous–Tertiary extinction. *Science*, 208(4448), 1095–1108.
- Barnosky, A. D., Matzke, N., Tomiya, S., et al. (2011). Has the Earth's sixth mass extinction already arrived? *Nature*, 471(7336), 51–57.
- Bell, E. A., Boehnke, P., Harrison, T. M., & Mao, W. L. (2015). Potentially biogenic carbon preserved in a 4.1 billion-year-old zircon. *Proceedings of the National Academy of Sciences*, 112(47), 14518–14521.
- Benton, M. J. (2015). *Vertebrate Palaeontology* (4th ed.). Wiley-Blackwell.
- Bobrovskiy, I., Hope, J. M., Ivantsov, A., Nettersheim, B. J., Hallmann, C., & Brocks, J. J. (2018). Ancient steroids establish the Ediacaran fossil Dickinsonia as one of the earliest animals. *Science*, 361(6408), 1246–1249.
- Briggs, D. E. G. (2015). The Cambrian explosion. *Current Biology*, 25(19), R844–R848.
- Burgess, S. D., Bowring, S., & Shen, S.-Z. (2014). High-precision timeline for Earth's most severe extinction. *Proceedings of the National Academy of Sciences*, 111(9), 3316–3321.
- Ceballos, G., Ehrlich, P. R., Barnosky, A. D., García, A., Pringle, R. M., & Palmer, T. M. (2015). Accelerated modern human-induced species losses: entering the sixth mass extinction. *Science Advances*, 1(5), e1400253.
- Chyba, C., & Sagan, C. (1992). Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules. *Nature*, 355(6356), 125–132.

BIBLIOGRAPHY

- Cohen, K. M., Finney, S. C., Gibbard, P. L., & Fan, J.-X. (2013; updated 2024). The ICS International Chronostratigraphic Chart. *Episodes*, 36(3), 199–204.
- Crutzen, P. J., & Stoermer, E. F. (2000). The “Anthropocene.” *IGBP Global Change Newsletter*, 41, 17–18.
- Daeschler, E. B., Shubin, N. H., & Jenkins, F. A. (2006). A Devonian tetrapod-like fish and the evolution of the tetrapod body plan. *Nature*, 440(7085), 757–763.
- Erwin, D. H. (2006). *Extinction: How Life on Earth Nearly Ended 250 Million Years Ago*. Princeton University Press.
- Hublin, J.-J., Ben-Ncer, A., Bailey, S. E., et al. (2017). New fossils from Jebel Irhoud, Morocco and the pan-African origin of *Homo sapiens*. *Nature*, 546(7657), 289–292.
- Imachi, H., Nobu, M. K., Nakahara, N., et al. (2020). Isolation of an archaeon at the prokaryote–eukaryote interface. *Nature*, 577(7791), 519–525.
- Koch, P. L., & Barnosky, A. D. (2006). Late Quaternary extinctions: state of the debate. *Annual Review of Ecology, Evolution, and Systematics*, 37, 215–250.
- Lyons, T. W., Reinhard, C. T., & Planavsky, N. J. (2014). The rise of oxygen in Earth's early ocean and atmosphere. *Nature*, 506(7488), 307–315.
- Margulis, L. [as Sagan, L.] (1967). On the origin of mitosing cells. *Journal of Theoretical Biology*, 14(3), 225–274.
- Martin, P. S. (1973). The discovery of America. *Science*, 179(4077), 969–974.
- Miller, S. L. (1953). A production of amino acids under possible primitive Earth conditions. *Science*, 117(3046), 528–529.
- Mojzsis, S. J., Arrhenius, G., McKeegan, K. D., et al. (1996). Evidence for life on Earth before 3,800 million years ago. *Nature*, 384(6604), 55–59.
- Moody, E. R. R., Álvarez-Carretero, S., Mahendrarajah, T. A., et al. (2024). The nature of the last universal common ancestor and its impact on the early Earth system. *Nature Ecology & Evolution*, 8(9), 1654–1666.
- Raup, D. M., & Sepkoski, J. J. (1982). Mass extinctions in the marine fossil record. *Science*, 215(4539), 1501–1503.

- Russell, M. J., Daniel, R. M., Hall, A. J., & Sherringham, J. A. (1994). A hydrothermally precipitated catalytic iron sulphide membrane as a first step toward life. *Journal of Molecular Evolution*, 39, 231–243.
- Spang, A., Saw, J. H., Jørgensen, S. L., et al. (2015). Complex archaea that bridge the gap between prokaryotes and eukaryotes. *Nature*, 521(7551), 173–179.
- Steffen, W., Crutzen, P. J., & McNeill, J. R. (2007). The Anthropocene: are humans now overwhelming the great forces of nature? *Ambio*, 36(8), 614–621.
- Vajda, V., Raine, J. I., & Hollis, C. J. (2001). Indication of global deforestation at the Cretaceous–Tertiary boundary by New Zealand fern spike. *Science*, 294(5547), 1700–1702.
- Wächtershäuser, G. (1988). Before enzymes and templates: theory of surface metabolism. *Microbiological Reviews*, 52(4), 452–484.
- Weiss, M. C., Sousa, F. L., Mrnjavac, N., et al. (2016). The physiology and habitat of the last universal common ancestor. *Nature Microbiology*, 1, 16116.
- Wilde, S. A., Valley, J. W., Peck, W. H., & Graham, C. M. (2001). Evidence from detrital zircons for the existence of continental crust and oceans 4.4 Gyr ago. *Nature*, 409(6817), 175–178.
- Williams, T. A., Foster, P. G., Cox, C. J., & Embley, T. M. (2013). An archaeal origin of eukaryotes supports only two primary domains of life. *Nature*, 504(7479), 231–236.
- Zachos, J. C., Dickens, G. R., & Zeebe, R. E. (2008). An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature*, 451(7176), 279–283.

APPENDIX A — GEOLOGIC TIME SCALE

A simplified overview of the major divisions of geologic time and the principal events discussed in this book. Boundary ages follow the International Commission on Stratigraphy (ICS) chart, 2024 revision.

EON	ERA	PERIOD	AGE (MA)	KEY EVENTS
PHANEROZOIC	Cenozoic	Quaternary	2.6 – 0	Ice Ages; evolution of Homo sapiens; megafauna extinction.
		Neogene	23 – 2.6	Spread of grasslands; first hominins; cooling climate.
		Paleogene	66 – 23	Adaptive radiation of mammals; PETM warming (~56 Ma).
	Mesozoic	Cretaceous	145 – 66	Flowering plants; T. rex; end-Cretaceous (K–Pg) impact.
		Jurassic	201 – 145	Giant sauropods; first birds (Archaeopteryx, ~150 Ma).
		Triassic	252 – 201	First dinosaurs and mammals;

APPENDIX A — GEOLOGIC TIME SCALE

EON	ERA	PERIOD	AGE (MA)	KEY EVENTS
				end-Triassic extinction.
	Paleozoic	Permian	299 – 252	End-Permian “Great Dying” — the largest mass extinction.
	Carboniferous	359 – 299	Vast coal swamps; high oxygen; the amniote egg evolves.	
	Devonian	419 – 359	“Age of Fishes”; first forests; first tetrapods; Late Devonian extinction.	
	Silurian	443.8 – 419	First vascular land plants; arthropods colonize land.	
	Ordovician	485.4 – 443.8	Great marine diversification; end-Ordovician glacial extinction.	
	Cambrian	538.8 – 485.4	The Cambrian Explosion; nearly all animal body plans appear.	
PROTEROZOIC			2500 – 538.8	Great Oxygenation Event (~2.4 Ga); first eukaryotes; Ediacaran biota.
ARCHEAN			4031 – 2500	Oldest firm evidence of life (~3.5 Ga);

APPENDIX A — GEOLOGIC TIME SCALE

EON	ERA	PERIOD	AGE (MA)	KEY EVENTS
				oxygenic photosynthesis evolves.
HADEAN			~4540 – 4031	Formation of Earth and Moon; first oceans; LUCA (~4.2 Ga).

Note: the original edition omitted the Ordovician Period and dated the base of the Cambrian to 541 Ma; both have been corrected here. Numerical ages in the Phanerozoic are formally fixed by boundary stratotypes (“golden spikes”), not by the round numbers; the figures above are the currently accepted values and remain subject to refinement.

APPENDIX B — A TWO-DOMAIN TREE OF LIFE

Evolution is not a ladder but a vast, branching tree. The diagram below is a highly simplified sketch of the relationships among the major groups discussed in this book. It reflects the modern, *two-domain* view of life's deepest structure: rather than three coequal domains, the evidence now indicates that the eukaryotes — the lineage of all plants, animals, fungi, and protists — arose from *within* the Archaea, most closely related to the Asgard archaea (Williams et al., 2013; Spang et al., 2015). The mitochondria and chloroplasts of eukaryotic cells, meanwhile, descend from once-free-living bacteria acquired through endosymbiosis.

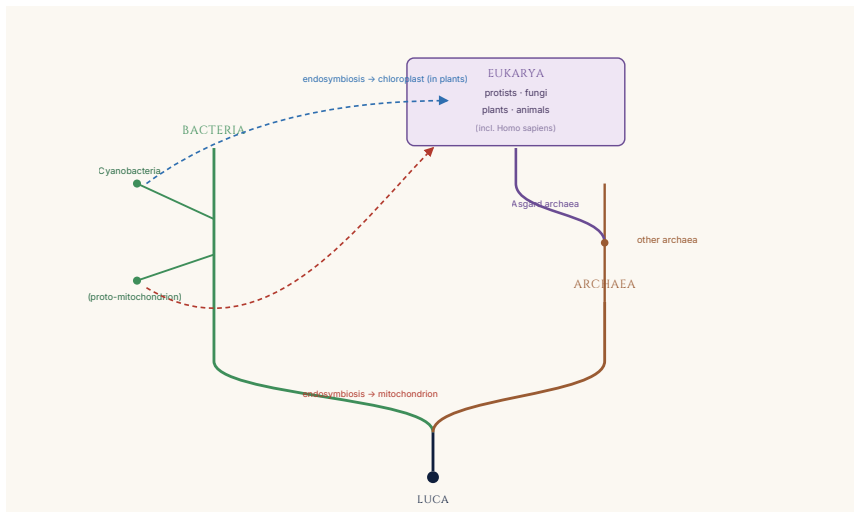


FIGURE 4. A simplified two-domain tree of life. From LUCA, life divides into two primary domains, Bacteria and Archaea. The eukaryotes emerge from within the archaeal domain, as the nearest relatives of the Asgard archaea; their mitochondria and (in plants and algae) chloroplasts descend from engulfed bacteria. Branch lengths and the great majority of lineages are omitted for clarity.

FURTHER READING

For readers who wish to go deeper into the topics of this book, the following are recommended for their clarity, scientific depth, and storytelling.

Your Inner Fish: A Journey into the 3.5-Billion-Year History of the Human Body — Neil Shubin. A lucid account of the fossil and developmental evidence linking the human body to its ancient aquatic ancestors, by one of the discoverers of *Tiktaalik*.

The Sixth Extinction: An Unnatural History — Elizabeth Kolbert. A Pulitzer Prize-winning work that interweaves the story of past mass extinctions with the biodiversity crisis unfolding today.

The Rise and Fall of the Dinosaurs: A New History of a Lost World — Stephen Brusatte. A vivid, up-to-date narrative of the Mesozoic, drawing on a wave of recent discoveries about dinosaurs and their feathered descendants.

Sapiens: A Brief History of Humankind — Yuval Noah Harari. A sweeping account of our own species and the cognitive and social revolutions through which it came to remake the planet.

Oxygen: The Molecule that Made the World — Nick Lane. A rich exploration of how oxygen shaped the evolution of life and the chemistry of the Earth.

The Tangled Tree: A Radical New History of Life — David Quammen. An engaging history of the molecular discoveries — from the Archaea to horizontal gene transfer — that overturned the old picture of the tree of life.

F I N I S