A History of Earth's Biota

A History of Earth's Biota:

The Blooming of Life

By

J. William Schopf

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Cover Image Buddhism's Sacred Lotus (*Nelumbo nucifera*), an aquatic plant having an underground stem and exceptionally long-living seeds that adapt it to a periodically wet and dry environment. *Nelumbo* seeds collected from a now-dry Lotus lakebed in Liaoning Province, northeastern China planted by Buddhist monks nearly two millennia ago, unearthed and germinated by the author's wife Jane Shen-Miller Schopf, have been radiocarbon dated at 1,300 years, the oldest directly dated viable seeds now known.

To my teachers, from whom I learned,
to my students, who teach me still,
and to my wife, who cheers me on.

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PREFACE

Background

As a second-year student at Oberlin College, a small undergraduate school in northeastern Ohio, I listened with interest to a stimulating lecture by Geology professor Larry DeMott during which he noted that the entire fossil record before the emergence of the oldest recognized animals (large many-legged trilobites) was *"unknown and unknowable"* – and had been for "*the past 100 years.*" He then went on to note, almost in passing, that this was "*the greatest unsolved problem in all of natural science*."

As a "wet-behind-the-ears" young college student, this hit a resounding chord – but I was skeptical. That evening I searched through my paperback copy of Darwin's 1859 *Origin of Species* to find the answer. The prof was correct, Darwin penning that this "missing" early fossil record was "*inexplicable,* [an absence that could] *be truly urged as a valid argument against* [his theory of evolution]*."* Darwin was also correct – this *was* inexplicable – but I could not imagine why the problem had remained unsolved for a full century. This made no sense! After all, evolution is a fact – not some fanciful made-up "fake news" – and trilobites were obviously far too complex to have anything at all to do with life's beginnings. Darwin had tried mightily to explain the problem away (perhaps primitive life was too small, too fragile to be preserved, or perhaps all truly ancient fossil-hosting rocks had eroded away), but his notions about pre-trilobite life and the surviving rock record were by this time 100 years out of date.

Later that spring (1961) I journeyed off to Harvard to meet paleobotanist Elso S. Barghoorn who had written the one published paper I could find on the topic, a 1954 report lead-authored by economic geologist Stanley A. Tyler (University of Wisconsin) reporting what they regarded to be authentic pre-trilobite (Precambrian) ancient fossils. At the end of my visit, Barghoorn handed me a chunk of the black shiny rock (from the 1,900 million-year-old Gunflint Formation of southern Ontario, Canada) that Tyler and he claimed to harbor the tiny fossils. That was enormously kind of him a splendid souvenir? Or, perhaps, he wondered what can this young upstart do with this?

After checking the Harvard graduate-school entrance requirements (*"only Honors Students will be considered"*) I petitioned the Oberlin Geology faculty to allow me to do a research-based undergraduate Honors Thesis. Though the Chair of the Department demurred, arguing that "undergraduates have no business doing research," my petition succeeded. Following a faculty vote, I thus became the first Honors student in the department since the program had officially been put in place in 1908. Upon graduation in 1963, I trekked back to Harvard to become Barghoorn's student.

For me, this undergraduate research project turned out to be a real boon. When I arrived at Harvard I already had a couple years' experience doing hands-on research and – more than that – it enabled me to play a part in the first two 1965 "breakthrough" publications that laid the foundation for the field. The first of these was a decade-long-delayed full-blown description of the Gunflint fossils (the subject of my undergraduate research) co-authored by Barghoorn and Tyler (who had unexpectedly died in the fall of 1964). Its publication, however, engendered widespread skepticism, the naysayers opining that *"the 'fossils' are much too old, there must be some mistake!"* The second paper, published some six months later and co-authored by Barghoorn and me, reported a completely new find – diverse exquisitely well-preserved pre-trilobite, Precambrian fossils, this time from the 850 million-year-old Bitter Springs Formation of central Australia (which would later become the subject of my doctoral thesis). This second 1965 paper was the "deal-sealer" – different rocks, different continent, different age, and chock-full of abundant, varied, remarkably well-preserved microscopic fossils, many easily relatable to microbes living today. Taken together, these two seminal papers laid the groundwork for the soon-to-emerge and now thriving field of Precambrian paleobiology.

To me, today, those early years are a blur. I co-authored with Barghoorn a dozen or so scientific publications, gave numerous talks at scientific meetings and various universities, was elected to Harvard's elite Society of Fellows (like Tom Kuhn whose seminal studies are discussed in Chapter 8) and, upon graduation in 1968, landed a faculty position at the University of California, Los Angeles (UCLA). A pretty nifty beginning!

In the years soon after joining the UCLA faculty I continued to have enormously good fortune – youngest to be advanced to tenure (age 27), youngest Full Professor (age 31), and a series of awards from the University (for teaching, research, and academic excellence). My science prospered. In my early years, I journeyed off to Australia, India, the former Soviet Union, and China – in each, "spreading the word" about life's wondrous Precambrian fossil record and, importantly, in each country making friends and discovering the most ancient fossils there known.

To my great surprise, a "Biggie" then arrived. In 1976, the bicentennial of the founding of the United States, the US Science Board established the Alan T. Waterman Award to honor "one outstanding young scientist in United States" and a $150,000 prize (an honor now, decades later, that carries a prize of one million dollars). What was I to do with the wholly unexpected largesse, the "manna from heaven" that had landed on my plate? I pondered the matter for several weeks and came up with a plan – use the prize money to set up an international interdisciplinary team to work together on life's early history. I did. My notion succeeded.

In 1978 I assembled a group of 22 mostly then-young workers from Australia, Canada, Germany and the USA to come to my lab at UCLA, families in tow. Calling ourselves the Precambrian Paleobiology Research Group (PPRG) we worked together as a team for the following 14 months. We did our stuff and produced *Earth's Earliest Biosphere, Its Origin and Evolution* (J.W. Schopf, Ed., Princeton Univ. Press, 1983, 543 pp.), a volume that received that year's US national prize for a scholarly volume in its field. But we had covered only the first half, the earliest two billion years of Earth's history. *A job half-done is a job undone!* So, I then put together a second PPRG team to investigate the more recent two billion years of our planet's history – this time numbering 42 participants with new members from Denmark, Sweden, South Africa, and the USSR – which produced *The Proterozoic Biosphere, A Multidisciplinary Study* (J.W. Schopf and C. Klein, Eds., Cambridge University Press, 1992, 1348 pp.). It, too, received a national scholarly publishing award. Taken together, these two mammoth volumes – jocularly (if affectionately) referred to by some in the group as the "Old and New Testaments" – brought together what was then known about Earth's first four billion years of evolutionary history, the exceedingly long pre-trilobite Precambrian interrelated biotic-environmental history of the planet.

Given that spur, and in an effort to make this new knowledge accessible to a wider audience, I then wrote *Cradle of Life – the Discovery of Earth's Earliest Fossils* (J.W. Schopf, Princeton Univ. Press, 1999, 367 pp) to use in my Freshman-Sophomore General Education course, "Major Events in the History of Life." My Goodness! This volume, too, was a national prizewinner.

Why this book?

As is suggested in the prologue of my earlier effort, *Cradle of Life*, if one considers Earth's entire four-and-a-half-billion existence, Darwin's "missing" pre-trilobite Precambrian fossil record would encompass the earliest nearly 90%. Pause for a moment and compare that with America's almost 250-year-history. What that would mean is that today we would have no writings, no evidence, no facts and no way to understand anything about our country's history except for its most recent 25 years! Knowledge of all earlier events would have been wiped away – Benjamin Franklin, the Declaration of Independence and the Constitution; George Washington, Thomas Jefferson, Abraham Lincoln and the Civil War; electricity, telephones, radio and television; the Great Depression, two World Wars and the 45-year-long East-West "Cold War"; personal computers, the internet, mobile phones and much, much more. The biota-birthing saga that unfolded during that earliest 90% of life on Earth is the focus of *Cradle of Life*.

But what about the last 25 years of American history, the most recent 10% – don't they matter, too? Yes, of course. Global warming, the Great Recession, unemployment, gender equity, LGBTQ rights, political divisiveness, racial injustice, nation-wide protest demonstrations, widespread economic woes, two presidential impeachments, the covid-19 pandemic, the crisis in Ukraine and on and on and on – all game-changers, each occurring at a seemingly ever-quickening clip.

Interestingly, this latest phase of the American experience has a near-perfect parallel in the most recent 10% of life's long history – a segment of geological time referred to as the "Phanerozoic" (the "Age of Large Life") – and it, too, is of great interest, maybe even more so than life's Precambrian origin and enormously long, laborious, formative beginnings. And the parallel is not surprising – both Phanerozoic life on Earth and societal life in the United States evolve over time, each building on that which occurred before, each testing one possible advance then another and another, each moving sporadically, haltingly, as they search for the best available solution.

Moreover, it is only at the very end of this latest Phanerozoic 10% of life's history that we humans entered the scene, in terms of any such "geologic clock" just a scant few seconds before the present! What happened before humans finally emerged? Why, for what reason and in what order, did those stage-setters occur? Why do we humans walk on two legs, not three (a lot more stable in a windstorm), and why do we have only two arms, not three or perhaps five or six (a lot better to handle multiple objects at the same time)? And what is "intelligence" – a human trait that we love to tout – where in the world did ***that*** come from? Fortunately, the answer to such questions is simple and amply evidenced by fossil record-recorded Darwinian biological evolution. Indeed, as Theodosius Dobzhansky (a pioneering gene-studying fruit fly expert) taught us in 1973, *"Nothing in biology makes sense except in the light of Evolution.*

For the past two decades, I have used *Cradle of Life* as the prime text for my yearly Freshman-Sophomore General Education Course. Yet, as several students have remarked to me, *"it is not like any textbook I've ever seen it reads much more like a novel, an engaging and thought-provoking good story."* And that, again, is the aim of this book, a needed sequel because I well know that *Cradle* is lacking, covering only the earliest 90% of life's existence. The more recent 10%, the latest half-billion-years and that part of the record when plants and animals set the stage for humans to at long-last enter the scene, is what this book is all about. In short, *Blooming of Life* fills in the most recent 10% – to us, the most interesting phase of life's long history – aimed at linking together the highlights of the past half-billion-years of life's existence and showing how we humans are very much a result of life's evolutionary past.

How does the story proceed?

To begin this remarkable story – to get our juices primed to digest the tale that follows – Chapter 1 presents an overview of the history of life highlighting the two great world-changing advances of the pre-trilobite pre-Phanerozoic world and a short summary of how evolution works (a curtain-raising brief reprise of topics addressed in *Cradle*).

The narrative then moves on, oddly, you may think, the first two following chapters dealing with plants, not animals. Why should this be? After all, Darwin was concerned with the "missing" pre-trilobite (*pre-animal*) fossil record, not with the history of plant-life! The answer is simple. A great many animals, like us, are "land-lubbers" – ants, beetles, countless insects, frogs, lizards, birds, lions and tigers, virtually all the animals we know. But we, and they, could not exist on the land surface (or in the oceans, either) without plants. Plants provide the oxygen we breathe and, via that oxygen, the Earth's ozone layer that shields the surface of the land and ocean from the Sun's harmful UV-rays. Moreover, all of us – and all other animals as well – each and every day devour plants and (except for vegetarians) the meat of animals that fed on plants. Thus, today's entire ecosystem is wholly dependent on plants, even though we humans –

again rather oddly – tend to take plants for granted (as evidenced, for example, by the estimated 175 million Americans, roughly half the total population, who visit zoological parks and aquaria each year compared with the vastly smaller attendance at botanical gardens and arboretums).

In the following chapters, the narrative moves on to outline the history of animals – first sponges, jellyfish, worms, crabs and the other major groups of non-backboned animals; then fish (some that trundled, or at least slithered across the land), amphibians (like salamanders and frogs that make up the half-way tribe to full-blown land-animals), then reptiles (like turtles and dinosaurs) and birds (first flightless then ultimately soaring); and finally, mammals like us – a progression from early egg-layers (like the duck-billed platypus), to milk-producers with pouches to protect the new-born (like kangaroos), to placental mammals like us, those with a water-filled belly-sac to protect the unborn before they enter the world. A remarkable story! How, why and when did all that happen?

Blooming heads toward the climax with a next-to-the-last chapter that, using the perceptive insights of Thomas S. Kuhn, shows how science advances by using examples previously discussed in the text. The narrative then ties together the evolutionary story of the time-and-again rise, fall and ultimate success of life on Earth during the past half-billion-years of our planet's existence. Perhaps most interestingly, this saga features a series of surprisingly parallel innovations in plants and animals – from marshes, to the uplands, to the entire globe – with plant-life, the "eatees," leading the charge and animals, the "eaters" soon following their food. And though the volume does not include a discussion of the (very) recent rise of the human lineage – a rapidly evolving subject best left to the expert anthropology-archaeology community – this chapter closes with a short discussion of the origin of intelligence, a trait that some suppose is uniquely human but that in fact has exceedingly deep evolutionary roots, in its basics extending to the very origin of life on Earth. As you will discover, the most recent Phanerozoic 10% of life's long history is a fascinating tale!

The concluding chapter of *Blooming* then provides a surprising clincher, a fanciful yet instructive thought experiment that shows how exceedingly intermeshed Earth's plants, animals and environment actually are. The scenario is simple. Imagine that Earth is visited by benign, inquisitive, highly intelligent aliens. Imagine further that all of their analytical instruments have been disabled during their voyage though the Cosmos leaving them only the ability to collect and bring back to their home planet for study a representative "Noah's Arc" of Earth life. What could they learn? As surprising as it may seem, they in fact would be able to unravel a tremendous amount not only about today's living world but also about Earth's place in the Solar System, Earth's daily, monthly and yearly cycles, how Earth-life came into being, and how life and Earth's environment have co-evolved over the past 4.5 billion of years. Amazing stuff, all recorded just in the living organisms around us!

Thus, via a simple imaginative thought experiment, this final chapter illustrates the way science works, illuminating and tying together the central theme of the preceding chapters – the interrelated evolution and total dependence of life on its environment both now and over all of the geologic past – into a coherent whole.

Why is this book worth your time?

This is ***not*** a nitty-gritty "hard-science" reference-laden textbook. Rather, like *Cradle of Life* – its predecessor in this two-part sequence – *Blooming of Life* is intended for a non-specialist general audience, students and laypersons alike who are interested in learning about the Phanerozoic history of life, the 550-million-year-long history of plants and animals that set the stage for the rise of humans. In short, if you ever wondered about how this world around us came to be, where we came from and why it is that humans are "smart," this book will answer your questions.

The book is factual (at least as up-to-date and factual as I can muster) and the narrative is intended to be informal, readable, sprinkled with surprises and occasionally with a bit of humor (when I can find a proper excuse). To highlight the human side of science, it includes personal vignettes about several of the prominent scholars who have shaped current understanding of the topics covered, "movers and shakers" such as origin-of-life biochemist Aleksandr Oparin, microbiologist Carl Woese, micropaleontologist Boris Timofeev, fish expert Colin Patterson, vertebrate paleontologist Al Romer, global environmental authority Mohamed El-Ashry, and historian and philosopher of science Tom Kuhn. Moreover, as you read along you will find that it contains a fair amount about the historical development underlying the various concepts discussed, included to illuminate how scientific discoveries are actually made, and that it is well illustrated (at least the students seem to enjoy these pics). Though it does contain a few unavoidable "technical terms" (items for which there are no common names in general use), each such term is defined in normal parlance when it is first used and backed by a Glossary of Technical Terms. Moreover – and importantly, as you will discover – almost all of the fancy formal scientific names are also backed by an explanation of their linguistic derivation from ancient Greek or

Latin, an "add-on" not normally included in books of this type that you will find, as have I, is hugely helpful in understanding and remembering such seemingly odd arcane terms.

In short, *Blooming of Life* is intended to be a book written for ***you*** – presented in ways ***you*** can understand – an up-to-date summary of what is now known about the development of today's modern world as the volume wends its way through a terrifically interesting, remarkable story. Have a look at the Table of Contents. Browse through the images. Have a read and see what you think. I hope that you will be pleased!

CHAPTER 1

PRELUDE TO THE BLOOMING OF LIFE

When did dinosaurs appear?

Most of us know a bit about dinosaurs – those great beasts, some lumbering, some agile – that roamed the Earth in the distant past. Lucky grade-schoolers such as my older brother and I even got to see them, on Saturday mornings racing each other up the long stairs at Pittsburgh's Carnegie Museum of Natural History to see who could be first to reach the Dinosaur Hall. And many of us have enjoyed the 1993 movie *Jurassic Park* and its various sequels in which, I am pleased to report, the dinosaurs and their behavior seem remarkably accurate (largely and perhaps entirely because the producers of the film enticed Montana's expert on dinosaurs and their behavior, paleontologist John R. "Jack" Horner, to be their consultant). Yes, as depicted in the films, dinosaurs *did* lay eggs, protect their nests, and trundle about in great "flocks" … think of them as huge scaly flightless birds. Some were fearsome, like *Velociraptor* (a genus name that means "quick plunderer") and *Tyrannosaurus rex* (meaning "king of the tyrant lizards"), but others were more docile vegetarians, plant-eaters like *Triceratops* ("three-horned dinosaur") and *Brontosaurus* ("thunder lizard," now known by its original name, *Apatosaurus*, "deceptive lizard"). And yes, some of the meat-eaters, like the 'raptors, did hunt in packs, much like wolves and lions.

Like the great majority of life forms that once populated the Earth, dinosaurs are now extinct, having died-out long ago. Still, it is worth wondering when, in the long sweep of the history of this planet, dinosaurs actually existed. For most of us, that is not an easy question, largely because we think of time in human terms. One hundred years, a decidedly long lifetime, seems old. A couple of thousand years, back to the time of Christ, seems really ancient. And 450,000 years ago, the time of *Homo neanderthalensis*, our Neanderthal-forerunners with whom we share about 2% of our individual genes, is essentially unimaginable. But, in geologic not human terms, hundreds, or thousands, or even hundreds of thousands of years are trivial, piddling. Instead, Earth history is counted in *millions* of years, hundreds of millions of years, even thousands of millions (billions) of years. After all, planet Earth has been here for some 4,500 million (4.5 billion) years!

So, to put the question of "when did dinosaurs exist?" in more human terms, let's imagine that all of Earth history were condensed into the height of a man (**Fig. 1-1A**). Have a look and take a guess. At the kneecap? At the belly? At the chest? No, much later, at the forehead (**Fig. 1-1B**). In other words, as surprising as it may seem, dinosaurs are relatively recent!

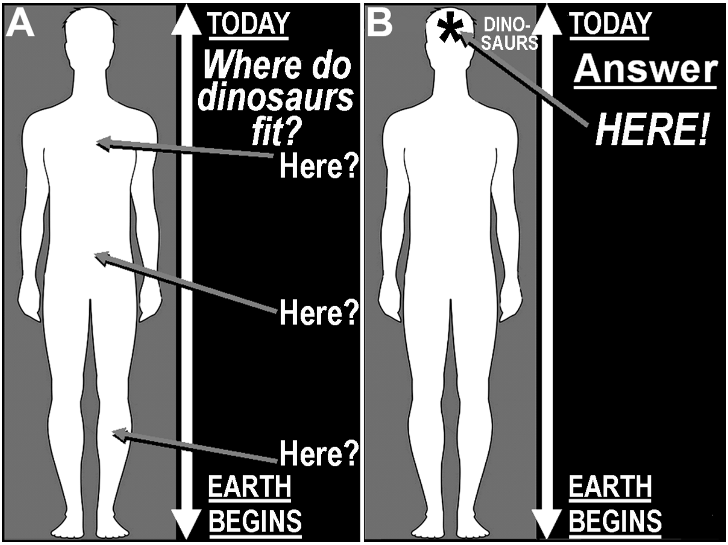

Fig. 1-1 (A) In comparison with the height of a human, when did dinosaurs appear in the history of the Earth? At the kneecap, the belly, the chest? **(B)** No, here, at the forehead! In the 4.5 billion history of the planet, the rise of dinosaurs was relatively recent, only a few hundreds of millions of years ago.

If that is so, what in the world happened earlier? The answer, now reasonably well understood, is an almost unimaginably long 4-billion-year-long series of events during the 4.5- to 0.5-billion year-long Precambrian Eon of Earth history that by about half-a-billion-years ago had finally set the stage for the rise of organisms that in their basic makeup, having heads, bodies, limbs, and so forth were like us.

Major advances of the Precambrian, pre-trilobite microbial world

Of all the vast number of evolutionary advances of the Precambrian pre-"life-like-like-us" world, two turned out to have monumental impact on the later history of life. Of these, the earlier – probably but not certainly as early as 3 billion years ago – was the advent of oxygen-producing photosynthesis (**Fig. 1-2**). Why did this matter?

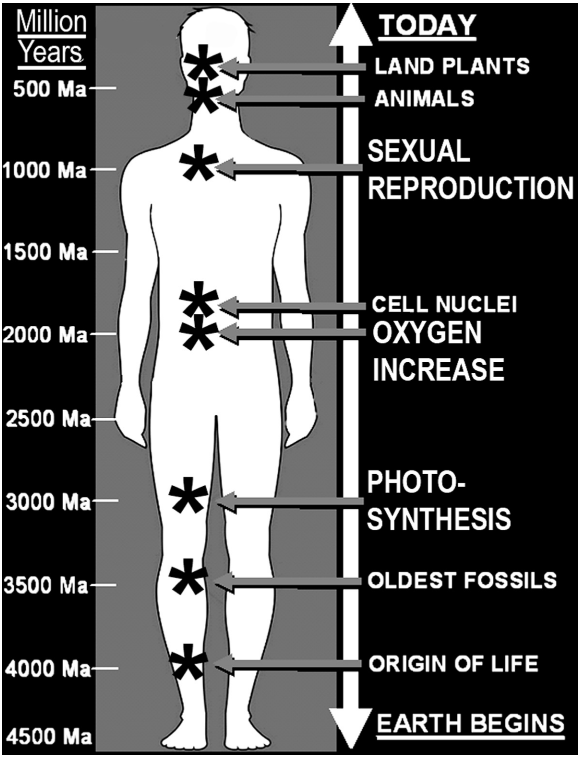

Fig. 1-2 Major events in the history of life, a great many dating from the earliest pre-animal Precambrian nearly 90% of Earth history. Among these game-changers, two stand out: The first, the microbial invention of oxygen-producing photosynthesis about 3,000 million (3 billion) years ago, with oxygen building-up to the amounts needed by oxygen-dependent life about a billion years later. The second, the origin of sexual reproduction about 1,000 million (1 billion) years ago, provided a huge advance for life that speeded evolution and life's ability to adapt to the ever-changing planet.

Life like us – all other animals and plants over the entire globe – relies on oxygen to breath. Think about it. That's the reason a flight attendant tells the passengers before a flight lifts-off that if the plane encounters problems and an oxygen mask drops from the ceiling, you should don it first and only then fix another mask to the youngster beside you. The attendant won't tell you why, but you have only about five minutes before you develop brain damage and another three or four before you are comatose. In other words, protect yourself first and only then "fight" with the little one at your side.

Our absolute requirement for oxygen is by no means a purely human trait. Indeed, all higher forms of life are wholly oxygen-dependent. Initially, however, when the planet formed, there was no oxygen to breathe. Where did it come from? Not from land plants – 4 billion years ago they did not exist. Rather, it originated in an early-evolved lineage of life – cyanobacteria, "pond scum," by far the most successful of all the truly ancient forms of life we know – microbes that could combine carbon dioxide with water to produce their life-sustaining glucose sugar and give off oxygen (in chemical parlance, $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$). In a short time, cyanobacteria took over the globe, chiefly as a result of "gas warfare," the oxygen they produced new to the environment and toxic to their competitors.

Nevertheless, it took a long while for environmental oxygen levels (now some 21% of the atmosphere) to build. Why? Mostly because oxygen is highly reactive, its nature being to combine chemically with other materials such as the gases issuing from volcanoes and the minerals of the Earth's crust. Because the planet had not seen this reactive gas before, the free oxygen produced by these microbes was sopped-up by the effluents of the volcanoes that peppered the early planet and by dissolved iron from deep within the Earth that belched forth from submarine fumaroles. When this iron welled-up from the ocean depths to reach the near-surface of shallow near-shore seas, it reacted in the uppermost thin veneer of oxygen-laden water to form tiny grains of the iron oxide mineral hematite (Fe_2O_3) that settled down to the sea bottom in a fine rusty rain. This then resulted in a long worldwide episode of the deposition of what are now known as "banded iron formations," mineable iron-rich rocks that form the basis of today's steel industry. Remarkably, the entire world rusted for hundreds of millions of years! Finally, by about 2.3 billion years ago, as the submarine sources of the iron slowly became depleted and early volcanism gradually abated, oxygen in the atmosphere began to build. Soon thereafter, oxygen-producing and -dependent algal plankton, single-celled "eukaryotes" having cells with nuclei as do we, entered the scene.

The second major game-changer before the evolution of many-celled higher forms of life like us was the advent of sexual reproduction about 1 billion years ago. Why sex? The answer is simple. Earlier life, both those with cell nuclei (single-celled planktonic eukaryotes) and those without nuclei (microbial cyanobacteria, for example) reproduced by cloning, each new generation having the same genetic instructions as the one before – the individual organisms died but their unaltered gene-based directives lived on generation to generation. However, with the advent of sex, the situation markedly changed. Sex combines the genes from two different parents – in humans from the mother and the father – the reason that offspring have traits from both and the source of what we call "family resemblance." Most of the two sets of parental genes handed down are pretty much the same, but there are enough differences that the offspring differ one from another.

Think about your brother and your sister. You and they are not exactly the same. Part of the difference comes from your genes, but another part from what you and they were taught as youngsters (an example of the continuous interplay between "nature," genetics, and "nurture," upbringing). Watch the kids in the checkout line at your local grocery store. Some children who are distraught will tug at their mother's skirt and call out *"mommy!"* while others will grab their father's shirt sleeve and holler *"daddy!"* Yet in some families, if the kids act-up they are likely to be scolded and told to *"act like adults."* Such variability illustrates aspects of the "nurture" side of the coin. And in most families, the first-born has a leg up on the siblings, a result of having received undiluted parental attention before the others entered the scene (leading to the 1- to 2-point slightly higher IQ test scores typical of the eldest offspring … "nurture," parental attention, here affecting the "nature," largely gene-based side of the equation).

Now, flip the coin over to its "nature" side. Genes, "nature," determine sexual characteristics and, even at a young age, the girls are likely to be more inquisitive, more imaginative and better with their hands – abundantly evident when grade-schoolers are introduced to cursive writing (a skill evidently no longer commonly taught). At a similar age, the boys typically are stronger, faster runners, more out-spoken, more rebellious. Such differences are of course not nearly as evident in genetically identical twins, especially in offspring of the same sex in which "nature" rather than "nurture" predominates. And this is true even for twins brought up in different families – they commonly like the same things, drink the same brews, wear similar clothes and share the same physical attributes as well as maladies – simply because their genes are identical as though they had been cloned.

Thus, such gene-based "natural" similarities among identical twins are not surprising. And because the precociousness of girls and comparatively laggard development of boys are also genetically determined, products of "nature" rather than "nurture," they too are easily explained. One of the most interesting and revealing studies on this subject, published in 2013 by Markus Kaiser and his colleagues at Newcastle University U.K., used brain-scans of a large population of young adults to document the development of their brains. What they found was that girls tend to optimize the nerve-connections inside their brains earlier than do boys, a ready explanation why females generally mature faster in certain cognitive and emotional areas than males during childhood and early adolescence. And all this, in turn, is a function of yet another genetically determine human trait, "puberty," when a child undergoes physical changes and becomes sexually mature, a process that typically begins around age 8 in girls and age 9 in boys. Indeed, the study found that girls begin to show greater brain-organization between the ages of 10 and 19 and that a comparable degree of brain maturation begins in boys between the ages of 15 and 21.

In sum, and regardless of how we humans have managed the situation, what this means is that the products of sexual reproduction, their offspring in every instance combining the "nature"-dependent genetic traits of two separate parental stocks, are bound to differ, at least slightly, one from another. Now, scale this up to the world's biota and compare the non-sex world with that after the advent of this new gene-mixing reproductive process.

Before life invented the process of sexual reproduction, the biota was fairly humdrum and monotonous, changing only very gradually – primitive microbes and even more advanced nucleated single-celled phytoplankton reproducing by the simple process of one cell dividing into two with their genes being passed along unaltered to the offspring – prompting some to refer to the billion-year lag between the origin of nucleated cells and the advent of sex as the *"boring billion."* Yes, life evolved, the ancient non-sexual bacterial microbes adjusting to exceedingly slow changes in day-length and solar luminosity and the later-evolved but similarly cloning single-celled nucleated phytoplankton gradually becoming a bit more diverse (with all such slow gradual changes being a result of random mutations of their genetic instructions).

Once sex arrived in nucleated cells, about 1 billion years ago, all this markedly changed – immediately, almost overnight. Why is that? Again, the answer is straightforward. By combining the gene-based traits of two different parental lineages their offspring also differed, not only from each other but from every other organism on Earth. In fact, you, me, and every one of us is unique – never before and never again will there be a human being precisely, exactly like a single one of us! And that it true as well about each organism of the entire sexually reproducing world. Thus, with the advent of sex, the diversity of living systems and their ability to adjust to and inhabit new environments immeasurably increased. In a flash, the speed of life's advance markedly accelerated. First known from the fossil record and now confirmed by gene-based phylogeny studies of living organisms, the results of this then newly devised method of reproduction is earliest shown about 1,000 million years ago by a rapidly accelerating increase in the varieties of single-celled nucleated plankton, protozoans and early-evolved multicelled algae. Within the next hundred million years this was followed by the proliferation of increasingly diverse many-celled seaweeds and then, later, by the forerunners of the many-celled animals and plants that, by 550 million years ago, began to populate the world.

Without the evolutionary inventions of early-evolved oxygen-producing photosynthesis, about 3 billion years ago, and the sexual reproduction of organisms having nucleated cells, about 1 billion years ago, we humans and all in the natural world around us would not exist.

Geologic Time Scale

Geologists, of course, do not think about the history of the Earth terms of the height of man. Rather, they and all of the scientific community uses the Geological Time Scale **(Fig. 1-3)** calibrated in millions of years (abbreviated as Ma, from Latin, *mega*, "very large, great" and *annum, "year'"*") and stacked from the oldest to youngest, bottom-to-top, like a layer-cake, the oldest first-baked layer at the bottom of the pile and the later-baked layers laid one over the other.

The ages of the geologic units come from their radiometric dating, detailed studies of the time indicated by the natural alteration of one variety of a chemical element's inner structure to form a new, different atom or element. Atoms of the element carbon, for example, occur in three such forms, "isotopes," each denoted by its atomic weight – ^{14}C, ^{13}C, and ^{12}C – "carbon-14" being the heaviest, its extra weight caused by extra particles in its nucleus. Because of these extra pieces, ^{14}C is unstable – over time it "decays," comes apart by spontaneously losing the extra bits and changing into a completely new stable element, an atom of nitrogen, ^{14}N. This process, called "radioactive decay," occurs at a constant average steady rate. Thus, for example, in 5,730 years a pound (0.45 Kg) of ^{14}C will decay such that only half-a-pound remains, the lost half changing to ^{14}N, a length of time referred to as the ^{14}C isotope's "half-life." After an additional 5,730 years, only a quarter of a pound of the original ^{14}C will remain, a regular predicable process that goes on and on, the original amount of the "parent isotope" becoming smaller and smaller and the amount of the "daughter product" ever-increasing. Thus, once the isotope-characterizing half-life is known, all science has to do to figure out the age of the original carbon is to compare the amounts of the parent still remaining and the product it has produced.

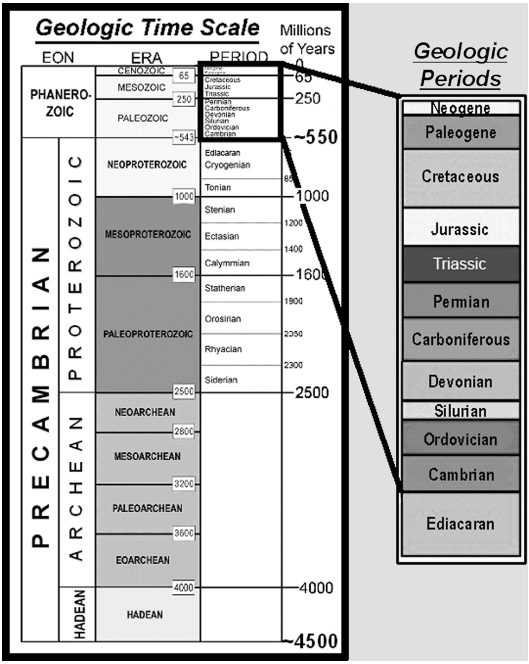

Fig. 1-3 Geological Time Scale. The total history of the Earth is divided into two great Eons, the earlier Precambrian Eon (from the formation of the planet, 4,500 million years ago, to the rise of many-celled animals 550 million years ago) and the later Phanerozoic, the Eon of large life, 550 million years ago to the present. Both the very latest Precambrian and the Phanerozoic are divided into Geological Periods, most named for the region in which its rocks were first studied.

This, of course, is the basis of the well-known carbon-14 method of dating, famous because of its use to date remains of early humans. But ^{14}C-dating has a serious drawback. As is true for all such radioactive isotopes, after about 10 half-lives – for ^{14}C some 57,300 years – too little of the parent isotope still remains for it to be accurately measured even by today's most sensitive instruments. Thus, carbon-14 dating works for only the past 60,000 years of human history, a paltry part of the human story which dates back to at least to Neanderthals, 450,000 years ago, and no doubt earlier.

How has science solved this problem? How is it that the 4,500 **million** years of the totality of the history of this world has been determined? In principle, the answer turned out to be simple – just use different naturally decaying elemental isotopes, particularly those having far-longer half-lives than ^{14}C. Here, the element uranium (U) which decays to lead (Pb) has especially come in handy, one of its isotopes having a half-life of 4.5 **billion** years, meaning that if a primeval chunk of Earth's original crust contained a pound of this isotope of uranium, only half-a-pound would still exist. And, as shown by U-Pb radiometric dating of the Moon rocks brought back by the Apollo astronauts in 1969, the Moon, formed at essentially the same time as Earth, is 4.5 billon years old (as are numerous meteorites, bits and chunks left over from the formation of the Solar System).

Because quite a number of such long-half-life isotopes have now been applied to the rocks of the Earth – measuring the isotopes in once-melted rocks, like volcanic lavas and thus showing the time when they congealed into solid minerals – the time-scale of Earth history is now well calibrated. Nevertheless, the high-tech instruments needed to make such measurements – mass spectrometers – are enormously expensive. For American colleges and universities this problem was solved in 1950 when, shortly after the end of World War II (an episode when *all* Americans, academics included, participated in the war effort), President Harry S. Truman (1884-1972) established the US National Science Foundation (NSF) to support fundamental research and education in the non-medical fields of science and engineering. Over the preceding decades, the basic science underlying the dating of ancient rocks had become increasingly better established and, with the founding of the NSF, funding for the equipment needed to make the measurements became widely available.

So far, so good. But what does this have to do with life's long history? After all, isotopically datable once-molten rocks, like lavas, cannot contain fossilized organisms – any form of life, like all else in the vicinity of an erupting lava would have been fried to a crisp! Moreover, the fossil-evidenced history of the most recent half-billion-years of life's existence, the Phanerozoic "Age of Large Life," was already well known nearly a century earlier than the discovery of radioactivity in 1896 by the French physicist Henri Becquerel (1852-1908) and confirmed only two years later by the husband-wife team of Pierre Curie (1859-1906) and Marie Curie (1867-1934) by studies of the mineral pitchblende, the crystallized form of uranium oxide, UO_2 (discoveries for which Becquerel and both of the Curies shared the 1903 Nobel Prize in Physics). Of these luminaries, perhaps the most outstanding was Marie Curie (**Fig. 1-4**), a Polish and naturalized-French physicist and chemist who is the only person to win the Nobel Prize in two separate fields of science (Physics and in Chemistry). In 1906, she was also the first woman to be appointed as a professor at the University of Paris.

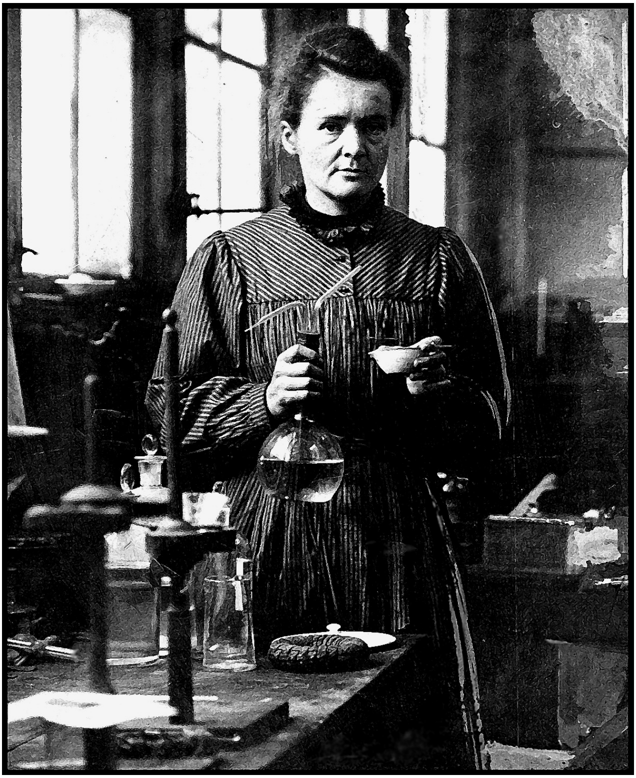

Fig. 1-4 Marie Curie, co-discoverer of radioactivity and the only person to receive the Nobel Prize in two separate fields of science.

Thus, in Darwin's time, the mid-1800s and a half-century earlier than the discovery of age-dating radioactivity, the basis for categorizing and systematically dividing-up the past half-a-billion years of the geologic column was provided by long-established knowledge of the fossil record, not by the radiometric dating of rocks. At first glance, this seems rather odd. Fossils, though sometimes almost whole and seemingly "life-like" are mostly just bits and pieces – shells, teeth, bones and the like – the resilient broken-up parts of the decayed bodies of dead organisms. How could such a messy mélange provide a reliable method for systematically divvying-up geological time – as in fact it did? And why did this development originate in England where it thus provided the basic underpinning for Darwin's theory of evolution?

In its essence, the development of this still-used system for ordering geological time was a result of the then-worldwide primacy of the British Empire and the Industrial Revolution it spawned – a good example of the interlacing of societal norms and the science it produces. British sailing ships collected raw materials from Britain's vast holdings – Australia, India, and large swaths of Africa and North and South America, nearly 25% of the land area and population of the world. The collected raw goods were then shipped to England to be converted into products to be sold back to the colonies.

The ships returned to their home port of Plymouth, at the southern edge of England, and because the manufacturing centers were to the north, in and around the Manchester area, an extensive canal system was built to connect the two. In the late1700s, William Smith (1769–1839), an English geologist credited with later creating the first detailed nationwide geological map of any country, served as a surveyor for the canal company. From this and his other geological work he became well acquainted with the strata country-wide and, importantly, the fossil faunas they harbored, the two together prompting him coin what he termed "The Principle of Faunal Succession," his observation that although the fossils changed from the lower (older) to upper (younger) rocks of a local sequence, the same faunas occurred place-to-place time and again in the same set of rocks throughout the country. Throughout his life, Smith continued to collect samples and map the locations of the strata he visited, thus amassing a large and valuable collection of fossils present in rocks he had personally examined – mostly preserved sea creatures such as trilobites, clams, brachiopods and numerous other types of "sea shells" – assembled not only from the sides of canals but from road and railway cuttings, and quarries and escarpments across the country.

This seminal work in England and adjacent Wales prompted systematic classification of the strata of the geological column and adoption of this system worldwide, a product – like England's extensive canal system – of the dominance of the British Empire. The Empire's hub, London, came to be regarded as the intellectual knowledge-rich center of the Western World. Even the "best and brightest" of colonial scholars – including those in Australia, Canada and the then-fledgling United Stares, for example – routinely sent samples of what they imagined to be major finds to London's Royal Society in the hope of obtaining affirmation from the experts. Thus, William Smith's fossil-based system for the ordering of strata in Britain had huge influence, particularly in adjacent Europe, while Darwin's proximity to London, his home in the nearby rolling hills ("Downs") of Kent, certified him as a serious scholar.

As a result, the major subdivisions of the past half-billion years of geological time, segments of Earth history known as "Geological Periods," were initially defined on the basis of the fossil faunas they contained – Smith's "Principle of Faunal Succession" – whereas the older underlying rocks, all lacking such fossils, were lumped together and mostly ignored. In ascending order, from oldest to youngest, these 11 Geological Periods are the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Paleogene and Neogene **(Fig. 1-3**). To these, in 2004 a 12th Geological Period was added, the very-latest pre-Cambrian (pre-trilobite, pre-animals-with-hard-parts) Ediacaran Period, named for the Ediacara Hills of South Australia and an Australian Aboriginal name that denotes a place where water is or has been present, water being synonymous with the presence of life in the "Australian outback."

Taken together, the sequence from Cambrian to Neogene (the initially named 11 Geological Periods) comprises the ***Phanerozoic*** Eon (from ancient Greek meaning "visible" or "large life") – The Age of Large Life – an Eon that in turn is composed of three major subdivisions known as Eras. These Eras, in ascending order are the ***Paleozoic*** Era (from ancient Greek *palaió*, "old" plus *zōion* "animal") – The Age of Spore Plants and Marine Animals – composed of the Cambrian to the Permian Geological Periods. The immediately younger Era, the ***Mesozoic*** Era (from ancient Greek meaning "middle life") – The Age of Naked Seed Plants and Dinosaurs – includes the Triassic to the Cretaceous Periods. And the most recent of the three Eras, the ***Cenozoic*** Era (from the Greek phrase meaning "recent life") – The Age of Flowering Plants and Mammals – contains the Paleogene and Neogene Periods.