Your Life as Planet Earth

HOWARD LEE

"**A fun read!**" – Prof ERIK ASPHAUG, University of Arizona, author of *Impact Craters in the Solar System*

"**I highly recommend this engaging book…**" – Prof MICHAEL E. MANN, Penn State University, author of *The Hockey Stick and the Climate Wars*

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Advance Praise for

Your Life as Planet Earth

"What a fun read! And a lot of great and important conclusions. I hope it finds a wide audience, because they will love its unique approach to making science interesting and accessible, yet complete."

Professor Erik Asphaug, University of Arizona,
author of *Impact Craters in the Solar System*

"I highly recommend this engaging book for anyone wanting to learn more about the planet we live on. Using the clever metaphor of Earth's planetary evolution as an individual passing through the various stages of life, "Your Life as Planet Earth" tells a remarkable tale of a planet that has witnessed tumult and turmoil, and experienced the full range of extremes from icehouse to inferno. Yet the book leaves no doubt that Earth faces her greatest challenge of all today, confronted with massive and unprecedented human interference, be it mass extinction, ocean acidification, or perhaps the greatest threat of all—human-caused climate change."

Michael E. Mann, Distinguished Professor Penn State University,
author of *The Hockey Stick and the Climate Wars*.

YOUR LIFE AS PLANET EARTH

A new way to understand the story of the Earth, its climate and our origins.

Howard Lee

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Dedicated to Scouts everywhere.
Keep leaving the world better than you find it.

“The keys to the future of our species
and our planet
have always lain in the deep past”
Richard Fortey, FRS

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a summer climate formerly associated with South Carolina by end-century, if business-as-usual emissions continue

Preface

I first became aware of how much we are at the mercy of climate while growing up in East Africa. I was on safari in Tsavo National Park hoping to see herds of bush elephant, but instead all I found was barren red dirt littered with bleached bones. Drought had always stalked East Africa but this time the adults around me were calling it "unprecedented" and were muttering about deforestation as the cause - nobody spoke of global climate change in those days. We almost ran out of water before the rains came.

Schooled on the rim of the Great Rift Valley, I learned that the valley's lakes – Magadi, Naivasha, Elementaita, Nakuru, Hannington, Baringo and Rudolph (as they were known then) had once been much larger, and that our *Homo habilis* ancestors, who made the stone tools scattered at my feet, had done so at the shores of lakes now reduced and distant. Dormant volcanoes came alive in legends of neighbors stealing each other's flame, and fiery devils dancing. It was in Kenya – I now realize – that I fell in love with geology and all it tells us of our planet's past.

I have split "Your Life as Planet Earth" into two parts.

The first is a fast-paced and lighthearted telling of the twists and setbacks of our planet's evolution, using the metaphor of a human lifetime to make the story of our world and its climate more easily relatable. I show how the strands of climate, evolution, tectonics and cosmic events tangled through time to drive changes in life and climate. Similar causes today must, logically, cause similar results.

In the second part, I explain the scientific evidence behind the story in plain English. I directly address some common myths that prevent many people from accepting human-caused climate change and evolution, and I explore what the science tells us about our future as far as we can tell from what we know of Earth's past.

We can't make sense of our future until we make sense of our past.

Part 1: Your Life as Planet Earth

To understand how we came to be, we must start at the beginning. To understand where we are headed, we must retrace the planet's odyssey of tectonic upheavals, life's adaptations, climate changes and cosmic chances, to the origin of it all – Earth, air, water, life.

The Earth made life, and once begotten life began to mold the Earth – fundamentally: chemically, physically and climatically. Earth shaped climate and climate winnowed life, repeatedly rewarding innovation, repeatedly wiping out the established and the maladapted. To understand our future we must learn from those times. We are far from the first inhabitants of the planet to have experienced climate change, but we are the first capable of understanding it, and the first to have choices in how we respond.

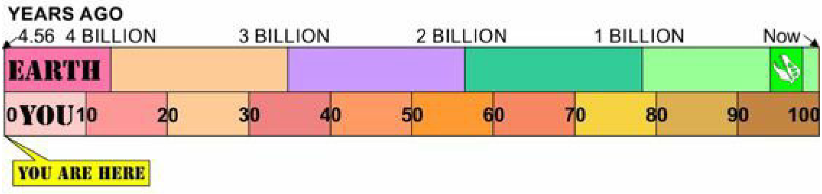
I want to show you how we got here by tracing the tangled threads of life, climate and Earth through deep time to today.

But deep time is very hard to grasp. Just like the vastness of deep space, it is so much beyond what we humans evolved to reckon intuitively. Instead I will tell the story of us, our climate and our Earth on the scale of a human lifetime. For simplicity I will make that life 100 years long, and to make it relatable I will ask you to imagine that YOU are planet Earth. After all, as you will see, your life and that of the planet have been uncannily similar.

Abbreviations

km	kilometers
mi	miles
°C	degrees Celsius
°F	degrees Fahrenheit
cm	centimeters
in	inches
CO_2	carbon dioxide

1. Traumatic Childhood

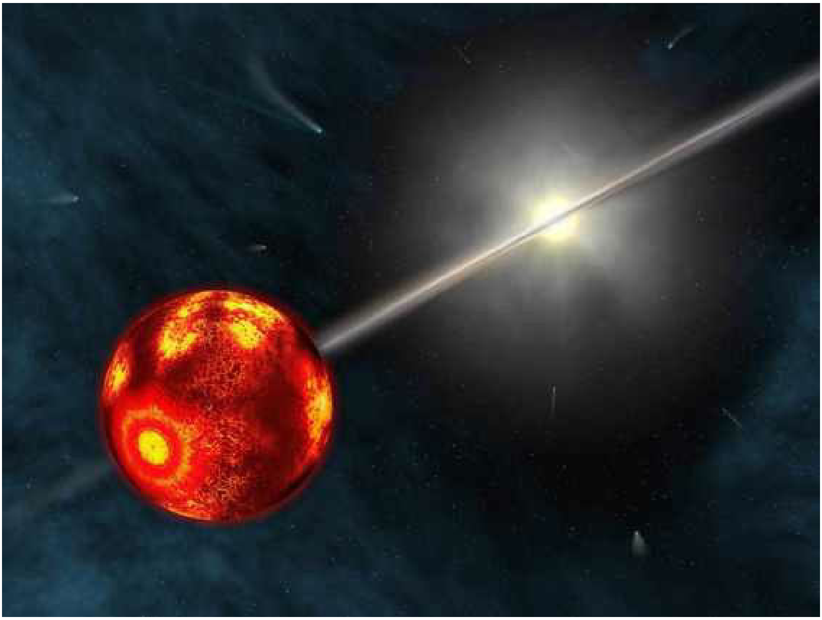


A gentle smack brings you into existence - a mere speck among specks, swaddled in soot and bathed in the soft glow of the Milky Way. An orphan of old stars who died an explosive death, you are dust within dust in a vast cloud of their ashes. Your midwife is a nearby supernova, her shock wave the smack that awakened you. It nudged you into the dust around you, and gentle gravity now gathers dust to grains, grains to clumps.

You are not alone. Your siblings are all around you, specks and clumps like you, floating in dark dusty space. One clump of specks is growing faster than you and all your siblings. Being heavier, its gravity draws in ever more gas and dust in runaway growth which begins to form the Sun. The weight of all that junk compresses it tighter and tighter into a ball and heats it to an ember, a crimson night light for your inter-stellar nursery. Around this glow, the immense nebula of dust and gas – with you in it – starts to spiral inwards towards the new Sun, and this motion flattens the nebula into a disk that rotates around the Sun at its center. It is this rotation – your orbit - that protects you from falling to an infant death in the hearth at the center of the Solar System. Over your first 3 weeks of existence (3 million years in real time)[1] you run a fever – heat from the decay of short-lived radioactive leftovers from the supernova. This heat and the warmth of the early Sun melts specks into mineral beads call “chondrules” and sticks them together in sooty rocks as you grow. Some of your siblings stop growing at this stage, doomed to remain forever as asteroids. But you go on growing at their expense, consuming any that stray near you!

You grow fast. As you put on weight, you gather up ever more rock and dust until the pressure deep inside you builds to melting point, and heavy metals like iron and nickel gravitate to your core. By the time you are cutting your first tooth you are already almost as large as you are today.[2]

A little after your first birthday (50 million years after your birth[3]), the battle between gravity and nuclear forces in the proto-Sun reaches the point when it crushes atoms of hydrogen together, igniting the nuclear fusion reaction that makes the Sun shine. A flash of insipid sunlight[4] now illuminates myriad embryonic planets and asteroids in the Solar System for the first time.



1 **The Infant Earth and the newly-ignited Sun** (© Walter Myers)

By now these space rocks are travelling at sizzling speeds (20-40 km per second [5] or 45,000 to 90,000 mph). They zing around the Solar System in curly oval orbits, nudged subtly in new directions each time they pass a planet or the Sun. With so many flying around they inevitably hit things. You are zapped and battered countless times by asteroids and comets of all sizes, adding their material to you. [6] They bring rocky minerals, metals, carbon, sulfur and water in the form of ice, as well as water chemically combined in asteroid minerals.

Each time they smash into you, they sear your surface and melt you. The bigger the rock, the larger and deeper the area that melts, but as each crater cools and solidifies, steam and other gasses are driven out into the atmosphere, rejected by the crystallization process, until over time a thick, humid atmosphere builds up. [7]

Your near-death experience

When you are aged somewhere between 18 months and 2 years old (70-100 million years after the formation of the Solar System[8]) you nearly die.

In your neighborhood there is an immature planet called "Theia." Even though she's only about a tenth the size of you, [6] she's destructive and headed right for you. She slams into you with enough force to rip a hole through your deep mantle [6] (halfway to your center), obliterating an entire hemisphere, [4] and knocking you off your axis so that your North Pole tilts away from the Sun in northern winters and towards the Sun in northern summers even today.

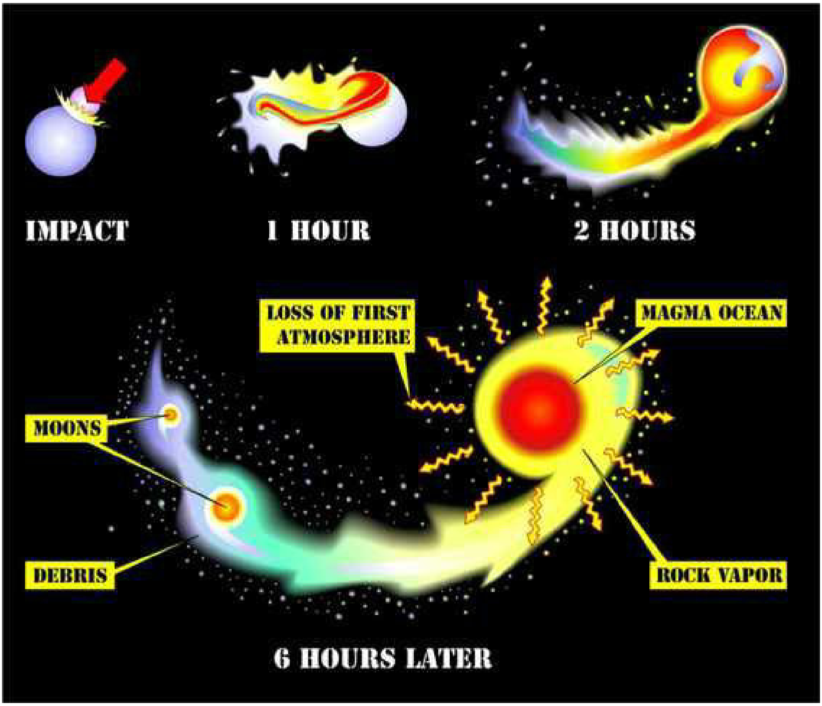
Wreckage and molten rock from the impact are flung out into space, and the intense heat liquefies the outer half of our world into a shimmering, yellow ball of magma. The temperature on the surface rises to around 6,000°C (around 11,000°F),[9] hot enough to vaporize rock and drive away the gasses of our first atmosphere into space forever. [4] Glowing drops of magma orbiting the Earth coalesce in a few decades (in real time) and either fall back to the Earth or combine into two balls of molten rock in orbit around you - your new siblings, better known as your moons.[10] Yes, in your infancy you have a pair of moons![10]

> "Twin moons now rise invisible over hellish skies"

As the Earth gradually cools over around a thousand real years, [11] it rains lava! The surface resembles crème brûlée, as black rock crusts over an orange ocean of seething magma. [4] During the next 5 months of your life (20 million years) [11] the rock veneer is flooded repeatedly with fresh lava that solidifies to form a thickening crust punctuated by volcanoes.[12]

Twin moons now rise invisible over hellish skies, the larger glowing molten red in its shadows, the smaller a third as big [10] and already a frozen, inert space rock.

Gradually your magma ocean begins to solidify, with mushy partly-melted patches here and there. [12] The iron from Theia's core trickles to your core, whose churning molten metals generate a powerful magnetic field to protect you from solar wind. The orbiting moons add their own protection by stabilizing the tilt of the Earth. As the planet solidifies, the crystallization of minerals expels water and other volatile elements, driving steam, nitrogen, hydrogen [13] and carbon dioxide (CO_2) into the atmosphere, replenishing the gasses that were lost in the impact. This is supplemented by a cosmic hailstorm of icy comets, adding their water to your steaming atmosphere when they vaporize. [14] [15]



2 **Moon-forming impact**. Redrawn from computer simulations by Canup (2008) with 2-moon idea by Jutzi and Ausphaug 2011

At this point there is still no oxygen in the atmosphere to breathe, and no life capable of breathing it. Water vapor, hydrogen, nitrogen and methane (from chemical reactions rather than from life) and the CO_2 in this primitive atmosphere form a thick blanket to trap the Sun's warmth (the "greenhouse effect") leading to a warm climate despite sunlight that is 30% weaker than it is today. [4] [11] [13]

In another year or two of your life (tens of millions to 100 million real years) the smaller of your two moons becomes unstable in its orbit and slowly crumples into its still partly-molten [16] bigger sibling, adding 10 km (6 mi) to its circumference and creating enormous expansion cracks filled with lava. [17] [18] The resulting rubbly debris forms the mountainous far side of the moon today. [10] [19]

Around this time your atmosphere cools to the point when it rains. [7] How it rains! It rains and pours an ocean's worth, submerging your hot crust under a global ocean with 26% more water than today's oceans. [20] [7] Water and rock begin an intimate relationship as ocean water penetrates the fractured crust and reacts with hot minerals to produce methane, hydrogen, carbon monoxide, and "organic" chemicals as it jets back into the ocean at submarine vents. [21] But this is no tranquil seascape - it is a raging ocean, pulled around the globe in 480 kph (300 mph) tsunami tides twice every 12-hour day, by our moon which is much closer, and looms much larger in the sky than in modern times. [22] [23] [24]

It's also an ocean capable of incubating life.

Your first memories

How many of us can remember anything from when we were younger than 4 years old? So it is with our Earth.

Rocks and minerals from the first traumatic years of your life have since been erased, or are yet to be found. Your earliest memory is from when you were 4 years old (4.4 billion years ago). [25] It is in the form of tiny, purplish and very durable crystals called "zircons", found at Jack Hills in Western Australia.

These zircons are our earliest surviving record of primitive continents, a glimpse of ancient magma that cooled and crystallized in the presence of groundwater. [26] [27] The tiny grains are only about 1/10th of a millimeter (about 4/1,000th of an inch), and yet they contain even smaller fragments of other minerals, including microscopic diamonds. [28] These pre-school memories are mere flecks today, worn from their original rocks when you are much older, washed away and tumbled along with pebbles and sand to form sandstones and gravels when you are in your 30's. [29] Yet these specks recall the conditions in the crust of our pre-school Earth, when the planet was still somewhat alien to our current conditions, full of childish energy and a good deal hotter inside (by 300°C or 570°F) than today. [30]

It is hotter because ever since you solidified after your Moon-forming impact, natural radioactive elements, mainly uranium-235, [4] have been decaying and building up heat throughout your interior. The solid planet couldn't churn to let the heat escape, so it just got hotter and hotter. Now it's hot enough to melt again, and some of this melt escapes through volcanoes. The Earth is now studded with massive volcanoes supported by a thick, deep-rooted crust [28] rather like Jupiter's moon Io is today. [30] [12] These volcanoes inject CO_2 and water vapor into the atmosphere, but at the same time hot lava reacts chemically with the humid atmosphere, capturing some CO_2. [11] As the crust cools, it is buried by more lava until it sinks back into the soft, hot mantle, [30] [12] taking the captured CO_2 with it.

In this way, by gradually reducing CO_2, the climate becomes a little more hospitable. [11]

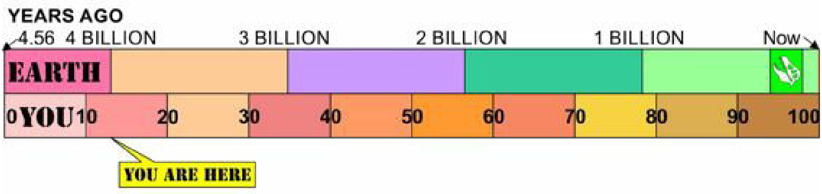
Asteroids and icy comets still occasionally smash into you, sometimes with enough force to boil the ocean, but thankfully never again on the scale of the impact that created the Moon, and much less frequently than in your first two years of life. They continue to add water, organic chemicals and rocky materials to you.

Things are hazy until your next oldest memories, which are from when you are 8 ½ (4.2 billion years ago) and then again at around 13 years old (4 billion years ago). These are not the tiny flecks of the Jack Hills zircons; these are fully-formed rocks. The oldest rocks on Earth that have been found to date [11] are in the "Nuvvuagittuq Greenstone Belt" by Hudson Bay in Canada, and the slightly more recent "Acasta Gneiss" in northwestern Canada. [25]

It's a wonder these ancient fragments exist at all, considering what a rough time you had as a teenager.

3 **Pre-teen Earth** (by the author based on NASA images of Io and Earth)

2. Troubled Teen



For humans adolescence can be an awkward, traumatic time. Hormones seethe, driving you towards maturity, and profound behavioral and physical changes leave you almost unrecognizable. The teen years for our Earth are the same, and yet they leave you fertile.

A bad case of acne

By the time you are 13 [30] the interior of the Earth has cooled sufficiently that areas of continental crust can remain stable, and some of these “cratons” survive within our continents today in northern Canada, Scandinavia and Australia, for instance. But it’s still too hot, and the rocks consequently are too weak and flaccid, to engage in “plate tectonics.” [31] In other words, you are still immature.

> “From age 14 to around age 17 your face is hideously pockmarked”

Many teens suffer from acne, and our Earth is no exception. When you are 14 (3.9 billion years ago) distant changes in the orbits of Jupiter and Saturn knock a host of asteroids and comets out of their previously stable orbits. [11] [32] [15] Many fall towards the Sun, colliding with anything in their way, including the Earth and the Moon, as well as Mars, Venus and Mercury.

From age 14 to around age 17 (3.92 to around 3.8 billion years ago) your face is hideously pockmarked by large impacts – over 17 thousand of them! [32] [5] This event is known as the “Late Heavy Bombardment” and it may sound like a pelting, but spread across that timeframe it averages around 1 impact every 7,000 years. They are more frequent to start with [32] and some were probably large enough to boil an ocean and fill the sky with rock vapor for a while. [32] Through this adolescence you gain some weight. Roughly 200,000 trillion tonnes (about 0.003% of the present mass of the Earth) is added to the Earth by these asteroids and comets, including water, [15] carbon-based, and nitrogen-based chemicals needed for life, [5] [33] [34] They also replenish some precious metals in the crust, like gold and platinum, which had sunk to the core after the impact that formed the Moon. [35] If you are wearing a wedding ring, some of its gold probably arrived on Earth from space at this time.

The Moon is also lit up with spectacular fireworks and its cratered face today is largely the result of the Late Heavy Bombardment. It remains permanently scarred to this day, but even though you suffer from huge recurring impacts into your early 20s, [36] your complexion will recover through the strong exfoliation of erosion by rain and rivers, and (later) by the action of plate tectonics.

And even though the Late Heavy Bombardment is traumatic, it doesn't prevent the development of life on Earth. [5] In fact it probably made you fertile.

You're a teen parent!

Congratulations – it's a slime!

The first evidence that you are in fact a parent shows up when you are 19 (3.7 billion years ago), [37] but you must have been harboring life for a while before then. The birth of "LUCA" (Last Universal Common Ancestor) is shrouded in mystery. Some say she was carried to Earth, stork-like, on one of those asteroids during the Late Heavy Bombardment – but that just begs the question of how life started wherever the asteroid came from. It seems more likely that LUCA was born on Earth around your underwater hot springs. [38]

In the beginning life is rock, and rock is life. [39]

Ever since the first ocean appeared, water seeping through fractures and pores in the hot ocean crust has been reacting with basalt minerals to form a greenish-brownish, scaly-looking mineral called “serpentine,” creating methane, hydrogen and “organic” chemicals, as by-products in submarine vents. [21] [40] And it is in these vents that life starts. But it’s the bombardment of asteroids that supplies the essential phosphorous required to make the genetic chemical RNA, the energy-storing chemical ATP, and cell membranes. [41][42]

The blistered encrustations that form at the vents of submarine hot springs are porous, creating natural, tiny, mineral cells. Hot fluids meeting the oxygen-less ocean water are transformed by iron, sulfur and nickel minerals into RNA (using phosphorous leached from asteroids), organic molecules essential in the “Krebs Cycle” (the basic chemistry for metabolism), and a “chemiosmotic membrane” (again essential for metabolism) coating the inside of each pore.[39] Eventually these cells use their RNA to copy themselves as life escapes its rocky womb, birthing into the global ocean, protected by asteroid-forged cell membranes, sometime in your teens. [43] [44] [41][42]

> “In the beginning life is rock, and rock is life”

All life on modern Earth is made of cells inherited from

LUCA, and these cells contain the special molecules RNA or DN. (DNA is essentially double RNA) to transfer their genes to thei offspring. LUCA had the simplest of these - "16S rRNA" - which a life on Earth has inherited in some form, [45] along with the Krebs Cycle, chemiosmosis, and phosphorous-based membranes. [39 42]

For now life is basically slime.

Where there are patches of slime on the seafloor, flecks of silt and sand stick to it, making that patch thicker. Over years this leads to hummocks and mounds about the size of a small turnip (rutabaga) to a large pumpkin, called "stromatolites." Many stromatolite fossils have been preserved to the present day, and some of the oldest are 3.4 billion years old and are from Western Australia. [46] Tiny fossil microbes from this time have also been found in Australia, along with chemical traces indicating that these bacteria were extracting energy from sulfur chemicals in the water. [47] Other fossil hints of microbes have been found that are 3.5 billion years old in South Africa. [48] These formed in seas around the early continent called "Ur" which includes bits of Antarctica and India. [49]

Purple life

It doesn't take long before some bacteria evolve that can use sunlight to get energy. By your late twenties (3.3 billion years ago) they are using sunlight to extract energy from sulfur compounds dissolved in water. [50] This early photosynthesis is based on more primitive chemistry than modern plants (it uses purple retinal rather than green chlorophyll) and it does not generate oxygen. So in this oxygen-less world, purple[51] slime-life is the most advanced life on the planet and it reigns supreme for a billion years (from your 20s to your 40s)!

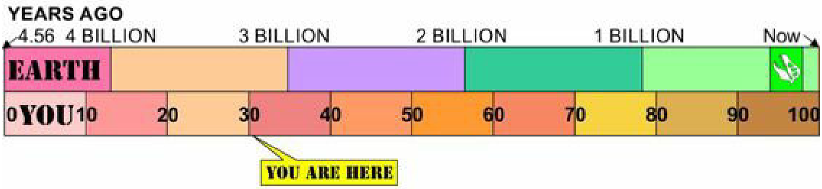
> “In some ways our young adult Earth is beginning to resemble the modern Earth”

In some ways our young adult Earth is beginning to resemble the modern Earth. Oceans with tides, rivers with deltas, and erosion of higher ground are all operating much like today, depositing sand and gravel into the oceans. [29] Those oceans have cooled to tropical temperatures by modern standards - the 30s°C (90s°F), or less than 10°C warmer than our modern warmest values. [52] [53] [20] Tides and ocean currents help regulate the temperature of the planet, toning down the extremes of hot and cold. Rivers, erosion and volcanoes regulate the chemistry of the atmosphere and oceans, and the giant magnet in the Earth’s core deflects harmful solar wind particles around you as in modern times.

But in the same way as a college student isn’t fully mature (despite what they think), neither are you at this age. The Sun is still only about 75% as bright as the modern Sun, and the Moon is some 15 % closer to Earth than today, and a day only lasts about 17 hours compared to our modern 24 hour day, and a year is 514 days long. [23] [24] Your protective magnetic field is only about 2/3 the strength that it is today, [54] exposing the Earth to higher doses of cosmic rays and high energy solar particles, generating spectacular auroras even in the mid-latitudes.

If a human were to land on the surface of the young adult Earth they would be asphyxiated immediately as there is no oxygen in the air. If a modern fish were to be plopped into the ocean it would suffer the same fate, as even the waters are devoid of oxygen. Instead the atmosphere is mostly nitrogen, hydrogen, CO_2 and small amounts of methane. [24] In this oxygen-free world, molecules of hydrogen and nitrogen interact to keep you warm by trapping heat, as does CO_2. [13]

3. Mid-Life Crises



Maturing into your 30s

When you turn 30 (3.2 billion years ago) [55] [56] [57] you mature and settle into adult life in the way many thirty-somethings do.

Until now, thick blobs of continental crust called "Cratons" have been sitting like spoonfuls of clotted cream floating on a warm, treacly mantle. They're more like big islands than continents, really, barely poking out from the global ocean. Beneath that ocean, the remainder of the "crust" has been a malleable, flaccid skin capping the mantle. But now the Earth has cooled sufficiently that the skin has stiffened to a global, peanut-brittle-like slab. [31] [12] The churning mantle beneath rents cracks through it and slowly, powerfully, drags the pieces into each other, drowning one under another (a process called "subduction"), and forcing mountains skyward in the process. The drowned slabs plunge into the hot mantle where they are smelted and recycled into magma which fills the cracks between the slabs, creating fresh crust. We call this "The Wilson Cycle" and it all happens at the pace of a fingernail growing, but over time it obliterates old crust, recycles it, and replaces it with fresh new crust.

This is the beginning of Plate Tectonics on Earth.

"Plate Tectonics" may sound geeky, but without it our Earth wouldn't have mountains or the rivers that drain from them, or the flow of nutrients from land to sustain life in the oceans, or the explosive volcanoes that pump CO_2 and steam into the atmosphere. It's the process that manufactures the continental crust we live on. It's the process that exposes fresh rock to react with CO_2 in the atmosphere, and plunges that carbon into the mantle, keeping our greenhouse gasses in balance (until now), and the climate livable. Plate Tectonics is fundamental to our landscape, climate and life today.

By your late thirties, crustal recycling has already generated much of your continental crust [25] by a process called "fractionation," which is a bit like cream rising to the surface of whole milk. It is responsible for separating the asteroid-like rock mixture Earth started with, into the kinds of rocks that continents are made from (granites and their like, which have a high proportion of silica in them), and the low-silica residue that remains in the mantle. As a side-effect it also drives water and gasses into the atmosphere.

It's now fair to say at this point you are mature: You are a parent of life, you have settled into your job of constructing continents, and destroying them through subduction at about the same rate. What could possibly go wrong?

It's a gas!

The "big 4-0" is a major milestone for us, often triggering mid-life crises and re-setting our direction in life. For Earth it is the same.

The first ice age

In your late thirties some microbes learn the trick of "methanogenesis" – combining hydrogen with CO_2 to make methane and water. Their invention enables them to extract energy from their environment, but they begin to use up hydrogen and CO_2 from the atmosphere, cooling the climate, and triggering the planet's first ice age when you are 36 (2.9 billion years ago), [13] leaving tell-tale traces in the rocks of Southern Africa. The ice age is temporary as this extra methane soon replaces the greenhouse warmth that you had been getting before from the hydrogen-nitrogen atmosphere, and the climate warms again under pink skies of methane haze. [58] [13]

4 **Stromatolites under pink methane skies in your late 30s** (© Walter Myers)

But that extra methane leaks into the upper atmosphere, where sunlight splits off its hydrogen, which escapes into space. Losing hydrogen is like losing water (H_2O), so life is now, very slowly, drying out your oceans.[59]

> "life is now, very slowly, drying out your oceans"

When you are around 41 (2.7 billion years ago) the first traces of a totally new kind of life begin to show up.[24] Life up to now has comprised just 2 broad types of microscopic germs - bacteria and archaea - collectively called "prokaryotes." These are 2 of the 3 recognized "domains" of all life on Earth today (as I write this, science may have recognized a 4th domain of life containing giant viruses[60] [61] but this is still debated). These lowly, single-celled organisms have dominated life on Earth for the last billion years despite their simplicity.

But now there's a fundamental innovation in cells.

In a fateful encounter, an archaeon cell engulfs a bacterial cell,[39] forming a new hybrid creature. Over succeeding generations the trapped bacterium simplifies to form "mitochondria," which generate energy for the cell. For now these new life forms are still single-celled creatures[62] different from their prokaryote cousins more on the inside than the outside (except they are typically much bigger). Yet their new more-energetic metabolism, their invention of a nucleus to house their DNA, a shuffled genome, and their larger size sets them up for the incredible revolutions of life to come. [39] The descendants of this hybrid cell today make up the 3rd domain of life: the "eukarya" or "eukaryotes," which include fungi, plants and animals - including you and me.

Oxygen

It's also around this time [63] that some photosynthesizing bacteria switch from using sunlight for processing sulfur chemicals, to using sunlight to make carbohydrate food by combining water with CO_2. This is a neat innovation for the cyanobacteria that managed it, but the process has a waste product.

Oxygen.

At first these little blue-green cells are minor players on the stage of life. They coexist with sulfur processing bacteria in shallow water stromatolites, exuding whiffs of oxygen here and there. [63] But even these small amounts are enough to begin to change the planet. [64] They are sufficient to allow a kind of air-breathing (well, absorbing really) bacteria to begin to form skins and crusts on land sediments and in freshwater pools, leaching nutrients from rocks. Their action increases the rate of weathering of rocks, sending unprecedented levels of dissolved metals and sulfur-chemicals into rivers and oceans. [65] [66]

Next, cyanobacteria evolve new strains that can tolerate saltier water, with bigger cells and filaments that enable them to make their own stromatolites. [63] They begin to dominate estuaries and coastal seas all over the world when you are about 46 (2.5 billion years ago) giving off oxygen wherever they go. [63] [63] [58] [67]

Each tiny cell is insignificant, but the combined oxygen emissions of billions of individuals transform the entire planet forever. They are terra-forming our Earth - an episode called the "Great Oxidation Event."

> "the combined oxygen emissions of billions of individuals transform the entire planet forever"

At first, most of the oxygen is consumed by chemical reactions in water, air and rock. It begins to rust the geosphere (the rocks of the Earth), creating a host of minerals and ores that have not been possible until now. [24] In the oceans oxygen reacts with dissolved iron creating a slow underwater snow of rust, lasting millennia, creating vast iron ore deposits known today as "Banded Iron Formations."

Eventually the cyanobacterial production of oxygen overwhelms the oceans' ability to absorb it, and oxygen becomes pervasive in the air. As oxygen seeps into the stratosphere it becomes ozone (O_2 becomes O_3) which acts as a sunscreen, filtering out harmful UV rays that would damage life on land.[68]

This doesn't mean a human could breathe on the Earth at this time. Oxygen levels in the air are only a measly 5% - 18% of the present level [58] [68] - not enough for us, or animals like us.

Life saves your oceans

As the oxygen in the atmosphere builds up it reacts with methane [69] causing the sky to flip-flop every few million years between a pinkish methane-dominated haze, and clear blue CO_2-dominated skies. [67] This chemical reaction saves your oceans! Up to now sunlight has been destroying methane in the atmosphere, allowing hydrogen to escape into space forever. Since water is made from hydrogen, losing hydrogen has reduced your oceans by about 1/5 since they first formed. [20] But now, instead of escaping into space, that hydrogen reacts with newly-minted oxygen to make water (H_2O), trapping it on Earth and halting the loss of our oceans.

But there is a downside to those atmospheric reactions. Methane is a potent greenhouse gas, so reacting it with oxygen removes a cozy atmospheric blanket.

So the Earth freezes.

Slushball Earth #1

We are not talking the ice age of wooly mammoths and animated films here – that won't happen until you are 99 years old! We are talking here about something much more extreme – ice covering most of the planet, even into the tropics. [24] You may have heard of "Snowball Earth" but that too comes much later.

This deep freeze involves 3 separate severe ice ages spread through the Great Oxidation Event; from your age 46 to 52 (spread over 200 million years [24]). This isn't a hard freeze of the entire planet, so it's more of a "slushball" than a snowball, and it coincides with the assembly of a new continent called "Kenorland" from separate bits of crust that were pushed together by plate tectonics. Kenorland includes parts of modern Canada and Wyoming.

You don't stay frozen forever because you keep producing gas – your volcanoes continuously inject CO_2 into the atmosphere, which slowly builds up, trapping more of the Sun's energy through the greenhouse effect. A precarious balancing act sets up between removal of methane by oxygen on one hand, and addition of CO_2 by volcanoes on the other hand. Like a circus high wire act, the climate lurches one way then the other, threatening disaster at each swing, but it ends safely as the climate emerges into warmer climes and blue skies once more.

Stand by me – cells make friends.

By the time you reach the age of 52 (2.2 billion years ago) life undergoes its next fundamental revolution. Some cells give up the solitary life of fending for themselves, and instead join together and cooperate as a single organism. Soon, on the cool, rain-drenched land of what will one day be South Africa, millimeter-sized, urn-shaped life forms appear in the soil, which may be the first fungi. [70] They are followed by marine creatures in the form of inch-size blobs with crenellated edges, which appear in the seas offshore what will eventually become the African nation of Gabon. [71]

These earliest multicellular creatures are the dawn of complex life [71] - our ancestors - showing up just as the continent of Kenorland is breaking apart.

But you're still not immune from huge meteor impacts.

Just after your 56th birthday (2.02 billion years ago) you get slammed by an asteroid in a place called Vredefort in South Africa. This impact is far more devastating than the one that will wipe out the dinosaurs in your 90s! [24] As if that weren't enough, it happens again when you are 59 (1.85 billion years ago), this time at Sudbury in Canada. [24] Coincidentally, and for reasons that aren't clear, oxygen levels reduce again to a fraction of what they were in the Great Oxidation Event, and stay that way until you are 78 (a billion years ago). [72]

Going critical – the world's first nuclear reactor.

No I'm not making this up! When you are 57 (1.95 billion years ago) a bizarre quirk of nature comes to pass in Oklo, Gabon, where uranium ore is forming naturally in waterlogged sandstones. Ore formation is all about nature concentrating metals - like uranium - together in one place. Well, nature at Oklo is very effective at this, so much so that a nuclear fission reactor sets up naturally. In fact it sets itself up in 16 different places, generating enough heat to boil away groundwater. This process continues in on-off pulses for hundreds of thousands of years! [73]

The climate for the next few years of your life flirts with freezing again and another ice age occurs when you are around 60 years old (1.8 billion years ago). [24] This coincides with the formation of "Nuna," a supercontinent made by joining several separate smaller continents together. Nuna includes a large chunk of modern North America, and parts of Siberia, Scandinavia, West and South Africa, and South America. Incidentally the rocks in the deepest part of the Grand Canyon in Arizona date from this time. [74]

After the drop in oxygen levels, large parts of the ocean are still like the old times before oxygen. Microbes there still generate methane that steadily seeps into the atmosphere, warming the planet. [69]

"giving you the faint stench of sewage"

Life continues to evolve strange evolutionary experiments such as the spiral strands known as "*Grypania spiralis*" [24] and sulfate-reducing bacteria in the deep oceans which begin creating new minerals like iron pyrite ("fools gold"). These are probably responsible for the worldwide disappearance of Banded Iron formations[24] and they exude hydrogen sulfide gas, giving you the faint stench of sewage.[75]

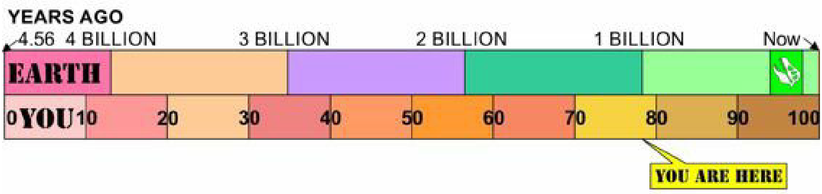
The origin of plants

It is around this time [76] that an ambitious eukaryote microbe eats something it can't digest. The microbe is swimming through the water, twitching its pair of hairs to propel itself, when it bumps into a cyanobacterium. The eukaryote tries to eat the cynobacterium and engulfs it, but fails to digest it, and a long, fruitful symbiosis ensues. The cynobacterium carries on photosynthesizing, feeding sugar to its eukaryote host, freeing it from the need to go around engulfing prey. This tiny new chimera is the ancestor of algae, and (eventually) land plants. The cynobacterium is passed on from generation to generation as a chloroplast – the photosynthesizing part of plant cells.[77]

By the time you are 74 (1.2 billion years ago) more weird but simple life forms have evolved, including something that resembles a pearl necklace called "*Horodyskia*" and a stalk-like red algae called "*Bangiomorpha.*" [24] These live in the seas surrounding a new supercontinent called "Rodinia," which is assembling at this time. Inland, Rodinia's lakes and rivers also support multicellular life in the form of tiny, enigmatic balls and disks. [78]

As individual continents collide to form Rodinia, they create an impressive mountain chain known as the "Grenville Mountains," the roots of which can still be seen today in the rocks of New York's Adirondacks and the bedrock in New York City. [79] Rodinia comprises much of today's North America, Scandinavia, Siberia, eastern Antarctica, India, the Congo and the Kalahari, Madagascar, and parts of China and South America. [69]

4. Retirement



Yes that's right, you are in your 70s and yet we still haven't seen the emergence of sea shells, fish, land plants or animals, let alone people. The most advanced life form is a kind of red algae. In fact there's still too little oxygen for fish or land animals to survive, yet.

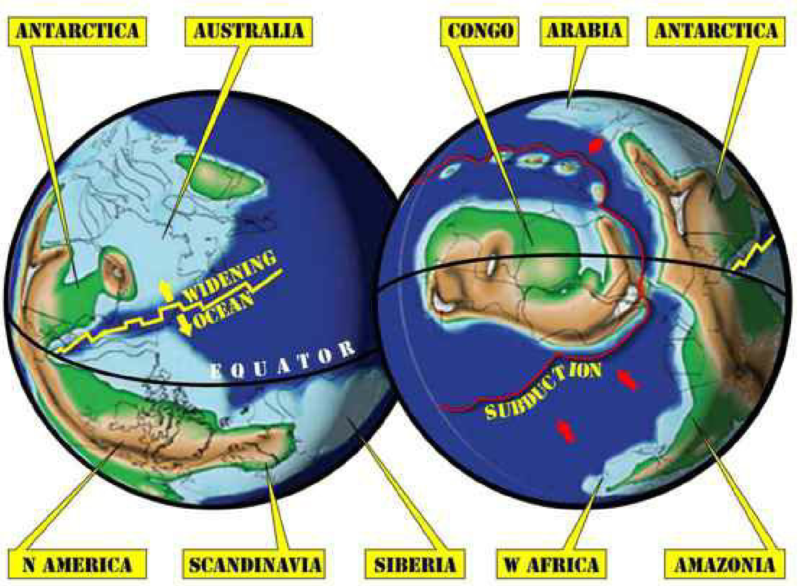
At this point in your life we have reached a numerical milestone. We are no longer talking *billions* of years ago, now we are talking *millions* of years ago.

Feeling cold in your 80s - Slushball Earth #2

At the closing of your 70s, something extraordinary starts to happen. Complex life boldly goes where none but a few bacteria dared to before – out of the water and onto dry land. [66]

Greening the land

By the time you are around 78 (1,000 million years ago) life in the form of a range of fungi, lichen, microbes, and algae begins to colonize the equatorial supercontinent of Rodinia. [69] [80] [81] [78] It takes a while to take hold, but when you are around 83 (780 million years ago) Rodinia begins to rift apart. The northern part, which includes Australia, India, Arabia, China, Antarctica and parts of Africa drifts northwards, and the southern part, which includes much of North America and Europe, Brazil, Wes Africa and Siberia drifts slowly in the other direction. [79] This warm, moist tropical landscape is ideal for early land life, and the result is a dramatic greening of the land. [80]



5 **Supercontinent Rodinia breaks apart.** Redrawn from Scotese Geol. Soc. Spec. Pub. 326, 2009.

> “This boosts weathering rates of rock, which sucks CO_2 out of the atmosphere, making the Earth colder still!”

This greening has two huge effects on Earth. The first is to increase the area of the planet that is given over to photosynthesis, which makes more oxygen.[80] [72] Of course, as we experienced before, this oxygen reacts with the methane that had built up since the Great Oxidation Event,[69] [24] making Earth cooler again, helped by the fact that the Sun is still only around 90% of present brightness.[69]

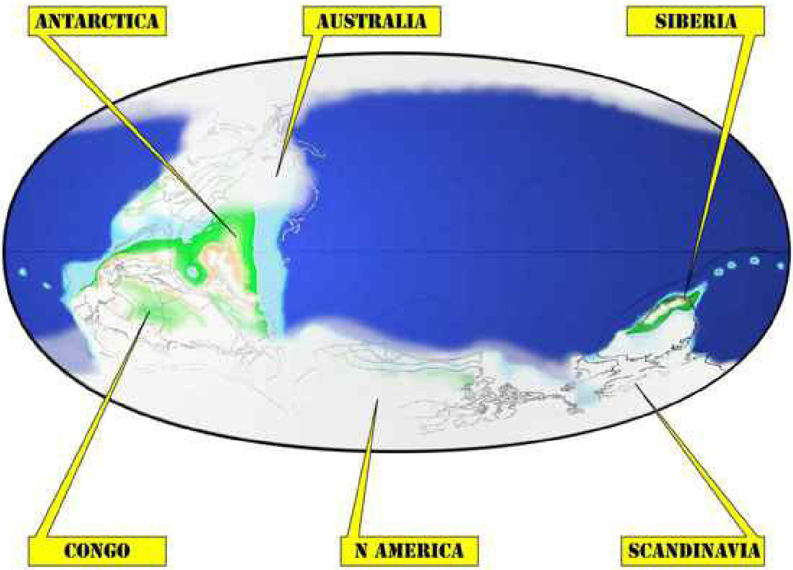
But this time something else turns down the thermostat too. Life on land, as simple as it is, breaks down minerals to make soil. [82] This boosts weathering rates of rock, which sucks CO_2 out of the atmosphere, making the Earth colder still! [69] [80] Now as if that isn't enough, rivers wash the soil nutrients into the oceans, where they are a tonic for more oxygen-producing life in the oceans. [69] [80] And to further chill the planet, the southern continent of former Rodinia begins to drift over the South Pole, [79] where higher elevations collect ice caps as the Earth cools – further exacerbating the cooling.

Freezing the land

As a result, the Earth freezes again, and the more it freezes, the more ice covers the land, which reflects the Sun's warmth back into space, making the climate colder and colder, until much of the planet is gripped by ice. Sea levels fall [79] and glaciers march from the mountains to the sea even in the tropics, where soils freeze and thaw with the seasons, and average temperatures are around 6-7°C (42-45°F). [82] Ice-ground rock turns to clay, and then to dust when the ice recedes each summer. Wind whips it away in terrible dust storms, to deposit thick coatings of it in places like Australia. [83] Only land at the equator stays ice-free, with Siberia and Antarctica being, ironically, two of the warmest places on the planet at the time. [79]

Covering most of the land with ice and dust largely reverses the greening, so volcanic CO_2 builds up again and it is this, probably in conjunction with orbital changes in the distribution and intensity of sunlight the Earth gets, that warms the planet again, only to see a repeat of the cycle. The result is a climate that see-saws between ice age and warmth at least 3 times, with major ice ages when you are 84 (720-700 million years ago), again when you are 85 (650-630 million years ago) and briefly when you are 87 (580 million years ago). [84]

This time has been called "Snowball Earth" but it is really more of a "slushball," because large areas of open ocean and equatorial land stay ice-free. [69] [85] [83] [82] [79]



6 **Slushball Earth – a planet frozen ito the tropics in your 80s**. Modified with permission from: Scotese, Geol. Soc. Spec. Pub. 326, 2009

At 86 - Getting a complex

The continents have continued wandering throughout the slushball age, and have now amalgamated into a supercontinent called "Pannotia,"[79] which has much of Europe, North and South America clustered around the South Pole. The collisions have thrown up a huge new mountain chain across Arabia, Africa, southern India and parts of Antarctica, called the "Pan-African Mountain Chain."[79]

Now, as ice recedes from the post-slushball Earth, resurgent land life retakes lost ground, greening the newly-uncovered rock and generating oxygen. Rain, glaciers and rivers erode the Himalayan-like Pan-African Mountains, flushing huge quantities of nutrients into the oceans, [86] causing plankton to flourish once more, giving the atmosphere another boost of oxygen. [87] The rain of dead plankton adds to deep water muds, eventually forming one of the oldest petroleum deposits in the world in Siberia. [88] The atmosphere slowly stabilizes at higher levels of oxygen (somewhere around 15% of present levels [89] [90]) in your late 80s.

This oxygen boost triggers another revolution in complex life. A strange new menagerie known as the "Ediacaran Fauna" appears, with scant resemblance to modern life.

Animals – the prototypes

With neither a shell nor a bone between them, and most of them unable to move about on their own, they nonetheless include the ancestors of many kinds of life today. There is *Dickinsonia* – a 10cm (4 in) pleated disk; there's a feathery frond that grew as tall as a man called *Charnia;* [49] and *Kimberella,* which resembles an elongate limpet with a tent, which seems to be a kind of mollusk. [91] We have *Marywadea* (named after palaeontologist Mary Wade) – a possible ancestor for crabs, scorpions, insects and spiders (arthropods), and *Spriggina*, a many-segmented thing with a crescent-shaped head that grows to 3cm (just over an inch) is possibly the ancestor to trilobites. We see *Parvancorina,* shaped like 2 cm (1 inch) slice of pizza with a slice of mushroom on top, and *Arkarua,* which is a blob that may be the ancestral sea urchin. [92] The ancestral jellyfish is there, before it evolves into sea anemones, corals and jelly fish, and floating in the sea are tiny spiky balls around ½ mm big (1/50th of an inch) called Acritarchs. There are also sponges, already resembling their modern counterparts. [93] [94] Several of these early creatures already have the biochemical tools to detect light – a prerequisite for developing eyes. [95]

> "the revolutionary idea of separating mouth from anus"

At around this time, a medium-sized asteroid slams into a place called Acraman, Australia, blasting a 90 kilometer wide (56 mi) crater and affecting the regional environment for around 20 million years. [96] [97]

Among the early experiments in animal body plans, the revolutionary idea of separating mouth from anus leads to a much more sanitary arrangement that we (thankfully) inherited. This separation of ends inevitably leads to animals having a front with sensory organs, a nerve cord and a brain. These creatures also develop muscles, and it's this new "bilateran" body plan that will overtake the Ediacaran Fauna. [98]

At 88 – To protect and to prey

The end of the Ediacarans is heralded by a huge volcanic eruption at Volyn in the Ukraine, which disrupts the global climate. [99] This is an age of global warming, despite the Sun still being only 95% of its current brightness. [100] Global sea levels rise dramatically by 10 to 70 meters (33 to 230 feet), [100] drowning parts of Pannotia and burying already ancient hills and valleys under marine sands, as more and more of the world becomes covered by shallow, fertile seas. [101] The buried landscape is known as the "Great Unconformity" and can be seen in the Grand Canyon today.

But it is life, and the multiplied effect of millions of insignificant individuals, that transforms the planet once again.

Worm power – unexpected chemistry

The Ediacaran creatures have been living on a luxury wall-to-wall carpet of slime – a so-called "microbial mat." [102] But 3 ½ months after your 88th birthday (541 million years ago) some enterprising worms (bilaterans) begin venturing into the sediments beneath the mat, churning them up and destroying the microbial shagpile. That seemingly unremarkable vandalism at a stroke turns the 2-dimensional sea bottom into a 3-dimensional world, [103] circulating oxygen through a volume of detritus that hadn't been exposed to oxygen before. [100]

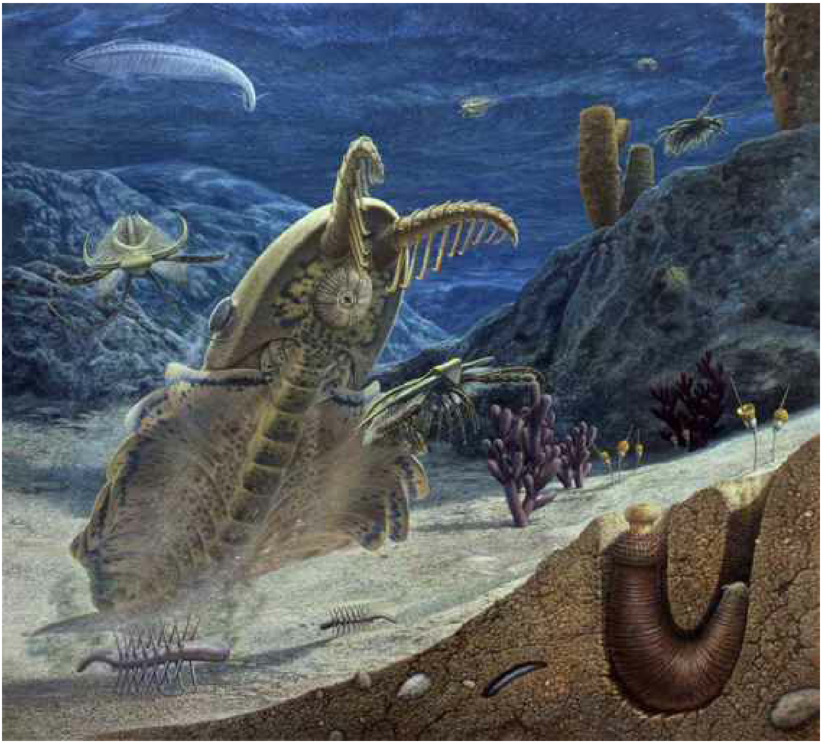
Perhaps they are motivated by all the nutrients from newly-drowned terrestrial soils, [101] or maybe burrowing is a way to hide from predators. [102] Whatever their motivation, their action triggers a chemical change in seawater, allowing quantities of sulfate and phosphate, [104] [105] to be recycled into the oceans at the same time as there is a surge in calcium levels turning ocean water alkaline. [106] [107]

> “life across a broad range of animal species now has to find biochemical ways to deal with this unexpected chemistry”

Changing the alkalinity or acidity of ocean water (changing its pH) has a large effect on the biochemistry of animals that live in it.[108] Suddenly calcium carbonate, which used to be dissolved in their body fluids, wants to precipitate out as solids – something that could kill them! So life across a broad range of animal species now has to find biochemical ways to deal with this unexpected chemistry.[109] Some solve this problem by depositing the unwanted calcium carbonate as shells, which turn out to be quite useful. Other creatures respond to the new ocean chemistry by making a new protein called collagen.[39] Collagen is a vital component of cartilage and bone and therefore a vital component of you and me. Skeletons with muscles allow movement, the ability to go after prey and the ability to escape, either into sediments or into the water above.

Now we have a predatory arms race, with some creatures hunting and others hiding in sediments, in protective shells, or swimming away. [110] At first the shells are simple and tiny – around 1mm (1/16th inch), but over the next 5 months of your life (20 million years) a cascade of new ecological niches – and the expansion of food webs - enables a huge increase in the number and size of shelly and soft-bodied, species – an event known as the "Cambrian Explosion." [100] [110]

Marine life bursts into new shapes and ways of life, resulting in swimmers, crawlers and burrowers, predators and prey, swift and stationary, large and tiny, hiding in a marine forest of sponges and sea lilies. The first fish, and in that way your ancestor and mine, *Haikouichthys* appears at this time. [111] Sea snails (gastropods) and other mollusks slither across the silt, recoiling from the attentions of crawling trilobites (marine creatures resembling the modern woodlouse). Dashing through the water are jet-propelled squid-like creatures called *Nectocaris.* With just 2 tentacles they are nonetheless the ancestor of squids, ammonites, and nautiloids. [112] The weird and spiky *Hallucigena* defied classification for years but is now considered a relative of modern velvet worms. [49] The monster of the day is *Anomalocaris,* a meter-long (3 foot) bug-eyed squid-like creature with prey-snatching arms, while the weirdo of the day is *Opabinia,* a 6 centimeter (2 ½ inch) creature with 5 eyes on stalks, a segmented body and a spiky mouth on the end of an elephantine trunk! [49]



7 **Protect and Prey - life in the Cambrian oceans. *Anomalocaris* about to pounce on a *Marrella*.** © John Sibbick

Fire and ice

The explosive evolution of new species to exploit new ecological niches happens alongside equally explosive geological changes, making this a turbulent and unforgiving environment. As life proliferates it uses up a lot of carbon,[113] causing a drop in CO_2 levels[114] and there is an ice age around 517 million years ago known as the "MICE event"[115] along with sea level falls.[115] But the supercontinent of Pannotia is being dismembered by continental drift, and as it rifts apart[100] violent volcanic eruptions let rip across a third of Australia 510.0 million years ago, forming basalts you can still find today at Kalkarindji. Underground magma there bakes the oily remains of plankton to give off huge quantities of natural gas (methane) and CO_2, reversing the cooling with strong, greenhouse gas emissions and global warming that turns oceans into oxygen-starved dead zones with global sea level rises. [116]

The nascent Cambrian Explosion is stopped dead in its tracks by this climate change, as around 45% of genera (species groups) go extinct in the Mid-Cambrian Extinction.[116] You will recognize these global warming symptoms as they recur many times as you age, often with similarly deadly consequences.

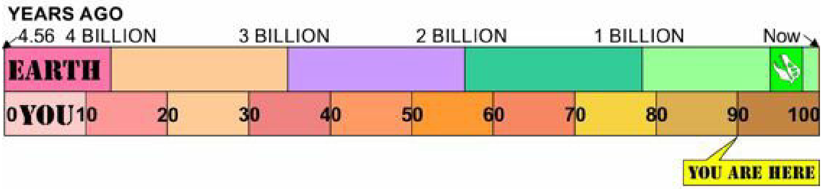
A new ocean – the "Iapetus" – floods the gaps between the dismembered bits of Pannotia. Widening tears in the ocean crust power an uptick in the activity of "black smokers" - underwater hot springs that inject iron and other nutrients into the oceans, as life begins to recover from the Mid-Cambrian Extinction. [100] The new pieces of the continental puzzle are now "Gondwana" (a continent comprising the Amazon region, much of Africa, India, Australia and Antarctica), which lies near the South Pole, and "Laurentia" (much of modern Canada and northeastern USA today), "Baltica" (modern Scandinavia) and Siberia.[100] [79] [117] Most land is in the Southern hemisphere.

Invasion of the land plants

As you reach your 89th birthday, life on land prepares the ground – literally – for big changes to come. It's around this time that freshwater pond-weed algae evolve into liverworts, [76] which begin to show up in Gondwana around 510 million years ago. [81] [118] [119] Not long after they appear, the Earth gets another sharp boost in oxygen levels, raising them from around 15% to about 25% of present levels. [89] Soon after the liverworts appear, there is also a jump in the diversity of plankton – taking advantage of higher oxygen levels. [89]

And it's this invasion of land by more advanced plants, coupled with that boost in oxygen, which sets off another step-change in diversity of life, and its knock-on effects on your global climate.

5. Old Age and Heart Attacks



At 90 – Heart attack!

As you approach your 90s, you may be a little unsteady but you have not lost your appetite for drama. The stage is set for your next act when Laurentia and Baltica converge. Volcanic islands emerge like sentinels ahead of their armies, signaling the impending clash of continents by spewing incandescent clouds of volcanic ash far and wide. Elsewhere in the world - near Siberia – there are some especially large volcanic outpourings, [99] and it may be those that inject such an excess of CO_2 into the atmosphere that the climate warms again, [120] and global sea levels rise, [121] creating oxygen-less ocean dead zones across the globe, and depositing dead plankton in stinking black mud on the sea bottom. [122] This causes a mass extinction, including the loss many trilobite species, [121] and a disruption to the global carbon cycle recognized in rocks around the world as the "SPICE event." [89] You recover in a few million years, and life continues to evolve.

The invention of coral reefs

Your warm, more oxygen-rich seas now support a resumption in the explosion of life that started in the Cambrian. This second phase is known as the "Great Ordovician Biodiversification Event," (mercifully shortened to "GOBE") because life diversifies into the remaining ecological niches that are still occupied today. [123] The open ocean is now colonized by a brand new food web of swimmers feeding on plankton and each other, including swimming trilobites, armored fish that haven't yet evolved jaws ("ostracoderms"), "caryocaridids" (shrimp-like crustaceans), and the top predators: "nautiloids" (squids in shells). Sea-scorpions prowl the depths, [123] as fronds of graptolites – tiny colonies of filter-feeders living in cascading cups – drift in currents or are rooted to the sea bed. [124] Trilobites evolve a wide range of sizes and shapes, including hedonistic giants about 1 meter (3 feet) long that reproduce in mass orgies![125] Now even the deepest ocean floor is colonized and churned up by animals for the first time.[123]

It's also the time that coral reefs, home to a quarter of all marine species today,[126] and nurseries for ocean-going life, first appear. They begin as modest mounds maybe 1m (3 feet) tall, dominated by algae and microbes, but by the time you turn 90 (458 million years ago), much larger reefs are being built by corals, sponges and coral-like bryozoans. They provide a home for a host of sea shells, sea urchins, trilobites, and a complex network of suspension feeders.[123]

The invention of wood

> "land plants invent something that will change the planet forever"

Like a pensioner fending off a gang of hooligans, you receive a nuisance-battering from a string of small asteroids a little before you turn 90 (470 Million years ago – during the "Ordovician Period") which leave a series of impacts scattered from Sweden to Estonia to Iowa.[127] [128] But these wounds are dwarfed by tumultuous tectonic transformations. As Laurentia (North America) and

Baltica (Scandinavia) gradually collide, volcanic islands and sediments of the Iapetus Ocean between them are squished upwards, creating the spine of a mountain chain that can be recognized today in the Appalachian Mountains, from Georgia through West Virginia and New Jersey, to New England through Nova Scotia and Newfoundland, and on through the Irish hills of Donegal and the Caledonian Highlands of Scotland, all the way to the Norwegian Alps.

On the banks and lakeshores of great rivers that wash from these new mountains, land plants invent something that will change the planet forever, around your 90th birthday (460 million years ago).[81][129]

They invent wood. [81]

The woody tubes of "vascular plants" allow them to transport water up their stems, and give stems the strength to stand upright. Suddenly plants are set free to colonize areas of land that they couldn't survive on before. They can grow taller to get more sunlight and to disperse their spores over a wider area. Vascular plants are better adapted to living on dry land than anything before, and so they explode across the landscape.

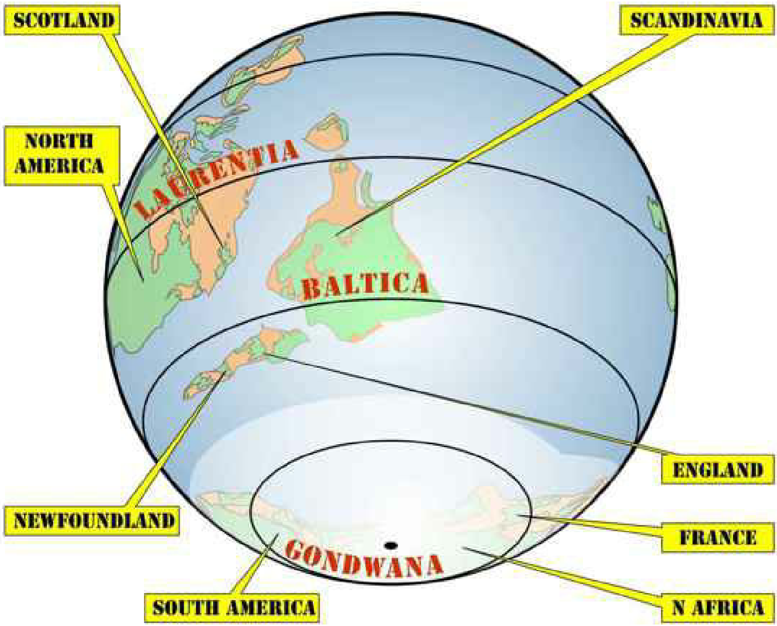
This new plant era begins, again, to make a significant dent in atmospheric CO_2. [119] You might think that one plant is much like another when it comes to impacting CO_2, so why the difference? Well, the difference is because woody plants have more carbon in them than other plants, [90] so when they die and get buried they are more efficient at locking away carbon, reducing CO_2 and cooling the planet by reducing the greenhouse effect. More importantly, these new vascular plants break down rock into soluble nutrients up to 10 times faster than plant-free rock. [129] These chemicals fertilize further plant growth, which sucks up more CO_2 from the atmosphere. [129]

We are still a long way from trees. The earliest woody plants are modest specimens, reaching an unimpressive height of a few centimeters (a couple of inches). Still, the land bristles with a designer stubble of simple branching plants like *Cooksonia* and *Aglaophyton* in suitably moist soils, because they have not yet evolved roots or leaves. The tallest thing on land is actually a giant fungus called *Prototaxites* that makes spires rising 8 meters (26 feet) high. [49]

8 **Early land plants**: ***Aglaophyton* bristle across the land** © Walter Myers

But even these early vascular plants are effective enough at locking away atmospheric CO_2 to cause another ice age beginning just after you turn 90 (458 million years ago). [129]

This "Hirnantian Ice Age," is preceded by another pulse of warming and ocean dead zones possibly due to eruptions in South Korea. [99] [130] But as rock weathering, plants and plankton lock away carbon over the course of 15 million years, [129] CO_2 levels drop and this cools the planet. [130] A huge sheet of ice begins in the polar mountains of Gondwana (Africa, South America, Arabia India, Australia and Antarctica combined), which happens tc occupy the South Pole at this time.[131] As the ice cap thickens, it spreads to an area much larger than modern Antarctica,[132] locking up more and more water. This causes a big drop in global sea level which leaves reefs high and dry, [133] triggering the Earth's equivalent of a heart attack – a huge mass extinction that wipes out 86% of all species. [134] [133] [129] Around ⅔ of sea-snail, mollusk, sea urchin, coral and bryozoan species disappear from our planet forever, and reefs disappear for several million years.[123]



9 **The world 450 million years ago, showing the Hirnantian glaciation.** Redrawn from Torsvik et al, Earth-Science Reviews (2012), Modern coastlines for reference. Hirnantian glaciation from Nutz et al, J. Sedimentary Res. 2013.

Jaws

The continuing collision of Laurentia (North America) and Baltica (Scandinavia) creates a new continent called “Laurussia” and intense volcanic eruptions. [135] These, along with eruptions near Siberia and Mongolia,[99] ensure that over the course of the next 25 million years (in the “Silurian Period”) you endure at least 8 bouts of volcanic-warmed fever accompanied by sea level rises, interspersed with ice-age chills with sea level falls. [135] The periods of global warming cause extinctions in many groups of creatures including conodonts (eel-like creatures), graptolites, polychaete worms, brachiopods (seashells) and acritarchs (microscopic spiky balls). [135]

The stresses of climate fluctuations drive the survival of the fittest, so life innovates and elaborates on land and in the sea.

> “These new kings of the food web have a new weapon - jaws”

Reefs eventually recover, and land plants take-off in a big way, developing more complex branching stems [81] [119] and raising oxygen levels even higher. As the higher level of oxygen dissolves in the oceans, it inspires the evolution of big fish as if an evolutionary hand-brake is released. [90] These new kings of the food web have a new weapon – jaws. They also have evolved something else that we inherited from them – live birth. [136]

The Silurian ocean is now a distinctly scary place: placoderms – large armored fish with faces like vampire turtles – stalk great expanses of coral reef, hunting jawless ostracoderm fish, nautiloids, and pretty much anything else. By the end of your 91st year the first sharks have appeared [137] but to this day they still have not evolved bones. A separate group of truly bony fishes – again, your ancestors and mine - appears on the scene around the same time in the late Silurian (about 420 million years ago). [138]

At 91 - The invention of walking

Plants have now found ways to nurture and protect their spores (seeds haven't been invented yet), so they can now colonize dryer areas. [76] To complement this they develop roots to extract water from dryer soils, and this allows plants to mold the planet, again. Rooted plants now stabilize river banks, leading to the first meandering rivers with muddy floodplains. [139] Roots get down deep and physical with rocks, helping to break them down into deeper, nutrient-rich soil, causing another step-change in the rate of rock weathering which draws down atmospheric CO_2. [76] Plants suck water up through those roots and transpire water vapor into the air through newly-invented leaves, promoting more continental cloud formation and rain, diverting water that would previously have run off to the ocean. [140]

The diminutive *Cooksonia* plant has now been joined by these more advanced plants with leaves, such as *Baragwanathia* which can grow 25cm (10 in) tall. [49] 10 inches may not seem like much, but it's 5 times bigger than *Cooksonia*, converting the land from a 2-dimensional photosynthesizing surface to a 3-dimensional photosynthesizing volume. Together the land plants have now elevated oxygen levels in the atmosphere to near present day levels by the time you are 91 (about 400 million years ago - during the “Devonian Period”). [90] You could say that the terra-forming project started by cyanobacteria 37 years ago when you were 54 (1.7 billion years before this time) is now complete.

First fires

Now that oxygen levels are at near present-day levels and the land is covered in combustible plant material, it’s inevitable that you experience your first wildfires at this time (around 418 million years ago). [141] But this new oxygen-rich world also allows life to get even bigger and more energetic, and in your 91st year evolution takes several steps forward – literally.

Fish evolve fins on stubby stalks, like the Coelacanth, the fossil fish *Kenichthys,* [142] and lungfish. [143] They continue to evolve increasingly land-adapted characteristics and reduce their fishy features in steps through *Gogonasus,* [144] *Eusthenopteron*, *Tinirau,* [142] *Panderichthys*, *Tiktaalik,* [145] [146] and other species. [142] Fins become feet, tails lengthen and lose their fins, gill covers are lost, ears develop and snouts get longer, until animals like *Tiktaalik* vaguely resemble a 3-9 feet long (1-3 meters) crocodile, with both gills and lungs. But its stubby toe-less legs still limit *Tiktaalik* to spending most of its life in shallow rivers and ponds, avoiding giant 3 to 4 meter (9 to 12 foot) predatory fish that lurk in deeper river channels. [145]

> “It is a free lunch every day!”

Soon creatures like these evolve into “tetrapods” (4-footed creatures) such as the salamander-like *Acanthostega* or the crocodile-like, 7-toed [49] *Ichthyostega* [146] even if they can’t really walk so much as shuffle. By the middle of the Devonian Period, however, tetrapods improve their legs and pelvis, enabling them actually to walk on land, leaving their tracks in Polish mud halfway through your 92nd year (around 390 million years ago). [147]

What advantage could there be in this move to dry land? Well, by now there’s a whole menu of land critters to eat. Insects, [148] spiders, millipedes, centipedes and scorpions are crawling in a monsoonal jungle of 10 meter high (33 foot) fern-fronded *Archaeopteris* trees rooted in rich soil with an understory of shrubs and bushes. But the climate isn’t always so hospitable and becomes semi-arid every hundred thousand years or so, due to variations in Earth’s orbit, [149] so tetrapods also thrive on tidal flats [147] where a feast is guaranteed twice daily from creatures stranded by the tides, and where tetrapods fear no predators. [147] It is a free lunch every day!

At 92 – A double heart attack

Economists talk about disruptive innovation being good for the economy, but when we are caught up in those changes it doesn't feel that way. It works in a similar way in Earth's evolution. The plant innovations and volcanic eruptions when you are 91 (in the Devonian period) create their own disruption.

The arrival of the first forests [141] allows peat deposits to form, creating reserves of carbon (coal) locked away in continents. The spread of trees means the spread of root systems which liberate phosphorous that eventually finds its way to the sea, fertilizing the oceans, where the resulting fecundity of shelly creatures locks yet more CO_2 away in limestone. The combined effect reduces CO_2 levels to something like present day levels. [150] [76] As CO_2 reduces, plant leaves evolve more pores (stomata) on their leaves, [151] allowing them to cool more effectively and therefore allowing them to get much bigger – locking away yet more carbon.

At the same time, an archipelago that constitutes the advanced guard of the continent of Gondwana (Africa and South America combined) begins its slow smear into Laurussia (North America, Britain, Scandinavia and Russia combined) to form what will become southern Europe. [117] Enormous volcanic eruptions occur in Russia, eastern Siberia and elsewhere [152] [153] [99] knocking the climate out-of-whack, triggering big fluctuations in sea level [154] and causing widespread, stinking dead-zones in the oceans with acid, shell-dissolving water. [155] The fluctuating climate stresses you to the point that you suffer a major double heart-attack, a 1-2 punch of mass extinction at 372 and then 359 million years ago as the Devonian period ends. [156]

In the oceans, the fronded-graptolites that had been so prevalent all but die out. [157] Placoderms, those bone-plated vampire-faced fish, vanish as 50% of vertebrate diversity is lost. [156] On land *Archaeopteris* trees disappear [158] as do so many other species in this, one of the 5 biggest mass-extinctions in all your life. Oxygen levels plummet to about 15%, which is equivalent to living at an altitude of 3,000 m (10,000 feet) today, a level not seen since before the Cambrian Explosion. [159]

But it's not bad news for the survivors who inherit the Earth. In the oceans ray-finned fish and sharks do very well after the mass extinction, [156] and ammonites (squid-like animals in spiral shells) evolve from nautiloids [160] to navigate the seas until you are 98. New seed-plant forests rapidly diversify into the plains and uplands vacated by *Archaeopteris* [158] as a bewildering variety of trees and shrubs claim every available niche of land. The extinction also sets up the deck of vertebrates that is in play to this day, and the surviving tetrapods standardize on 5 toes, [156] paving the way for reptiles.

Age 92 to 93 - Swamps and giant bugs

The Carboniferous period (359-299 million years ago) is so called because of all the carbon fuel (coal) that forms at this time across Europe, America and China. Great rivers meander from the Appalachian – Caledonian Mountains into sluggish, densely-forested swamps and deltas. The buzzing of flying insects [148] emanates from the canopies of scaly-barked lycopsid trees (relatives of modern club-mosses) as tall as 35 meters (115 feet) high, that tower over bottle-brush-like *Calamites* trees (relatives of modern horsetails), in vast expanses of Everglades-like wetlands. [161] [162] Amphibians and reptiles hunt insects, while millipedes and snails crawl over rotting tree stumps. [163] As each tree dies, it splashes into the stinking swamp where its wood slowly blackens to coal, locking atmospheric CO_2 away in the ground until humans dig it up and burn it in hundreds of millions of years' time.

10 **Carboniferous swamp forest** © Walter Myers

Inland, early conifer forests are dominated by 25 meter (80 foot) tall *Walchia* trees that resemble modern pine trees, and by giant 45 meter (150 foot) *Cordaites* trees with long strap-like leaves. An undergrowth of ferns and palm-like cycads spreads across the dryer hinterland. [49] [164]

> “Scorpions the size of a Labrador retriever”

With more and more of the world’s land dedicated to forests, oxygen production bumps up several notches, rising to about 35% of the atmosphere in your 93rd year [165] [159] (it’s about 21% today). Freakishly large insects evolve to take advantage. Scorpions the size of a Labrador retriever (*Pulmonoscorpius*) cower from giant 2.6 meter (9 foot) long millipedes (*Arthropleura*) while dragonflies the size of an albatross (*Meganeura monyi*) buzz through the air. Oxygen promotes fire, so these forests are susceptible to conflagrations that leave behind quantities of charcoal that we find to this day. [162]

Offshore in the tropics, where North America and Europe are at this time, warm seas support sea-lily-, sponge-, and coral-reefs frequented by spiral ammonites, sharks and other fish. The Grand Canyon’s famous Redwall Limestone is forming at this time.

The world is not all tropical, however. Africa, South America, Arabia, India and Antarctica are still welded together as the Gondwana supercontinent, centered near the South Pole. Coal formation drops CO_2 levels to roughly half modern values (to around 220ppm)[166] and this combined with the fact that there is a huge continent sitting at the South Pole, again triggers global cooling. Ice caps take hold in mountains and plateaus all across Gondwana, [166] waxing and waning in cycles due to variations in Earth’s orbit around the Sun. [167] [168] [169] With each cold era, ice caps near the South Pole expand, the tropical hinterland dries and the wetlands shrink as sea levels fall, giving up territory to conifer forests. In each warm and wet phase ice melts, sea levels rise, wetland forests expand, and another seam of coal forms.[164]

At 93 – The invention of the eggshell

America and Europe have now encroached on Africa, so New Jersey and Morocco are now joined as one,[117] sacrificing the Jersey Shore to create the supercontinent called "Pangea." Any islands in the way are smeared into the ever-expanding Appalachian Mountains.

Tetrapods are having a field day.

> "the egg is a portable pond"

They diversify into an amazing diversity of creatures adapted to all the permutations from wet to dry habitats. One branch of tetrapods has invented the shelled egg, as in a durable reproduction capsule that can survive on dry land. Amphibians and primitive tetrapods are tied to the water to reproduce the way fish do, but the shelled-egg sets the newly-evolved reptiles free to reproduce on dry land. In effect the egg is a portable pond [170] - a distinct advantage in this capricious climate. Just after you turn 93 (315 million years ago), reptiles like *Hylonomus* are running about, chasing insects[171] and leaving their distinctive tracks in the muds of seasonally dry riverbanks. [170] Already we see 2 distinct lineages of reptile, the *Synapsids*, which will eventually give rise to mammals, and the *Sauropsids* which will later give rise to dinosaurs and birds. [170]

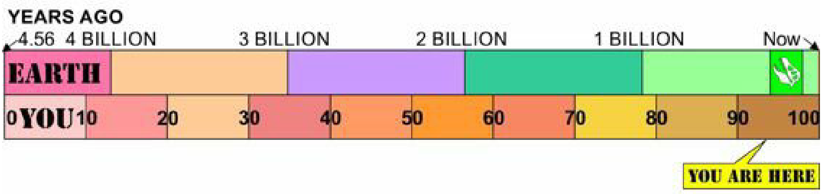
Out of the blue, a random space rock threatens to annihilate all this.

At some point when you are 93 (roughly 305 million years ago) an asteroid bigger than 10km (6mi) wide slams into Australia, creating an enormous 200km wide crater. [172] For comparison that's the same size as the impact that will wipe out the dinosaurs later in your life. Shock waves send violent earthquakes across the planet as a vast amount of rock is vaporized and sent around the world to block out the Sun. It may be this that tips the climate into a severe ice age that lasts 4 months of your life (until 290 million years ago) at the close of the Carboniferous and into the Permian Period. [166] [172]

As more of Earth's water is locked away in ice, and as shallow seas are annihilated by continental drift, we see a progressive drying of Europe and America and a collapse of the rainforests, isolating land animals in shrinking 'islands' of forest. This has a devastating effect on amphibians, many of which become extinct. [173] But reptiles with their durable eggs survive the more arid conditions, and evolve new feeding strategies (some become predators as others specialize as herbivores). [173] Conifer forests take over the drying continent, while tropical coal-forming rainforests persevere in the islands that will eventually become China, central Asia and Siberia. [167] [174] The loss of vegetation causes oxygen levels to fall to modern levels, [159] leading to the disappearance of those giant bugs.

11 **The world 300 million years ago, with glaciation.** Redrawn from Torsvik et al, Earth-Science Reviews (2012), Modern coastlines for reference. Glaciation from Isbell et al, Gondwana Research (2012).

6. The Day You Set Yourself On Fire



In Your Life as Planet Earth you are now in your mid-90s and let's just say you aren't as reliable as you once were. It's only to be expected, since many people your age suffer from dementia. [175] At 94, your self-inflicted accident is your closest brush with death since the formation of the Moon in your infancy.

The omens in the early Permian are not good. You are assaulted by a pair of asteroids in a double-impact at Clearwater in Canada that leaves two wounds tens of kilometers wide. [96] Meanwhile the ocean that separated Europe from central Asia and Siberia is shrinking to extinction, and you must still endure chills when ice takes hold on the mountains of Australia – which is not far from the South Pole – and expands to ice caps 3 times (each smaller than the last) during the Permian. [166]

Just as one's skin dries in old age, so does the Earth's at this time. The great drying of Pangea causes deserts to spread across vast swathes of land where once there were tropical rainforests. Desert Dunes blow across western America and parts of Europe, while extremely salty seas build up thick salt deposits in northern Europe and southern America. [117] In cooler climes, forests of conifers and *Glossopteris* trees fringe polar regions. [49]

> "these early mammal ancestors are everywhere, but their rule is about to be rudely cut short"

The Early Permian "top dogs" are synapsid reptiles, with a sprawling komodo-dragon-like gait. The 3 meter (10 foot) long *Dimetrodon,* for example, has a fearsome array of teeth and a bizarre sail on its back for warming its cold blood in the mornings. [49]

Eventually by the late Permian, we see herds of pig-like *Pelanomodon* roaming the dusty plains, crushing and grinding plants with their bony beak-like jaws, while small *Diictodon* burrow for shelter like modern groundhogs. Nearby, herds of thick-skulled *Moschops*, also plant eaters, give *Scutosaurus*, with its medieval-looking studded armor, a wide berth, while the catsized *Robertia* scurries around the herds looking for roots of its own to eat. These are collectively called "dicynodonts," which evolve into "cynodonts" (such as *Procynosuchus*) who are beginning to develop the higher metabolic rate of their mammal descendants, and they becoming furry. [49] These early mammal ancestors are everywhere, but their rule is about to be rudely cut short.

As Siberia and central Asia finally crumple into Europe the sediments that occupied the gap between them get pinched into the peaks of the Ural Mountains. At the same time, northern China attaches itself to Siberia. [117] There is now a single colossal continent – Pangea – which straddles the globe from the South Pole to the North Pole, leaving only the remote islands of Southeast Asia, parts of the Middle East and Tibet unattached.

Catastrophic fire

The first warning signs of the catastrophe start in South China – hundreds of miles across the ocean from Northern China at the time. A plume of hot magma from deep in the Earth's mantle surges to the surface 262 million years ago, inundating the area of Emeishan with deep lakes of glowing, churning basalt lava covering an area of nearly 1,000 km diameter (600 mi). [176] The gasses and ash from these eruptions cause climate change, which results in some plant and marine extinctions. [174] This Chinese burn is serious enough, but the next is life-threatening.

Very nearly the end – the "Great Dying"

Halfway through your 94th year, a medium-sized asteroid smashes into southern Brazil, 254.7 million years ago. Its 40 km (25 mi) crater isn't especially large, but landing in oil shales it ignites a large amount of carbon into the air. Powerful earthquakes from the impact shake the ground, fracking the oil shale and liberating a large amount of atmosphere-warming methane that was trapped there. [177]

That would be bad enough, but it gets much, much worse.

At around the same time, a searing slug of magma rises from the core-mantle boundary until it meets the ancient craton roots of Siberia. [178] Burning its way towards the surface, the poisonous plume impregnates any sediments it encounters with many subterranean sheets of magma that spread across more than 1.6 million square kilometers (618,000 square miles), and which swell to hundreds of meters thick. But these aren't ordinary sediments. These contain petroleum reserves created in Ediacaran times, salt deposits created in Cambrian times, and Carboniferous coal. [88]

Like a heating element in an electric kettle, the magma bakes the sediments, the oil, the salt and the coal, generating a noxious cocktail of CO_2, methane, sulfur dioxide, hydrochloric acid and halocarbons. These gasses burst to the surface through hundreds of underground chimneys to vent into the atmosphere, billowing vast quantities of coal fly-ash and smoke like William Blake's dark satanic mills, 251.9 million years ago. [88] [179] [180]

Boiling lava now vomits into the Siberian landscape deluging an area over 4,000 km (2,500 mi) in diameter – an area the size of Europe – in fuming, seething, molten rock, eventually building to 3 km (2 mi) thick. [181] [178] [88]

> “equatorial and tropical regions become lethal for most life”

The explosion in greenhouse gas levels over perhaps as little as 2,100 years [179] [181] causes rapid global warming with average temperatures jumping by more than 15°C (27°F), which bakes the planet to the point that equatorial and tropical regions become lethal for most life on land and in the sea. Equatorial ocean temperatures reach 40°C (over 100°F), while land temperatures considerably exceed that – too hot for plants to photosynthesize, and hot enough to cause protein damage in animals (i.e. to cook them). [182]

But that is not all, not nearly.

The halocarbons destroy the planet’s ozone layer, exposing land life to damaging levels of UV radiation, even as sulfuric acid rain burns plants and leaches away soil nutrients. [88] [183]

We call it "The Great Dying." In the ensuing 61,000 years, more than 90% of species go extinct. [179] [184] Woodlands are devastated, as half of all plant species die out. [49] 96% of invertebrates and over 60% of reptile and amphibian species are lost. [49] Gone are the trilobites, some corals, eurypterid sea scorpions, 5 entire orders of insect, and *Glossopteris* forests. [49] It's a massacre of species, the worst in your life.

Age 94 - Dawn of the dinosaurs

You begin the Triassic on your hospital bed, a comatose world baking in a sweltering hothouse. Complex life is all but absent in the equatorial and tropical regions for hundreds of thousands of years. [182] Once-vibrant coral reefs are covered in morbid bacterial slime, [181] once-fecund forests lie desiccated and deserted, [182] and wide areas of oceans are oxygen-starved dead zones. [184] The loss of plants causes oxygen levels to drop back down to 15% (compared with today's 21%) - a level not seen since the Devonian Mass Extinction.[159] Low oxygen and lack of vegetation mean that wildfires no longer occur. [185]

It takes some 10 million years for you to recover. [179]

And even when you do, for the most part Pangea is a hot and arid land. The exceptions are the polar regions, now ice-free, which begin to support temperate coal-producing forests after a gap of several million years, [182] while the islands that make up modern Turkey, Iran and Tibet are monsoonal tropics. [49] Gradually through your 95th year the climate cools to the point that a tropical monsoonal climate can spread to mainland Pangea, greening Europe, [49] and boosting oxygen levels again. [159]

In the sea, modern corals evolve and simple ammonites are replaced by ones with fancier shells. Already a few species of reptiles have returned from land to the water. Some have developed a dolphin-like shape as Ichthyosaurs, some are the ancestors of turtles (but with only the lower half or their shell), and some have elongated necks and tails like *Lariosaurus* and *Tanystropheus*. [49]

Triassic land life on Pangea must be adapted to arid conditions to survive.

> "leaving reptiles the masters of land, sea and air"

The first dinosaur, a 2-footed creature called *Nyasasaurus*, appears halfway through your 95th year (around 247 million years ago) in the near-polar south, scampering across the plains of Tanzania. [186] Dinosaurs will have their day, but for now they are minor players compared to crocodile-like crurotarsan reptiles. Primitive plants hanging on from the Permian lose ground to seed plants like *Dicroidium* trees and newly-evolved *Gynko*s. The few groups of mammal-like reptiles that survived the Permian extinction (such as the pig-like *Lystrosaurus*), still dominate at first, but they are gradually out-competed by the swifter bipedal dinosaurs. Mammal-like cynodonts evolve to the point that they are now almost mammals, such as the dog-like *Cynognathus* and the mouse-like *Morganucodon*. [49]

By the time you are 95 (215 million years ago) the first true mammals such as the rat-like *Eozostrodon* appear [49] but they are dwarfed by giant reptiles like the vicious-toothed carnivore *Postosuchus,* and bulky herbivores like *Plateosaurus*. The sky has now been conquered by reptiles – pterosaurs like *Eudimorphodon* [49] - leaving reptiles the masters of land, sea and air.

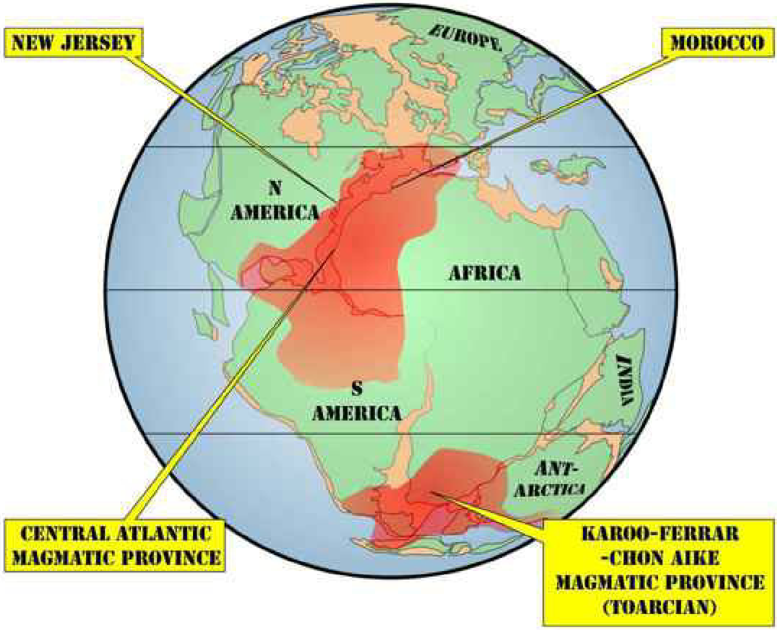
The unified continent gives evolution a boost, because any land animal that evolves in one location can radiate to all areas of the globe without being obstructed by ocean. This way reptiles and primitive mammals get to spread across the planet to take over ecological niches where they can specialize.

Back to the burn unit

But trouble is, once more, afoot. Around 228 million years ago a profound but short-lived change in the weather drenches a wide area of the northern hemisphere with megamonsoon torrents. [187] The culprit is a huge flood of basalt erupting in Alaska and the Yukon which causes another CO_2 spike and global warming. [188] [189] [190]

At the end of this bizarre climatic blip the weather returns to its regular aridity, but we now begin to see those tiny chalk-forming algae with a giant name, *Coccolithophores*, [188] which make their skeletons from calcium carbonate. They start a subtle but fundamental change in ocean chemistry by raining their carbon-rich skeletons into the deep abyss of oceans when they die. This gradually exports carbon to the deep oceans as a calcareous ooze, which will eventually serve as buffer against extreme global warming events like the Permian Great Dying in the future. [181] [191]

Suddenly you are slammed by another asteroid. It gouges out a huge crater 100 km (60 mi) wide at Manicouagan in Quebec, Canada, 214 million years ago, that can be seen from space even today. Devastating as it is, it is still just a foretaste of worse to come.



12 **The world 200 million years ago, at the birth of the Atlantic Ocean.** Red patches are large provinces of volcanic and igneous activity that occurred at about the same time (The Toarcian eruptions are 20 million years later). Redrawn from Torsvik et al, Earth-Science Reviews (2012), with magmatic provinces added. Modern coastlines for reference.

The real trouble is that the enormous supercontinent of Pangea just can't hold together for long, and now it begins a slow self-dismemberment. Cracks begin to spread between Europe and North America. The cracks become rifts that fill with algae-choked lakes surrounded by vegetation, which get continually buried, building ever-thicker deposits of oily, organic-rich sediments like the black shales of the Lockatong Formation of New Jersey. [192]

The messy birth of the Atlantic Ocean

> "greenhouse gasses cause a 10°C jump in sea temperatures and rapid sea level rise"

As the rift dilates, fissures tear deep through the crust to the mantle, where they gash into molten rock. Red magma sears through the tears, injecting itself between layers of sediment before gushing out enormous lakes of lava all along the eastern edge of North America, Western Europe, West Africa, and into Brazil. At least four hemorrhages of magma spew through hundreds of deep-rooted fissures over 600,000 years, each releasing massive amounts of CO_2 and resulting in some 2 million cubic kilometers (480,000 cubic miles) of basalt lava, forming the "Central Atlantic Magmatic Province." This is the messy birth of the Atlantic Ocean. [193] [194]

In a similar process to what happened in the Permian

Great Dying, oily lake sediments get baked and belch out massive quantities of methane [195] and other pollution into the air, including sulfur dioxide and toxic chemicals. [189] [192] [196] The extra greenhouse gasses cause a 10°C (18°F) jump in sea temperatures and rapid sea level rise. [192] [197] [194] [195] Lava flows ignite all vegetation they touch, and even far from the lava, dead vegetation fuels huge wildfires. [193] Seas are starved of oxygen, clogged with algae and stink of rotten eggs. [198]

And, to add insult to injury, you are mugged by another asteroid that hits shallow seas in Rochechouart, France, leaving an impact crater 23 km (14 mi) wide and sending a tsunami into Britain 201 million years ago. [199]

Not surprisingly all of this triggers another mass extinction at the end of the Triassic, [192] one of the 5 biggest in Your Life as Planet Earth.

Around half of marine biodiversity is lost, [195] including a number of ammonite and 'clam' species. Many land vertebrates including large amphibians are gone. So are most of the previously dominant crurotarsans, except crocodylomorphs that will later give rise to crocodiles and alligators. Forests collapse and are replaced by ferns [196] causing oxygen levels, which were improving in the Triassic, to fall back to 15%. [159]

It's disaster for those extinct species, but it's just the break others need.

95 to 96 – Jurassic giants

Freed from domination by the crocodile-like crurotarsans, the dinosaurs we have grown to love from the movies now inherit the Jurassic Earth.

A bewildering array of land and marine reptiles, including dinosaurs, now colonizes every niche of the recovering Jurassic planet. In this warm and humid climate, coal-forming conifer forests return to polar latitudes and palm-fronded benetitalian plants shade the tropics. As they proliferate, oxygen levels begin to recover to levels that we find today. [159]

But the dismantling of Pangea continues to cause disruption.

> "The climate stays hot with sea surface temperatures rising by around 10°C (18°F) for around 300,000 years"

When you have just turned 96 (180 million years ago - in the "Toarcian" stage of the Jurassic) the restless mantle begins to pull South Africa apart from Antarctica and South America sending floods of lava from southern Africa as far as South America, [200] and across central Antarctica, even to Australia. In a repeat of the end-Triassic events, CO_2 and methane from cooked organic sediments get released into the atmosphere. The climate changes gradually over a hundred thousand years but then warms suddenly in as little as 650 years, and stays hot with sea surface temperatures rising by around 10°C (18°F) for around 300,000 years. Reefs dissolve as the ocean acidifies and sea creatures have trouble growing shells. Ocean depths become oxygen-less dead zones again, devoid of the usual "benthic" fauna, and on land chemical weathering of rock increases due to the heat and acid rain. [201] [202]

Many marine species die out [201] but on land it seems to promote a turnover in animal and plant species. Giant sauropod dinosaurs take off after this event, and so do ornithischian dinosaurs – the group that includes armored, beaked and horned herbivores, including iconic species like *Stegosaurus* and *Triceratops*. Monkey-puzzles and cypress trees also seem to profit from the experience. [200]

As the fragments of Pangea spread apart, the gaps between them form an extensive network of shallow seas teeming with marine life. The island chain that includes Turkey, Iran and Tibet has now begun to scrape off onto Asia, while India and Madagascar are just beginning to break away from Africa. [117]

The world is not all dinosaur. The largest fish that ever lived, *Leedsicthys*, cruises the oceans feeding on plankton. It grows to 22 meters (over 70 feet) long – the size of a large luxury yacht - and shares the ocean with a range of reptilian monsters and a chunky shark that's been around since the Permian, called *Hybodus*. The marine reptile *Lipleurodon* stretches to 10 meters (30 feet) with jaws as big as a man and 30 centimeter (1 foot) long teeth. Curly ammonites diversify rapidly and sea urchins and corals thrive in the warm shallow seas, as do a host of other mollusks and crustaceans. [49]

After an asteroid blasts an 80km (50mile) wide hole into the rocks at Puchezh-Katunki in Russia[199] 167 million years ago, just 7 million years later the Earth undergoes a big decline in dinosaur diversity as a number of species go extinct, possibly as a result of more eruptions in South America. [203] [204]

But after that the world of dinosaurs becomes even more spectacular. It is a time of giants and staggering statistics. *Brachiosaurus* and *Diplodocus* grow to lengths of 25 meters (over 80 feet). [49] *Allosaurus* is a hunter that grows to 12 meters (40 feet) and resembles a T-Rex with exaggerated eyebrows. Barely noticeable in comparison, mammals like the tiny mouse-like *Megazostrodon*, and *Sinoconodon*, which resembles a miniature weasel, scurry and burrow in the Jurassic undergrowth. [49]

On the origin of feathers

While all this is going on, the first bird – *Aurornis* – has evolved, around 160 million years ago. [205] Feathers are a dinosaur innovation early in their development, and a number of different groups of dinosaur already had primitive feathers by the early Jurassic, long before birds. [206]

By now the 2 main branches of dinosaurs both have species that possess either feather-like filaments (such as *Tianyulong*, which had a Mohawk) or they have actual (albeit primitive and flightless) feathers such as the pheasant-like *Epidexipteryx*. [207] Some dinos have a fuzz of filaments when young, and then grow wings when they mature to impress potential mates, [208] while other, small dinosaurs use downy feathers to keep warm. Over millions of years feathers become fluffier and more complex, and eventually – in some species – actual flight feathers. [207] At this point in Your Life as Planet Earth bird ancestors are living in trees and using their wings to glide from tree to tree, or as a kind of parachute to break their fall to the ground. [209] Others may use their wings as a speed-boost for running. [210] Feathers next evolve into airfoils through the development of tiny barbs and barbules that help the feather keep its shape against the air, enabling birds to fly.

Early birds like *Aurornis* and *Microraptor* are still transitional creatures, not fully birds. They have feathered legs that function as hind-wings [211] so they fly like biplanes. [212] Many still have claws on their fore-wings and teeth rather than beaks. [49] By the end of your 97th year (around 150 million years ago) creatures like *Xiaotingia* [213] and *Archaeopterix,* with fully recognizable feathered wings and larger tails have evolved, [207] and they're already beginning to lose their leg feathers.

Dino crisis

As you approach your 97th birthday in the latter portion of the Jurassic Period (around 160 million years ago), Europe and America experience big 3 to 4 million year swings between warm-humid spells and cold snaps in an increasingly cold-arid climate, with corresponding changes in global sea level. [214] In global warming periods, coral reefs disappear from equatorial latitudes where sea temperatures are too hot for them, and spread north to latitudes where we find Nova Scotia, Brittany and Vladivostok today.[215] In cold snaps CO_2 drops and seasonal ice can be found in the poles. [216]

"In global warming periods, coral reefs disappear from equatorial latitudes where sea temperatures are too hot for them, and spread north"

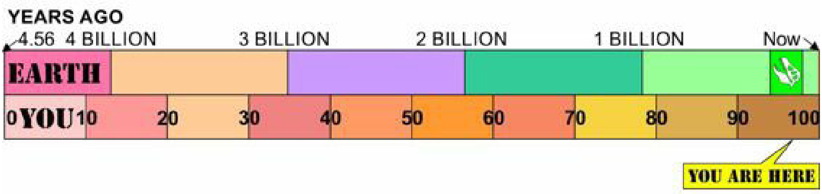
The causes of these fluctuations are uncertain but the ongoing separation of continents provides plenty of volcanic suspects through this time period, from Sweden and the North Sea to Japan, Western Australia and the western Pacific. [217][218] [219]

A crash in dinosaur diversity ensues as several sauropod species (a group which includes many giant dinosaurs) and stegosaurs die out at the end of the Jurassic, probably because food plants are affected by these climate shifts. [203]

The final punctuation mark to the Jurassic is an errant space rock that slams into you, blasting a huge 70 kilometer (43 mile) crater at Morokweng in the Kalahari of southern Africa [96] followed soon after by pair of smaller asteroid impacts, one in the Barents Sea near Norway, and another in central Australia at Gosses Bluff.

You end the Jurassic shivering in an arid ice-house. [214]

7. An Overaged Hippie!



You might think that at your ripe old age of 97 you would be too old for flower power and grass, but in Your Life as Planet Earth this is the year you go hippie. The age of T-Rex can't exactly be called the time of peace, love and understanding, but just as the optimism of the sixties ended in violence, so will yours.

It takes 4 to 5 months of your life (15 to 20 million years) for the climate to warm and dinosaur diversity to recover from the extinctions at the end of the Jurassic, [203] and how it recovers! This is the era of the movie stars of dinosaurs: the feathered *Velociraptor*, the massive-jawed *Tyrannosaurus Rex*, the sail-backed *Spinosaurus* and the horned *Triceratops*. Hundreds of other kinds of dinosaurs of all shapes, sizes and fluffiness fill every niche, some active by night, some by day, and some grazing both day and night. [220] Pterosaurs the size of aircraft cruise the skies above migrating herds of *Iguanodon* each the size of a schoolbus. Ammonites (the spiral-shelled relatives of squid) and belemnites (a kind of squid with a bullet-shaped internal shell) dart through the oceans.

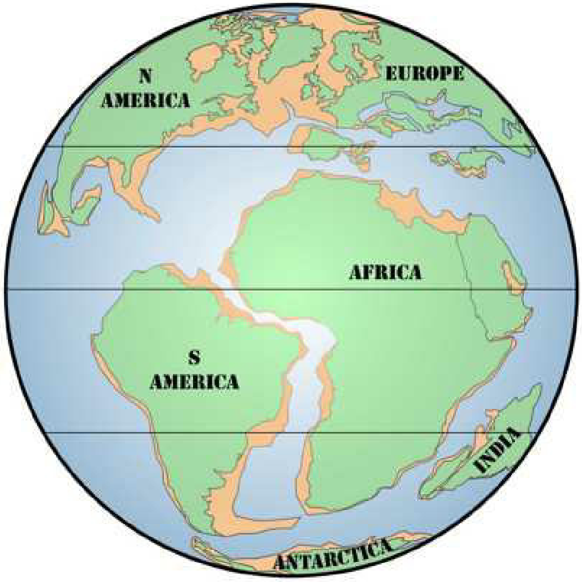
Coexisting with this exotic menagerie are creatures we would recognize today. Birds come into their own and take to the skies. Sharks, turtles and fish cruise coral reefs while sea urchins creep across sandy sea beds, dodging crabs and mollusks.

Falling Apart

In this "Cretaceous" period, South America and Africa turn their trial separation into a full divorce as the southern Atlantic Ocean widens. North America and Africa have already drifted far apart, and southern Europe loses touch with Newfoundland by 112 million years ago. [221] [222] As North America bulldozes its way across the Pacific, it encounters volcanic archipelagos which scrape off and accumulate as mountains on its western edge. [223]

Northern Europe, however, maintains a lingering attachment to Canada through Greenland, [117] and India and Madagascar are inseparable as they start their estrangement with Antarctica, even as cracks emerge between Antarctica and Australia.

You are finally enjoying a stable, steamy climate. Tropical sea temperatures are around 32°C (90°F), [224] which compares with current Caribbean Sea temperatures of around 27°C (80°F). Even northern and southern extremes like the southern tip of South America are pleasantly warm with sea temperatures to match the modern Caribbean. The poles are ice-free and Antarctica is forested, supporting a healthy population of dinosaurs. [49] Oxygen levels, which were already healthy at the end of the Jurassic, rise steadily to 25% (today's are 21%). [159]



13 **The world 100 million years ago.** Redrawn from Torsvik et al, Earth-Science Reviews (2012). Modern coastlines for reference.

Flowering plants appear right after your 97th birthday (130 million years ago)[225] and by 3 months of your life later (125 million years ago) they have already diversified widely into landscapes previously been dominated by conifers, ferns, horsetails, cycads and palm-like bennettitaleans.[226] [49] Now flowers like magnolias bloom color into the monotonous greenscape as deciduous trees and palms take over. Today over 250,000 different flowering plant species dominate most terrestrial ecosystems.[226]

This era is known as the "Cretaceous Terrestrial Revolution" because animals undergo a rapid increase in diversity, probably in response to the explosion in flowering plant diversity. We see the rise of social insects like ants, termites and bees, and the first snakes evolve from burrowing lizards. [227] Birds lose their wing-claws and leg feathers and develop beaks so that they look like birds today, exploiting varied habitats, from the seagull-like *Icthyornis* (which still had teeth in its beak), to the goose-like *Vegavis*, to the diving *Hesperornis*. [49]

New dinosaurs also evolve (armored ankylosaurs, hadrosaurs and paracephalosaurs) but it's not clear that this has anything to do with the emergence of flowering plants. [228]

Mammals, who have clung doggedly to existence since you were 95 (the Triassic), also diversify. By 6 months after your 97th birthday (115 million years ago) the first monotremes – egg laying mammals like the modern platypus – appear. [49] Most mammals are small, furry rat-like creatures (actually rodents are yet to evolve) but some are different. *Volaticotherium* climbs trees and glides just like a flying squirrel, [49] and *Repenomamus* is a dog-sized devourer of young dinosaurs. [229]

The first sign of trouble starts 4 months after you turn 97.

A brief period of cooling, complete with ephemeral ice in the poles, is sharply reversed by a major spike in volcanic activity coinciding in the southern Indian Ocean and western Pacific[219] which injects a whole lot of extra CO_2 into the atmosphere, causing another period of global warming known as the "Aptian Anoxic Event." [230] Oceans warm and turn mildly acidic, leading to extinctions and the spread of cyanobacteria and algae where corals had thrived. [231] The warming oceans expand causing sea levels to rise, and reducing their oxygen content - turning large areas into dead zones once again. [230]

After some 5 million years, weathering of rock and burial of sediments brings the CO_2 and global temperatures down again, returning you to the cooler climes that you felt before the Aptian

Anoxic Event, and sea levels fall by 50 meters (160 feet). This "new normal" of relatively low CO_2, temperatures and sea levels lasts another 5 million years before things go wrong again as you approach your 98th birthday (94 million years ago). [232] [150]

This time the cause is a massive burst of volcanism as Madagascar and India rip apart, along with giant eruptions in the Caribbean and the Arctic. [233] [234] [219] [235] In a carbon-copy (pun intended) of the Aptian event, this "Cenomanian/Turonian Anoxic Event" sees a spike in atmospheric CO_2 and corresponding jump in global temperatures, [189] leading to a die-off and a lack of oxygen in the oceans. [234] Sea levels rise to about as high as they have ever been in the entire history of the planet, and for 450,000 years the previously healthy oceans turn sluggish and stagnant, depositing black muds that will eventually become one of the world's most important sources for oil. [236] [233]

At 98 – grass and chalk

As the world recovers and you turn 98, the Cretaceous oceans are alive with spiral and uncurled ammonites, giant 50 foot long (15 meters) reptiles called "mosasaurs" and long-necked plesiosaurs almost as big. The warm seas are the perfect environment for *Coccolithophores*. Their cell walls comprise plates of pure white calcium carbonate and when they die they sink to the sea floor to make chalk, which gives its name to the "Cretaceous." Eventually great thicknesses of their skeletons are deposited, some of which will eventually be exposed in the White Cliffs of Dover in England.

On land, the first grasses have evolved in India as minor vegetation in forest clearings [237] and are being grazed by dinosaurs and mammals alike. [238] In fact mammals seem to have come out from the Cenomanian/Turonian Anoxic Event better off than most. Their success tracks the proliferation of flowering plants that they eat, and it's these adaptations that set our ancestors up to survive the rapidly approaching catastrophe for the dinosaurs. [239]

But this idyllic image of rural grazing is about to end. The world begins a period of pronounced cooling and a drop in rainfall 2 months after your 98th birthday (82 million years ago), [189] apparently due to changes in ocean circulation brought about by drifting continents. [240] Sea levels fall, exposing the sea bed to weathering which reduces CO_2 levels further, and so on in a slow feedback loop of increased cooling. [240] Temperatures in the Arctic also decline because of the closure of the "Western Interior Seaway" – a broad shallow sea that had up to now connected the Arctic to the Atlantic through the American Mid-West. [241]

Despite the relative cooling, the Cretaceous climate remains much warmer than today. Even the Arctic stays wet and humid, with summer temperatures averaging around 14°C (57°F), and winter temperatures dipping only to around -2°C (28°F), a climate not unlike Portland, Maine today. The Arctic margins of North America and Russia are forested and populated with dinosaurs, and the Arctic Ocean remains largely unfrozen even in winter, as a persistent cover of cloud keeps North Pole temperatures from getting too cold during the 5 months of winter darkness. [242] [241]

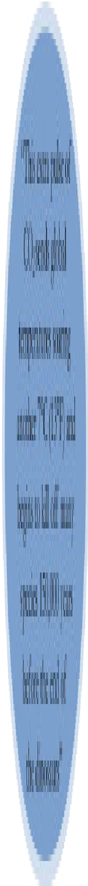
Meanwhile, in a premonition of the calamity that is about to befall the planet, an asteroid blasts a 120 kilometer wide (75 mile) hole at Kara in Russia. [96] [243]

The violent death of the dinosaurs

The tragic chain of events just 6 months after you turn 98 is like a serious car crash.

The blow-out…

India's breakneck race northwards takes its toll on the subcontinent. A few degrees south of the equator [117] it passes over a hot plume of magma in the mantle, 68 million years ago. Fissures hundreds of kilometers long open up, spewing fuming lava over an area 1200 km (750 mi) wide. Just as we have seen so many times in your life before, this expels vast quantities of CO_2, with profound effects on the global environment, [244] raising average global temperatures by around 5°C (9°F). [245] The eruptions continue over the next 3 million years, building up 1.3 million cubic kilometers (312,000 cubic miles) of lava to a height over 3 ½ km (2 mi) thick. That's like burying the states of Utah, Colorado, Arizona and New Mexico in fuming, molten rock, to a height of 8 stacked Empire State Buildings! Each individual eruption may have lasted a decade or more, sending fountains of fire high into the atmosphere. [244] The resulting rugged landscape in India is known today as the "Deccan Traps."



Temperatures cool a little before the next, most intense phase of eruptions starts just 2 days in your life (around 300 thousand years) before the dinosaurs are wiped out. [245] [246] This extra pulse of CO_2 sends global temperatures soaring another 7°C (13°F) and begins to kill off many species 150,000 years before the end of the dinosaurs. [245]

But the Indian eruptions aren't the kill-shot for the dinosaurs. [246]

… sideswipe…

An asteroid hits Boltysh in the Ukraine half an hour in your life (2,000 years) before their demise, [247] but even that isn't the fatal blow.

... head-on collision

The coup-de-grace comes in the form of a much larger asteroid that crosses the orbit of the Earth 66 million years ago.[248] At 10 km wide (6 mi) it's about the size of Manhattan, and much too large to burn up in the atmosphere. Travelling at cosmic speeds,[249] it barely registers the atmosphere before it vaporizes on contact with the Caribbean coast of Mexico.

The shock wave excavates a vast hole 200 km (120mi) wide in the limestone seabed,[246] generating earthquakes at least a thousand times stronger than the magnitude 9 Tōhuku earthquake that hit Japan in 2011.[246] An air-blast levels forests for

"hot fallout makes the sky across the world glow red-hot for an hour or two, enough to broil a good portion of land life" thousands of miles and a cataclysmic tsunami [246] sweeps across the Atlantic Ocean, engulfing all low-lying land, leaving it strewn with death and debris. The rebound from the shock wave ejects rock vapor and rubble at speeds faster than 11 km per second (7 miles per second) into space and the upper extremes of the atmosphere, where it spreads around the planet, raining hot cinders.

This hot fallout makes the sky across much of the world glow red-hot for an hour or two, enough to broil a good portion of land life and set light to dry vegetation, so wildfires rage across the planet. [246] [250]

Around 500 billion tonnes of sulfur is instantly sucked into the atmosphere, along with fine dust and soot. This causes acid rain which acidifies the ocean surface and inland waters. It also plunges the world into darkness, which quickly cools the planet surface by 10°C (18°F). [246] It stays cold for years. [246]

Already stressed by global warming, this is the final straw for many species.

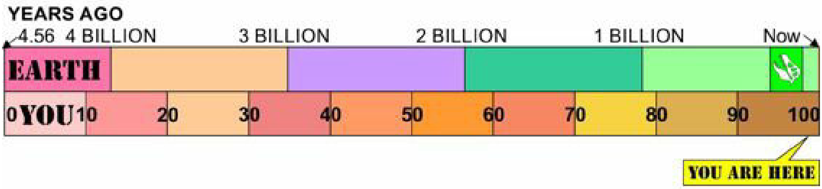
All the dinosaurs, all the marine reptiles (except turtles and crocodiles), and all the flying reptiles (pterosaurs) and 83% of snakes and lizard species die out. [251] The ammonites, belemnites and “rudist” mollusks vanish, along with nearly half of all invertebrate species. [49] 98 % of northern nanoplankton and 73% of southern nanoplankton species at the base of the marine food chain die out, [249] so marine creatures all the way up the food web starve. On land, forests choked by ash and darkness molder and decay as 60% of plant species go extinct. [246] [49] Most animals starve to death.

You are in intensive care for 2 ½ days of your life (300,000 years).

Creatures that can burrow (like some mammals) and those that live off detritus survive. As the dust settles and shafts of sunlight once more dapple the moldering ground, ferns take over the landscape [246] and life begins to renew itself. The ocean depths hold enough heat to be minimally affected by the cooling and they warm the planet up again in a few years, [246] but it still takes 300,000 years for marine ecosystems to recover. [249]

You slowly heal, but to this day you still have a scar from this wound at Chicxulub in the Yucatan peninsula of Mexico.

8. Hot Flashes



You hobble out of hospital on crutches into a strange new dinosaur-free world. The steady cooling trend of the Cretaceous has been completely reversed by the CO_2 released by the Deccan Traps eruptions in India, so the climate is hot and humid once more.

India is on a collision course with Asia, and already the seabed sediments in between are being crumpled into islands that begin to emerge from the sea. Australia and Papua are starting to separate from Antarctica, while the Rocky Mountains rise in North America. South America retains a narrow attachment to Antarctica, and Central America is still just an island chain, allowing the waters of the Pacific and the Atlantic Oceans to mix. [117] Much of Central Asia is a shallow sea connecting the Arctic Ocean to the Mediterranean and a waterlogged North Africa. Most of Europe is a tropical archipelago. [117]

Just 20,000 years after the impact, mammals begin to recover, [248] indeed some groups are remarkably unaffected. [239] Seizing their head start, they proliferate now that their erstwhile predators and competitors have been wiped out. Within 400,000 years of the impact the first mammal with a placenta in its womb – our ancestor – has evolved. It’s a small insect-eating, shrew-like thing. [252] By 5 million years after the impact, large flightless birds like *Diatryma* have already taken over the role of king hunters from the dinosaurs. Early anteaters, shrews and moles, and even the distant ancestor of elephants, have now evolved. [252]

As the world recovers, it cools, and as it cools it begins to lock away reserves of carbon in peat, permafrost, and methane hydrates. [253]

Atlantic fizz

The North Atlantic Ocean is tearing open as far as the Arctic, triggering a heated divorce of Europe from Greenland. As the tear develops, cracks rip deep into the crust all the way to the mantle, where they puncture a magma artery – a mantle plume – which will later fuel the volcanoes of Iceland. [254] Like blood rushing into an open wound, lava erupts into the tears, clotting as basalt over large areas including the Faroe Islands, Northern Ireland, western Scotland and offshore Norway, emitting large quantities of CO_2. The basalt landscapes of Northern Ireland and the Scottish Hebrides, including Giant's Causeway and Fingal's Cave, originate in these eruptions.

This is enough to turn the climate from cooling to warming again, and as it does so those reserves of carbon from peat, permafrost and methane hydrates are liberated back into the atmosphere to amplify the global warming. [253]

Now some more magma spreads, bruise-like, deep inside the North Atlantic marine sediments. More and more magma bleeds internally, swelling these subterranean abscesses to almost 100 meters (300 feet) thick, forcing its way through more than 85,000 square kilometers (33,000 square miles) of seabed near Norway. [255] [256] The heat bakes oil-rich Cretaceous sediments, generating thousands of billions of tonnes of carbon gasses, mostly methane. [257] 3 months before you turn 99 (56 million years ago), that gas bursts through the Atlantic sea bed, erupting from more than 700 craters, some as much as 12 km (7 mi) across [255] and the north Atlantic Ocean fizzes like soda.

Methane is 25 times more potent as a greenhouse gas than CO_2, [255] [258] [259] so the injection of thousands of billions of tonnes of it into the atmosphere can't help but trigger more global warming. The result is a pronounced warming of the climate, known as the "Paleocene-Eocene-Thermal-Maximum" or "PETM," that lasts about 170,000 years.

> "It is the biggest global warming event until the age of humans"

It is the biggest global warming event until the age of humans. Global average temperatures rise by 6 C (11°F) [260] and in what is now a familiar pattern of symptoms, oceans develop dead zones and global sea levels rise. [261] Oceans acidify and coral reefs decline. [260] Wet climates become monsoonal and dry areas get dryer. Wildfires are common [262] as rainfall becomes more seasonal, eroding the land and choking rivers with sediments. [260] Global ecosystems are profoundly affected as in some places 20% of land plants go extinct and plant diversity drops by more than a third, [263] and there is also a significant extinction of marine creatures. [255] Even though there is no vertebrate mass extinction, mammals respond to the environmental stress by getting smaller. [264]

Jungle planet - the first primates

You recover, cool a little, and adjust to a hot and humid world – on average 10°C (18°F) warmer than today.[265] Palm trees fringe the Arctic,[266] lowland Antarctica is warm and covered in near-tropical vegetation,[267] and London is a mangrove swamp[49] as rainforests spread across much of the planet.[268] But you experience repeated hot flashes called "hyperthermals" as you approach the last year of your life.[269]

These hot flashes are caused by variations in your orbit, which alter the intensity of sunlight at high latitudes, and are regularly paced at 100,000 year and 405,000 year cycles.[253] As these orbital cycles bring more high-latitude solar warmth, even more carbon is released from reserves in permafrost, peat, methane hydrates, and from the oceans, exacerbating global warming.[270] [269] [260] As your orbit cycles bring less intense sunlight at the poles, your climate cools a little, until the next warm cycle, over and over again. Your hot flashes are probably made worse by occasional CO_2 additions from ongoing North Atlantic volcanic activity.[271] [272]

The jungle planet spurs the evolution of new species. On the shores of India, early whale species like *Ambulocetus* – a 3 meter (9 foot) long, walking, furry, web-footed creature, adapted to underwater hearing[49] - show up. Primitive horses graze in the undergrowth: the tiny *Protohippus,* which is hardly 40 cm (15 in) tall, evolves into several versions of *Mesohippus*, a knee-high horse with toes rather than hooves.[49] Early versions of elephants and rabbits have appeared, while bats flit through the night air and dugongs nose along sandy sea beds. Multi-horned rhinos with tusks (*Uintatherium*), face off against hyena-like predators bigger than a modern lion (*Andrewsarchus*),[49] while small deer-like ruminants called *Leptomeryx* gingerly pick their way through the undergrowth - the ancestors of modern cows, deer and camels.

Many modern birds can now be found flitting through the rainforest canopy, including songbirds, parrots, swifts, and woodpeckers. [49] Flowers are becoming increasingly adapted to pollination by bees, while fruits and seeds are getting larger to tempt birds and mammals into spreading their seeds for them. [49]

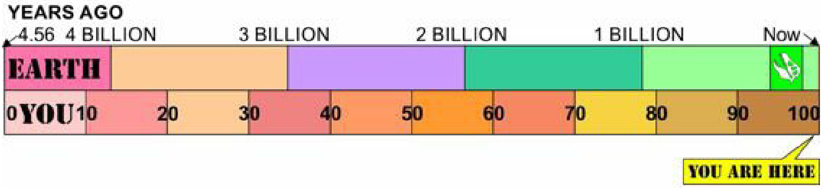
Crucially for us, the sultry forests provide ideal habitats for small tree-scampering mammals, and by 55 million years ago the first primates have evolved in Asia, including *Archicebus*, a mouse-sized, long-tailed insectivore, which is very closely related to our ancestor. [273]

Train wreck

1 month before you turn 99 (50 million years ago [274]) India finally crumples into southern Asia, but it doesn't just slide under Asia and disappear quietly into the mantle. Instead it rams into the larger continent, forcing great slabs of Asian rock to ride up and over the collision zone like carriages in a train wreck, squeezing millions of years' worth of sediments and bedrock into lofty peaks that we call the Himalayas. [275] The rising range of mountains is ravaged by erosion which, as we saw before, slowly depletes atmospheric CO_2. This process will intensify over the coming 20 million years (5 months of your life) and it continues to the present day. [276]

At around the same time there is a series of minor asteroid impacts, at Montagnais in Nova Scotia, and a double impact at Kamensk and Gusev in Russia[96] but these don't seem to have had much effect on biodiversity.

9. Your Last Year - A Chiller



You turn 99 in the middle of the muggy Eocene epoch. We'll pretend that your birthday is at midnight on New Year's Eve, so that we can count the months off towards your century. Anyway, happy birthday! You don't know it yet but it will be your last...

Central heating failure

As people age, we find it harder to regulate body temperature, and our average temperature progressively decreases. [277] The Earth has the same trouble.

Lush swamp forests, inhabited by turtles, alligators, primates, tapirs, and the hippo-like *Coryphodon*, now inhabit your Arctic shores. The Arctic Ocean is rain-drenched and almost land-locked, to the extent that it's practically a freshwater lake. These are perfect conditions for a kind of bright-green floating fern called *Azolla*, which practically chokes the ocean surface. Over about 800,000 years this *Azolla* bloom captures CO_2 from the atmosphere, locking it away in sediments as the ferns die and sink. [278] They are so prolific that they make a significant dent in global CO_2 levels, [279] which together with the cooling caused by the eroding Himalayas, cools the global climate enough for glaciers to advance on higher elevations of Antarctica a week before your 99th birthday (49 million years ago). [280]

Out of Asia

Africa's northward drift has brought it tantalizingly close to the archipelago of Europe, and to Asia through Arabia (which is still part of Africa). [281] The climate cooling causes sea levels to drop just enough to allow the first land connections between Asia and Africa since they broke apart in the Jurassic. [282] Many kinds of lizards and mammals emigrate from Asia to Africa, including mole rats, porcupines, and anthracotheres – a group related to hippos. [283] [284]

This is also the time when Africa imports primates from Asia – our distant ancestors. [283]

The fecund forests of Africa are now home to a diverse collection of new primates including tarsiers (big-eyed nocturnal tree climbers with long-fingered hands), *Parapithecus* (resembling a monkey) and *Oligopithecidae* (small insectivorous primates). [285]

But the days of the jungle planet are numbered.

Heating breakdown

It all starts when your central heating system fails…

Ever since you were 93 (in the Triassic), land bridges have connected Antarctica to South America and Australia.[117] These have blocked ocean currents, forcing north-south circulation of oceans, which carries tropical heat to polar areas, keeping them almost as warm as the tropics [286] in just the same way that a central heating system carries heat from a furnace to rooms in a house.

South America and Australia continue to drift north, placing unbearable strain on their connections with Antarctica. The world keeps cooling, and now seasonal ice rafts appear in the Arctic Ocean by the end of February (38 million years ago). [287] In early April (33.5 million years ago) the link between Tasmania and Antarctica is breached like a broken levee, spilling cold currents from the Indian Ocean into the Pacific, and precipitating a steep drop in global temperatures and atmospheric CO_2. [288] [289] Soon after, in early May (30 million years ago), the Drake Passage between South America and Antarctica finally breaks, opening the floodgates for South Pacific water to surge into the South Atlantic. [290] Antarctica is finally marooned in the Southern Ocean.

"Antarctica's isolation is like a breakdown of your heating system"

Antarctica's isolation is like a breakdown of your heating system, starting your fitful descent into an ice-house, caused by a "perfect storm" of tectonic and climactic coincidences. [287] [280]

First, chill gales blasting the Southern Ocean drive a new and powerful current that encircles Antarctica, isolating it from tropical warmth and plunging the southern continent into cold. [286] This new current, which persists today, is known as the "Antarctic Circumpolar Current" or "ACC," and it is the only current that extends from the surface all the way to the abyssal depths. [290] Being so deep and powerful, it is like a blender that mixes surface and deep waters, increasing the nutrient supply to plankton that consume CO_2. [291] Colder water also dissolves more atmospheric CO_2 than warmer water, [292] increasing the oceans' capacity to reduce atmospheric CO_2, further cooling the climate.

Second, the Tethys Ocean, which up to now had allowed Indian Ocean water to flow through the Mediterranean region into the Atlantic, closes as Arabia begins to bulldoze into Turkey and Iran. [281] This action reboots global ocean currents, enhancing the effect of the Antarctic current. It also closes off the large Central Asian Sea called the "Paratethys." Isolated, this stagnant sea now accumulates black, carbon-rich muds that will form Caspian Sea oil, to be extracted later by humans. [281]

Third, the Himalayas undergo intense uplift, [276] almost matched by powerful erosion and weathering that absorbs even more CO_2 from the atmosphere, [281] further cooling you.

Consequently, like a room in winter whose heater has broken, Antarctica begins to freeze. As the CO_2 levels drop, [288] the South Pole first develops isolated ice sheets at higher elevations, which coalesce into a large ice cap in early April (33.7 million years ago). [293] Antarctic forests recede and are replaced by mosses and ferns as the ice-free portions of Antarctica turn to tundra. [294] The first persistent glaciers develop on upland Greenland at the same time. [295] As more and more water gets locked up as ice, sea levels around the globe drop by 50 to 60 meters (160-200 feet). [296]

The fourth driver in this cooling trend is the ice itself. Like a shiny bald head, it reflects what little sunlight reaches the polar ground back into space, where previously rock and vegetation would have absorbed it and warmed up. This "albedo effect" exacerbates the cooling further, contributing to a feedback loop of cooling and CO_2 reduction.

The result is plunging global temperatures - average air temperatures in mid latitudes drop by 4-6°C (7-11°F), as do ocean temperatures. [297]

Seas of grass

It's hard to imagine a world without grass. Today grass dominates much of the world, from the lush lawns of England to the brassy stalks of the Serengeti, from the billowing prairies to the Pampas of South America, to the sea of grass on the Asian Steppes that gave Genghis Kahn his name.[298] Around 20% of the modern land surface is covered in grass [299] and the staples of human diet across the globe: corn (maize), wheat, barley, rice, sorghum, millet, rye and oats are all grasses.

Up to this point in Your Life as Planet Earth, grasses have been shy, retiring plants in forest clearings. [237] [299] But in the new colder and dryer [300] climate of unreliable rainfall, the rainforests recede. Clearings enlarge into patches of open grassland, growing ever larger as time passes and the climate dries further. [237]

In the new dry, lower-CO_2 environment, shallow-rooted grasses have a problem. To get the CO_2 they need for photosynthesis they must open up more pores in their leaves, because CO_2 levels in the air are lower. But more open pores mean more water-loss, risking desiccation and death. At this point some grasses invent new kind of photosynthesis that solves this problem. [301] Called "C_4 photosynthesis," it appears by the end of February in your 100th year (35 million years ago), [237] and is much more efficient in hot, sunny conditions than the older C_3 photosynthesis, and it also allows the new C_4 grasses to conserve water. [299] In other words, it's a great adaptation for sunbaked, dry grasslands.

Grasslands also bring with them a new kind of soil known as "mollisols," which have a deep organic rich layer – where CO_2 is buried. It's possible that the spread of C_4 grasses has a side effect of locking away even more CO_2.[302]

It takes a while, but C_4 grasses come to dominate increasingly arid grassland habitats while C_3 grasses remain prevalent in more temperate climates. Open grasslands had already appeared in South America in mid-February (around 40 million years ago), [237] and now they spread to North America, Asia and Africa and eventually Australia.[237] The new savannahs, prairies and chaparrals favor new creatures: giraffes, pigs, gazelles and goats all appear at this time. [49] Small horses like *Merychippus* roam the plains. [49] Elephantine creatures like *Deinotherium* (with tusks curving from its lower jaw) or *Gomphotherium* (with tusks on both jaws) compete with giant hornless rhinoceroses like *Paraceratherium* and *Teloceras*, or their miniature cousins *Menoceras*. [49] Feeding on these herbivores is the marsupial saber-toothed cat *Thylacosmilus*. [49]

But before you get used to this idyllic scene of grazers and grasses, the world changes – explosively!

Volcanoes and instant diamonds

On the spring equinox of your 100th year (35.7 million years ago) an asteroid collides with Earth at a place called Popigai in Russia, leaving a crater 100 km (62 mi) wide,[96] instantly transforming natural graphite in the rocks into diamonds! [303] Then, just 3 days in your life later (35.3 million years ago), [96] there is a double asteroid impact on the east coast of America at Chesapeake Bay[96] and offshore New Jersey. The Chesapeake Bay impact blasts a crater nearly twice the size of the state of Rhode Island, and nearly as deep as the Grand Canyon, sending a giant tsunami clear over the 3,500 foot high (1,000 meters) Blue Ridge Mountains.[304] [305] The crater affects the shape of the bay and the distribution of aquifers there to the present day.

April to June (around 33-23 million years ago) sees Africa pushing further into Europe and the Middle East, squashing the old Tethys marine sediments into Alpine and Pyrenees peaks.[306] But now Arabia starts to fracture from Africa. The split releases floods of basalt lava across Ethiopia and the Yemen around 30 million years ago.[307] By chance, unusually violent eruptions are burying a large area of Mexico in ash and lava at the same time.[272] Consequently the atmosphere sees a spike in CO_2[308] and a corresponding global warming by about 2°C.[309]

With CO_2 at roughly present day levels of around 400ppm (parts per million),[310] the Antarctic ice sheet is now very sensitive to such shifts in climate, and it partially thaws, leading to sea level rise.[308] Going forward, your climate is so finely balanced that variations in solar warmth caused by Earth's orbital wobbles trigger many large advances and retreats of the Antarctic ice, with corresponding large (around 20 meters or 66 feet) seesaws of global sea level every few tens of thousands of years.[311] [310]

The first apes

> “Like the slow unzipping of a dress, East Africa begins to part from the rest of the continent”

Like the slow unzipping of a dress, East Africa begins to part from the rest of the continent, and the Great Rift Valley develops progressively from Ethiopia into Kenya and into Tanzania, [312] and the eastern edge of the Congo, in June of your last year (25 million years ago). [313] The rift zone is buoyed up by hot mantle and rises thousands of feet in altitude, raising savannah to plateaus susceptible to the occasional night frost, altering the local climate to the present day. [313] This divides formerly continuous habitats and also puts the area east of the rift into a rain shadow.

As a result, apes (our ancestors) begin to evolve separately from monkeys,[314] and so we owe our ancestry to this geological marvel. The oldest ape is called *Rukwapithecus*[314] and it is soon joined by other ape species like the waist-high *Proconsul*.[315]

Yellowstone blow-torch

Meanwhile mountains are also rising at the western edges of the Americas, as the seabed of the ever-shrinking Pacific Ocean is consumed under them, melting into gassy magmas that fuel violent volcanoes. In Colorado, magma works its way through old flaws in the crust left by the welding together of ancient continents back in your youth, causing huge explosive eruptions that bury the surrounding land in volcanic ash.[316] One eruption alone in the San Juan area 28 million years ago sprays out 5,000 cubic kilometers (1,200 cubic miles) of ash.[317] The Mexican eruptions set off again around 24 million years ago,[272] and over time there are many such eruptions all around the Pacific, a situation that continues to modern times.

> "like a blow-torch that sears a trail of burn marks"

North America is drifting westwards at a rate of around 2 cm (1 inch) a year over the Pacific plates.[316] Deep in the Pacific mantle there is a plume of hot magma acting like a blow-torch that sears a trail of burn marks into the over-riding American crust, which sizzles as it passes over it, spurting out massive flows of basalt lava between August 21 and September 3 (16.6-15 million years ago). Hundreds of eruptions build up to over 4km (2 ½ mi) thick, covering much of Washington State, northern Oregon, and western Idaho in a few hundred thousand years.[318] This lava is known today as the "Columbia River Basalts"[316] and the mantle plume will later fuel the Yellowstone Supervolcano. But right now its heat melts bits of crust that had scraped off onto the underside of North America since the Cretaceous, releasing their trapped CO_2 to add to the CO_2 that would normally accompany such eruptions.[223] [319] [178]

The result – as you have experienced many times before – is a rise in atmospheric CO_2 (to levels similar to today's), and corresponding global warming by 2 to 4°C,[310] and the Antarctic ice sheet reduces to around 10 to 25% of its current size as sea levels rise roughly 50m (160ft).[308] [310] But in time, as all that fresh basalt weathers, along with ongoing weathering in all the active mountain ranges (the Rockies, Andes, Alps and Himalayas), i absorbs CO_2 from the atmosphere, so global temperatures drop markedly. Antarctica's ice cap stabilizes in early September (15 million years ago), Greenland's ice expands, and the Arctic Ocean develops perennial sea ice at around the same time. [295] As the ice caps expand, they lock in more and more water, and global sea levels drop again, by between 55 and 75m (180 to 250 feet). [310] [290]

The day the sea dries up

As India wedges itself ever further under Tibet, and Africa's advances to Europe continue, they force the Paratethys Sea to retreat further towards the modern shores of the Black and Caspian seas. Arabia continues its separation from Africa with the opening of the Red Sea, pushing its way into Iran which responds by throwing up the Zagros Mountains. [117]

Apes have now spread from Africa to Europe where we find *Dryopithecus*, and to Asia where we find *Sivapithecus* (the ancestor of orangutans). [320] But back in Africa we find apes like *Kenyapithecus*, whose teeth, face and elbow more closely resemble modern apes and our pre-human ancestors. [320] *Kenyapithecus* becomes very successful and spreads as far as Turkey, and it's possible that it is our ancestor. [320] [A]

Then in mid-October (10 million years ago) the Andes undergo rapid uplift of over 2 km (1.2mi or about half the height of the Rocky Mountains) in under 2 million years. [321] That's the geological equivalent of taking the rapid elevator, and provides yet more eroded rock to weather and cool the climate. At the same time weather patterns around India and East Africa change temporarily, turning dry African savanna into wet lakelands, as India's monsoon intensifies. [322] As ice sheets grow, global ocean currents switch over to the modern "conveyor" pattern at this time, changing the distribution of nutrients between the Pacific and Atlantic – an event known as "The Great Silica Switch." [323]

By November (7.3 million years ago) your climate has now cooled enough for most of Greenland to be covered in ice.[295]

Toumaï, Ardi and the dawn of humankind

Coincidentally, a new ape called *Sahelanthropus* (but nicknamed “Toumaï”) appears on the tranquil shores of a vast Saharan lake, in the 1st week of November (7 million years ago). What sets Toumaï apart is his more upright stance. And even though his brain is small (a chimp-like 370 cubic centimeters (cc), or 27% of modern human brain size), its shape is new. It has the distinct brain stem, occipital lobes, and prefrontal cortex that mark him out as our earliest upright-walking “hominin” ancestor. [324] [325] So Toumaï stands – literally – at the dawn of humankind.

“The screeches come from a troop of new upright-walking apes”

He is soon joined by another ape-like creature called “*Orrorin,*” who is also adapted to spending at least some time on 2 legs. [325]

By the middle of November (5.8 million years ago) the lush forests and river banks [326] of the Afar region in Ethiopia are echoing to a new call. The screeches come from a troop of new upright-walking apes [327] at the water’s edge, vigilant for predators, before they retreat into the branches of fig trees and palms as a herd of Kudu antelope approach. [327] Among them is your ancestor, “Ardi.” Ardi is a young mother standing about 4 feet (120cm) tall, with large hands and thumb-like big toes on her feet, and a brain larger than Toumaï’s at around 450cc. [49] She is an *Ardipithecus*, a group of primitive human ancestors that survive until about 4.3 million years ago (the end of November).

Costa Del Salt

In the continuing game of continental "Sardines," Morocco is now touching Spain at Gibraltar, constricting the connection between the Mediterranean and the Atlantic. A sharp cooling phase now triggers a drop in sea levels, leaving the Straits of Gibraltar high and dry on November 14 (5.96 million years ago). [328] [329] The land-locked Mediterranean Sea begins to evaporate, and over 360,000 years the level falls until it is two small seas separated by Italy, and it keeps on falling. Eventually it drops by 5 km (3 mi) (that's 3 times deeper than the Grand Canyon) depositing a 2.5 km (1.5 mi) thick layer of salt and gypsum on the sea bed. [330] In fact, so much salt and sediment is deposited so quickly that its weight depresses the crust of the Mediterranean into the mantle a little, sending a topographic bulge rippling outwards across Europe. [330]

While this is happening the polar latitudes end their latest glacial phase, [329] raising temperatures and rainfall around the world. As ice melts, so sea levels rise, and it may be that or the ongoing seismic jostling between Morocco and Spain, which releases the deluge.

It is a deluge on a colossal scale!

On November 19th of your life (5.33 million years ago) water bursts into the Mediterranean from the Atlantic Ocean through a 200 kilometer (124 mile) long channel. Like a fire hose, water cannons onto the desiccated saltpans at 100 million cubic meters every second (130 million cubic yards per second), with the power of a thousand Amazon rivers. [331] The Mediterranean Sea level rises as much as 10 meters a day for a year or two in real time, until the Atlantic and the Mediterranean are level once more. [331]

Of ice and man

North America reaches for the companionship of South America, coupling through the Isthmus of Panama around

November 23 (4.8 million years ago).[332] Their union blocks ocean currents from crossing between the equatorial Pacific and the Atlantic, rebooting deep water currents in the Pacific Ocean.[332] Consequently, eastern Pacific water temperatures cool substantially and so global temperatures drop another 1.5°C (3°F) over the next million years or so. [332] [333]

Lucy

Into this capricious climate a new creature is born in Africa, at the end of November (4.2 million years ago).[325] She is a human ancestor called *Australopithecus* but she goes by the easier nickname: "Lucy." [49] She is your great, great… (280,000 times) grandmother! She is more comfortable walking on 2 legs than Ardi was[334] [327]and has a brain capacity slightly larger than Ardi at 380-485cc, which is 28-36% of that of modern humans. [49] But she is still fairly ape-like, spending a good amount of time climbing in trees to avoid predators and gathering food. [335] Lucy is one of several different varieties of *Australopithecus* that spread across the continent of Africa during the next 2 million years, sometimes leaving their footprints in fresh-fallen volcanic ash[325] of the Great Rift Valley.

It isn't long before the environmental rug is pulled from under our *Australopithecus* ancestors. A small asteroid blasts an 18km (11mi) hole at El'gygytgyn in Siberia 3.6 million years ago, [96] [336] and you experience another warm period between December 2nd and 3rd (3.6 to 3.4 million years ago) whose cause is unclear.[337] [336] In this Pliocene epoch, summer Arctic temperatures are 8°C (14°F) warmer than today, and CO_2 levels are similar to today,[336] as rain-drenched forests fringe the Arctic Ocean again, and ice-averse mollusks live in Arctic waters. [295] But the ever-drifting continents still have some moves to pull. This time it's Australia that shoves its way towards China, bullying the Indonesian islands on its way. Between November 29 and December 7 (4 and 3 million years ago), the rearrangement of islands changes the ocean connection between the Pacific and the Indian Oceans, turning off a warm flow to the Indian Ocean and switching it over to a cold current from the Northern Pacific that still flows today. [338]

“average global temperatures fall below today’s around December 7 (3 million years ago)”

The change in heat distribution substantially cools higher latitudes, so ice begins its grip on the Arctic while Greenland’s ice cap expands and thickens. [339] Antarctica cools substantially and develops a skirt of sea-ice that lasts through the summer. [340] Cooling and mixing the deep ocean waters, along with erosion and weathering in the Himalayas, the Andes and elsewhere, draws down CO_2 further. [291] This sends you yo-yoing down a cooling trajectory [332] [339] [336] until average global temperatures fall below today’s around December 7 (3 million years ago). [341]

And you keep getting colder.

Ice age

Like a dose of the ‘flu, your temperature goes through the climate equivalent of a “bucking bronco.” [341] [339] You suffer at least 15 temperature swings just between December 2 and December 10 alone (3.6-2.6 million years ago). Then the fluctuations become even more extreme, with each cold swing colder than the last. [342] Ice now envelopes the northern latitudes of America, Europe and Asia, advancing and retreating with each climate swing. In the tropics, especially Africa, cold swings bring drought and warm swings bring rain.

The icy harmony of orbital wobbles

These climate swings have a regular pattern. Up to December 26 (700,000 years ago) the icy cycles are every 41,000 years punctuated by warm respites lasting from 500 to a few thousand years. [342] Some warm episodes, like the one 2.4 million years ago, result in substantial melting of the Greenland Ice Cap. [295]

“the harmonic combination of these orbital cycles drives the waxing-waning song of the ice ages”

These swings are mainly caused by Earth’s orbital wobbles. As our Earth circles the Sun, the orbit isn’t a perfect circle, so the planet is fractionally closer and further from the Sun at different times of the year. This “eccentricity” changes on a 100,000 year cycle. Also, the axis about which we spin giving us days and nights is on a slant (a hangover from the Moon-forming impact). But there is a slight wobble in that slant, called “obliquity,” which varies on a 41,000 year cycle. There is another orbital cycle called “precession,” which is the wobble of our rotation axis about every 22,000 years - like a toy spinning top tracing out ever-widening circles before it falls over. Just as a guitar chord is made from the combination of several different individual notes, so the harmonic combination of these orbital cycles drives the waxing-waning song of the ice ages.

The ice sheets spread and thicken during cold swings. The thicker they grow, the more their weight depresses the crust beneath them, like a boat loaded with cargo (this is called “isostacy”). The more the ice sheets thicken, the lower the crust sinks, and the colder the climate must remain to preserve them. Eventually, as your orbit brings more intense solar warmth to the northern hemisphere, it’s just not cold enough to sustain the low-altitude ice. So the ice sheets melt away rapidly, retreating to the far north in just a few thousand years, before the cycle begins all over again.[343]

But there is more to ice age cycles than orbital wobbles alone.[342] Cooling oceans absorb more CO_2 but this effect lags behind the orbit cycle by a thousand years or so,[344] and it is countered by changes in ocean salinity, sea levels, and reduction in vegetated land area.[344] There is also the albedo effect, where the increasing area of bright ice reflects more of the Sun's heat back into space, amplifying cooling (the shiny bald head analogy, like you experienced in the Permian).

Ocean currents such as the North Atlantic Conveyor System slow or shut down altogether during cold stages, changing the heat distribution around the globe,[342] while variations in sea level have knock-on effects themselves. When sea levels are low enough to turn the Bering Strait into a land bridge, the Arctic Ocean is cut off from the Pacific, but in warming cycles the two oceans reconnect. This is like throwing a switch in the heat-distribution pattern for the oceans, which may be responsible for the sudden, extreme flip-flops in climate known as "Dansgaard-Oeschger" and "Heinrich" events.[345]

Volcanic eruptions disrupt the cycles with random timing. Large eruptions of ash and sulfur create a temporary cooling by screening out solar radiation, a much shorter-term effect than warming from their CO_2 output.[342]

So the climate cycles are not at all like a classical guitar chord of clean orbital notes. Rather they are noisy and distorted, more like a Jimi Hendrix electric guitar chord.

Drought and tsunami

As ice sheets spread across North America, Europe and Asia, they pick up billions of rocks and boulders to grind the land under them. Each summer retreating ice exposes the fine dust produced by this grinding, and wind whips it into dust storms, depositing it in thick "loess" deposits in Asia. In fact there's 100 times more dust in the air at this time than in the modern era. [346]

As temperatures fall so does the humidity of the atmosphere, so tropical monsoons weaken and conditions become ever more arid. Even C_4 grasses can't cope, so tropical grasslands now give up territory to arid scrubland and then desert. [347] Large swathes of mid-latitude land alternate between arid steppes in cold cycles and temperate forest in warmer interglacials. [348] Global sea levels fall with each ice age, exposing continental shelves and providing land bridges between former islands, reconnecting Arabia and Africa, and across the Bering Strait between Asia and North America. There is no English Channel, and the Thames and Rhine rivers join in a single estuary in the North Sea. [49] With each interglacial, sea levels rise, monsoon rains return to the Sahara, turning desert into pasture, and filling lakes and numerous rivers that wind their way across the Sahara to the Mediterranean. [349]

Out of the blue you are slammed by another asteroid, which hits in the southeastern corner of the Pacific Ocean 2.51 million years ago. Known as the "Eltanin Impact," it vaporizes water and rock into the atmosphere, and sends a giant tsunami throughout the Pacific and the south Atlantic where it devastates coastal land and buries it in meters of debris. And it may be the ocean salt and rock dust from the impact, spreading through the high atmosphere, which amplifies an already cold climate into a powerful ice age. [350]

Large animals can conserve body heat more easily than smaller animals, so giant mammals begin to dominate. 5 meter high (16 feet) wooly mammoths evolve, bearing huge tusks to clear snow from the ground so that they can eat. [49] In South America giant ground sloths as big as an elephant and brandishing claws as long as a man's arm fight off packs of saber-toothed tigers. [49] Woolly rhinos and herds of modern-sized horses vie with giant elk for grazing. [49]

Yellowstone

All this time North America has continued to creep westwards over the blowtorch-like mantle plume that caused the eruption of the Columbia River Basalts back in August. It has burned an 800 kilometer (500 mile) chain of volcanoes that stretches from northern Nevada all the way to Yellowstone in Wyoming, [316] where it now it creates havoc.

On December 15 of Your Life as Planet Earth (2.1 million years ago) the Yellowstone Supervolcano explodes with titanic force, depositing a blanket of volcanic ash over more than half of the present United States. [351] The eruption sprays so much molten rock into the air that the roof of its magma chamber collapses, creating a caldera 100 km (60 mi) wide. It will do it again on a slightly smaller scale on December 21 (1.3 million years ago), and again on December 26 (640,000 years ago). That last eruption again covers about half of the United States in ash. [351] Shortly after that, an eruption at Long Valley in California blankets about a third of the United States with ash on December 26 (630,000 years ago), [351] and eruptions like these occur sporadically all around the Pacific.

But we are getting ahead of ourselves.

Becoming human

Your see-sawing temperature means the environment is constantly changing. In East Africa woodland gives way to savannah, then returns to woodland in pace with the climate cycles, placing great environmental stress on our ancestors. This winnows the fittest and most adaptable from the rest, forcing their rapid evolution. [352]

The first stone tools

> "it starts humankind's obsession with technology"

During the reign of Lucy and her *Australopithecus* relatives, someone invents simple stone tools. [353] It's not clear exactly which species is responsible, but it starts humankind's obsession with technology. It is now around December 15 (1.98 million years ago), and *Australopithecus* has evolved a more human creature, called *Australopithecus sediba*. Sediba walks upright on arched feet like modern humans, [354] and her hands, pelvis and feet are more human-like than Lucy's. Her hands are even dexterous enough to fashion tools, [355] and her brain, though still about the same size as earlier *Australopithecus* varieties, is shaped like a human brain. [356] Her brain is different because a crucial gene for brain development called "SRGAP2" has recently undergone its second big mutation (around time the first tools were invented) resulting in an extra copy of the gene, which we have inherited to this day. [357]

She coexists with a variety of other early humans spread across Africa. *Paranthropus* has evolved from *Australopithecus* into thickset creatures with powerful jaws and thick teeth for chewing grasses in the savanna.[358] Their brains are around 30-41%[49] of modern human brains but they don't appear to make tools. But Sediba is soon eclipsed by her descendants.

The first cook

December 16 (1.8 million years ago) unveils a tall, slender East African human, similar in height, gait and stature to you and me. *Homo erectus'* physique is adapted to hot, dry conditions, and he can run and walk as effectively as modern humans.[325] [49] *Homo erectus* is such a diverse group that several varieties look almost like different species - *ergaster, habilis, rudolfensis, antecessor* and another as-yet-unnamed creature currently labeled "KNM-ER 1802."[359] His brain enlarges from 44-67% to 95% of ours[49] in the first few hundred thousand years. His face is distinctly human with a pointed nose, but he has a low forehead and a massive monobrow, and lacks a chin.[325]

What sets *erectus* apart from his ancestors is how smart he is. He soon learns to make fire and use it for cooking, which provides the nutrition to support his enlarging brain.[360] [361] He also makes a variety of sophisticated "Acheulean" stone tools, sometimes in dedicated factories,[362] and he can throw, enabling him to kill from a safer distance.[363]

Armed with tools, hunting and defending by throwing, nourished by cooked food and supported by cooperative social skills (possibly including some form of language),[364] *erectus* wins out against large carnivores in Africa for carrion and prey. As *erectus* takes over at the top of the food chain, dethroned carnivores like the "bear-otter" go extinct.[365] He now begins to travel the world, spreading out of Africa into Europe and Asia, reaching as far as China and Indonesia,[366] [325] even as his *Paranthropus* cousins begin to die out.

Christmas in England

Early humans – probably a variety of *erectus* - have now arrived in East Anglia, England, just in time for Christmas (between 970,000 and 814,000 years ago).[366] They are camping on a grassy plain by the Thames estuary (which is in Norfolk at this time), leaving footprints in estuarine muds and fending off the occasional hyena.[366] [367] As they chip flints into tools near a conifer forest, they are surrounded by horses and antelope. An icy wind blows off the North Sea from the advancing ice sheet a few days' walk away, signaling the onset of another cold phase.[366] They will leave England soon, and their descendants will return when the ice recedes again on Boxing Day (700,000 years ago).[366]

14 **The first cook: *Homo erectus*** (by Cicero Moraes - via Wikimedia Commons)

By now the climate has cooled so much that ice sheets no longer melt away in the warm parts of the 41,000 year cycle, so they now last for entire 100,000 year orbital cycles (now responding more to orbital eccentricity than orbital obliquity). [342] [295] Also, the scouring effect of the ice has cleared away all the loose sediment beneath it, so the ice changes from a flattish quick-responding sheet to a high plateau of persistent thick ice, welded to bedrock. [295]

It's also around this time that another mutation in the genetic code for human brains occurs, creating yet another copy of the SRGAP2 gene.[357] This may be a crucial factor in the gradual emergence of humans with brains about the size of our own brains.[325] Known as *Homo heidelbergensis,* they make their way all across Africa and into Europe between December 27 and 29 (600,000 to 250,000 years ago). They are archaic versions of ourselves, and they look like us except they have a low forehead and large eyebrow ridges, and lack a chin. These people also behave like us in many ways, efficiently using fire[368] and hunting with spears, some with stone tips that they hafted onto wooden shafts,[369] and others that they have whittled to a sharp point and then hardened with fire. They are also creating and using a range of sophisticated stone tools,[49] and have language.[364]

heidelbergensis is one of several regional varieties of human spread across Africa, Europe and Asia. As *heidelbergensis* emerges into Europe and Africa, tribes of *erectus* are now evolving in Asia. Some spread from Southeast Asia to Siberia, eventually becoming "Denisovans."[370] Others become isolated on an island in Indonesia, where limited resources drive them to evolve into the miniature *floresiensis,*[325] nicknamed "The Hobbit."

Each time the ice advances, it isolates human and animal populations in refuges like Spain, Italy, and the Balkans where they begin to evolve in response to local conditions, differentiating from the original population.[371] Brown bears, bison, musk ox and even hedgehogs also undergo differentiation at this time.[371]

Man

Our species, *Homo sapiens,* gradually emerges in Africa around December 29 (around 208,000 years ago).[325] [372] They are your great, great... (13,000 times) grandparents!

> “We seem to be the product of the continuing extreme climate fluctuations.”

We seem to be the product of the continuing extreme climate fluctuations. Soon after our lineage appears, the world is gripped by an extremely cold and hyper-arid phase known as MIS6. [373] A terrible drought grips Africa at this time: lakes and rivers dry up, and the parched savanna swirls with dust devils. [374] Desiccated corpses and bleached bones are all that remain of the herds of antelope and gazelle. Our ancestors survive by their wits and migrate to isolated refuges, [375] such as the caves at Mossel Bay in South Africa, where they survive on shellfish and fynbos plants. [373] [374]

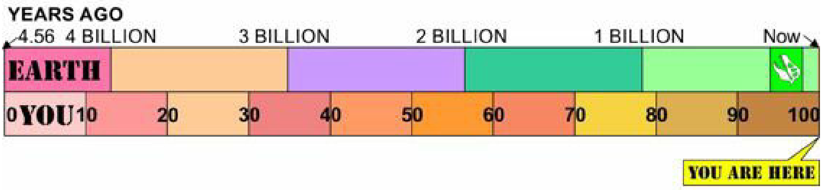
To start with, these humans look more like *heidelbergensis*, [325] but over time they come to look like the modern humans of today. They use fire not just for warmth and cooking, but they have also figured out how to heat-treat stone to improve their tools, [376] resulting in advanced stone tools like “bladelets.” [373] They hurl spears rather than just stabbing with them, making them much more effective hunters. [377] They also have a rich culture, using ochre pigment for painting. They clearly have the “smarts” for technological and cultural innovation, cooperation and communication skills - language - to teach them to others.

Around the same time, European *heidelbergensis* develop into the muscular, thick-boned and big-eyed Neandertals. [325] [378] Neandertal anatomy makes sense for a cold-adapted people that range the fringes of the ice sheets. Far from being the brutes of popular culture, they are people with brains actually larger than mine (and maybe even yours) at 1412cc or 105% of modern humans.’ [49] They probably speak a language, [364] [49] and they have a culture which has a special regard for black bird feathers and eagle claws. [379] From an initially small population, [325] they spread across Europe, North Africa, [380] the Middle East, and as far as western Asia, hunting in the fluctuating forests that fringe the ice sheets and glaciers, and living in large huts constructed from mammoth bones. [381]

Our ancestors eke out an existence in their separate refuges, evolving independently, until the climate begins to improve roughly 140,000 years ago. [382] When the hyper-arid MIS6 period is over, the rains return to Africa they bring with them the herds of game and mankind can multiply and wander through Africa once again. Monsoon rains refill Saharan lakes and rivers, tempting game and humans alike towards the Mediterranean. [349]

And yet there is a “sucker punch.” A new colony around the oasis at Dakhleh in Egypt is decimated by a meteorite impact on December 30 (around 145,000 thousand years ago). The blast snaps trees for thousands of miles, injuring and killing people and animals alike, while molten ejecta sets wildfires across the area. [383] Fortunately the damage is local to Egypt, and humans keep spreading.

10. Your 100th Birthday!



You start your birthday – your last day - on an optimistic note.

At midnight (126,000 years ago) you begin to feel the lovely warmth of an interglacial called the "Eemian," with Arctic temperatures rising to 8°C [384] warmer than in the mid-20th century, but globally it will only reach about 1°C warmer than modern times. [295] It's warm because our orbit is delivering about 11% more solar radiation to the Arctic than the present day. [295] Sea levels will soon rise up to 9 meters (30 feet) higher than modern times, as a result of a drastic reduction of ice sheets in Greenland and Antarctica. [384] [385]

> "they find the waters have been miraculously and biblically parted due to low sea levels"

But before the sea levels rise, our ancestors are already on the move. Arriving at the southern tip of the Red Sea, they find the waters have been miraculously and biblically parted due to low sea levels. They cross into Arabia by around 125,000 years ago [386] and fan out, wandering the wilderness until they reach the Straits of Hormuz. They gaze down from the Omani heights at a river (the Persian Gulf is all but empty due to low sea levels) in search of a ford. From there they move into Iran and further into Asia, [386] [387] where they encounter vestigial bands of *Homo erectus* and Denisovans.

Further waves of human tribes emerge from Africa through the eastern Mediterranean, encountering Neandertals in the process. Some of us take a fancy to the Neandertals (or the other way around) and there is some interbreeding, to the extent that modern Europeans, North Africans [380] and Asians are genetically about 2% Neandertal, [388] whereas Africans south of the Sahara are mostly pure *sapiens*. [389] Those of us with Neandertal genes inherit their genes for hair, skin, and enhanced risk of various diseases like lupus and Chron's disease. [388] The offspring of these unions are also less fertile than purebred sapiens. [388]

As we spread into Asia we colonize new areas and mix with the local populations, including Denisovans. Some close encounters are of the sexual kind, with the result that Melanesians, Polynesians and Australian Aboriginals[390] have inherited up to 5% of their DNA from Denisovans.[391] Still later populations emerge from Africa and spread and breed, masking the genetics of earlier interbreeding.

But you're already plunging into another icy chill that will last all day. Occasionally, warmer ocean currents from the tropics eat away at northern sea ice until a large area collapses. [392] This generates a warm flash (known as a "Dansgaard-Oeschger Event") that comes on suddenly (in just decades in real time), warming the North by 9-15°C (16-27°F), but barely affecting the South. Within 30 minutes (3,000 years) the sea ice regrows and you are back to numbing cold in higher latitudes, and drastic drought in the tropics. This happens at least 25 times on your birthday alone! [342]

Change forces innovation. It drives our ancestors to develop new technology, craftsmanship and adornments in fits and starts, coinciding with periods of increased rainfall that accompany each warm swing in the global climate. [393]

The Asian front of our exodus receives a small setback when the Toba supervolcano in the island of Sumatra explodes around 9:55 AM on your birthday (73,880 years ago). [394] The eruption is extremely explosive, and it hurls immense quantities of ash and sulfur into the upper atmosphere to circle the globe.

Ash blankets a 6,500km (4,000mi) wide area that extends from Arabia to China and the southern Indian Ocean, covering India in ash 15 cm (6 in) thick. Amazingly it has very little effect on our ancestors, who quickly return to the affected areas. [395]

World tour

We humans continue our peripatetic habits, multiplying and expanding our range. At 2 PM, as an asteroid blasts the Barringer Meteor Crater in Arizona[96] (49,000 years ago), we have already reached Australia. [396] Even in these times of low sea level this requires crossing about 70 km (40 mi) of open ocean on some kind of raft or boat, and it's therefore no surprise that fishermen are soon harvesting tuna and other fish from the deep ocean by 42,000 years ago. [397]

By 3:30 PM (45,000 years ago),[398] taking advantage of a temporary respite from the extreme cold and aridity, we have spread through the Middle East and Europe as far as England,[399] and through Asia to southeast Asia. [400] By 4 PM (40,000 years ago) some of us have made it to China. [401]

> "As we go, either by genocide or by competition, *Homo sapiens* eliminates all other claims to the *Homo* throne"

Along the way we adopt man's best friend – domesticated dogs - by 33,000 years ago,[402] and by 20,000 years ago in China, some of us have moved from heat-treating stone tools to heat-treating clay. This is the invention of pottery (a.k.a. China) and we're already cooking food in those pots. [403] [404] By around 17,000 years ago we are angling using fish hooks made from shell.[397]

Fratricide

As we go, either by genocide or by technical superiority or by sheer superior numbers, *Homo sapiens* gradually eliminates all other claims to the *Homo* throne. At tea-time on your birthday when you are snuffing the solitary candle that represents your 100 years, the last of the Neandertals finally dies out (around 40,000 years ago), some 2,500 to 5,000 years after our arrival in Europe. [398] The Denisovans, the Hobbit-like *floresiensis* people, and a mysterious Chinese group known only as the "Red Deer Cave People" also disappear. [405]

Your long goodnight

It is now 8:30 PM (18,000 years ago) and you are as cold as you have ever been. You have a thick ice sheet all across North America, from New Jersey and Long Island in the east, as far as Washington State in the west. [342] Ice has also overrun Greenland, Iceland, most of Britain, Scandinavia, northern Europe and Russia. Neandertals have long since died out but the rest of our ancestors are doing OK.

By 8:45PM (17,000 years ago), as your orbit brings you warmer northern summers, there is the first hint of a thaw. Melt water pools behind lobes of receding ice sheet in western Montana [406] and builds to a vast lake called Glacial Lake Missoula, covering 7800 square kilometers (3,000 square miles) to a depth of 610 meters (2,000 feet). [406] As warming continues, the ice dam weakens until it ruptures, sending a wall of water 240 meters (800 feet) high surging across western Idaho and eastern Washington state, travelling at 85 kph (50 mph), ripping away the ground in its path to the Pacific Ocean, leaving a wide, barren landscape of "scablands" in its wake. [406] Amazingly this is just the latest of many similar catastrophes during the ice ages. [406]

Ice has now receded enough from the Aleutian Arc [407] to expose a land connection between eastern Siberia and Alaska, and by 9PM (15,000 years ago) some of us have already spread across both American continents. [49]

> “Wherever we go, animals begin to disappear”

Wherever we go, animals begin to disappear. Not long after we arrive in Australia we hunt the giant kangaroo, a 2-tonne wombat and other large animals into extinction, causing a permanent change in vegetation patterns and promoting wildfires. [396] [408] [409] Before we arrive, the Americas are crammed with large herbivores like mammoths, camels and giant ground sloths, but within about 1,000 years of our arrival, 80% of the large-bodied mammals are extinct. [410] Over the planet as a whole, our arrival coincides with the extinction of ⅔ of mammal genera and ½ of large animal species. [411] Some of the stress on these creatures may be due to climate change, but we are the main culprits. [411]

By 9:15 PM (14,000 years ago) the thaw turns to lasting warmth and the ice continues to retreat all across the world. As it departs it abandons its rocky luggage as piles of sand and boulders that mark its furthest extent, creating Long Island in

New York, [412] and stranding improbably large boulders on hilltops across the hinterland as they settle through melting ice. Global sea levels are rising fast – by as much as 5m (16ft) per century for a while, then slowing to 40cm (16in) a century. [258] [413] They will eventually rise by over 120m (400ft) from their lowest levels in the ice age.

Inventing agriculture

By 9:30 PM (about 13,000 years ago) humans take control of their food supply by turning to agriculture, and they begin to settle in villages. [414]

But just as you are starting to get comfortable, something tips you back into ice - at 9:33 PM (12,890 years ago). [415] [416] It's possibly an asteroid impact that hits somewhere in Quebec, Canada, spraying platinum-rich ejecta across Europe and the Americas, and into the upper atmosphere, darkening the Sun and returning you to an ice age climate for another 1,200 years ("The Younger Dryas cold period"). [415] [417] [416] [418]

The end

The cold snap is relatively short-lived, and at 9:45 PM (11,700 years ago) you feel another hot flash come on... and this time you stay warm - the ice age is over!

But you don't feel much like celebrating. You feel the end approaching.

Temperatures around the world rise until around 10,000 years ago, when they level off creating a stable and benign climate, cooling slowly, that lasts until the modern era. [419]

By 10:15 (9,000 years ago) Middle Eastern people are making pottery.

In the continuing thaw, melt water has pooled between the dwindling ice cap in northern Canada and the Great Lakes o North America. Called "Lake Agassiz," it now covers a large swathe of Canada in up to 250m (820ft) of water. At 10:24 PM (8,330 years ago) the last of the ice in Hudson Bay collapses, sending the icy waters of Lake Agassiz and an armada of icebergs flooding through the Hudson Strait into the North Atlantic chilling ocean temperatures, and cooling the climate in Europe and America for 3 or 4 centuries. [420]

And it may be this that prompts Middle Eastern people tc invent irrigation and cheese making by 10:30PM (8,000 years ago). [421] [414] 10:50PM (6,000 years ago) sees the adoption of metal tools to replace the stone tools used over the previous 4 million years. [414] At around this time the Egyptian civilization begins.

...one hour to go...

Age of empires

At 11PM (3,400BC) the Mesopotamians invent writing a the earliest city-states take hold on the shores of the Persian Gulf. [414] Soon after, the Brits begin construction of Stonehenge (3,100BC) and then Egypt goes on a pyramid binge, constructing the Great Pyramid at Giza and the Sphinx around 11:06 PM (2,560BC). [422] Not to be outdone, Sargon of Akkad begins the world's first empire in Mesopotamia at 11:10PM (2334BC)[414] around the same time as some Indians colonize Australia, bringing dingoes and new technology. [423] At 11:30 PM Cyrus the Great of Persia creates an empire 50% larger than the Roman Empire, gives the world its first bill of rights and a "Suez" canal. [414] Then at 11:33PM Alexander the Great defeats the Persians in 331BC. [414]

11:36PM- Julius Caesar is appointed dictator of Rome (44BC) ... 11:37 - the birth of Jesus... 11:44 - The birth of Mohammed (570 AD)... 11:49 - Leif Ericson discovers America in the year 1003... 11:54 - Columbus discovers America again in 1492... Between 11:54

and 11:58 Europe goes through a “Little Ice Age” in the 14^{th} to 19^{th} centuries caused by a colossal eruption of the Samalas volcano in Indonesia [424] [425]... 11:58 - The Wright Brothers make the first powered flight in 1903 and in 1908 a meteorite explodes over Tunguska, Siberia, flattening over 2,000 square kilometers of forest and showering the ground in iron and diamond dust.[426]

...1 minute (70 heartbeats) to go...

55 heartbeats – the end of World War 2... 39 heartbeats - The Beatles arrive in America... 35 heartbeats – the first human on the Moon... 8 heartbeats – terrorists attack the US on 9/11...

Your life has flashed before your eyes, and you are barely aware of your last breath leaving your body...

11. Bottom Line

Your planet is very, very old.

Measured in the life span of a centenarian, simple life emerges in your teens. You are well into your mid-life crisis before life starts polluting the planet with oxygen. You are in your late 70s before primitive plants and fungi begin to colonize land. You are 86 before complex animals show up, 88 by the time worms alter ocean chemistry and the seashell is invented, and 90 when fish evolve jaws and live birth. In your 90s 4-legged life evolves from fish, and then dinosaurs, mammals, birds and flowering plants (including grasses) emerge. The dinosaurs are extinguished when you are 98, leaving the field clear for mammals and birds. Primates evolve in your last year of life, and in your last month primitive pre-humans appear. Early humans spread from Africa to Europe and Asia by Christmas in your last year, and then modern man evolves 2 days before you turn 100 and spreads across the globe only during your last day.

Through all this, the planet shaped life, life shaped the planet, and cosmic events shaped both.

Cosmic events shaped the Earth. The Moon-forming impact changed our atmosphere and the core, which generates the magnetic force-field that protects us from so much harmful solar radiation. The Moon's tides stir the oceans, and the off-balance tilt of our planet gives us seasons and orbital cycles of warmth and cold that even drove the evolution of humans. Comets and asteroids have pelted us from the dawn of time, sometimes bringing life-enabling chemicals, sometimes devastation.

Geologic events shaped life. Shifting tectonic plates gave us CO_2-producing volcanoes, mountains that erode and trap CO_2 in the process, and ocean depths where old crust and carbon is consumed for recycling in more eruptions. Shifting continents at times allowed the global spread of creatures like dinosaurs and mammals, and at times marooned life to evolve independently, like the kangaroo and apes. It reconfigured ocean currents that changed global climate, tipping the planet into the ice ages that gripped the world over the last 3 million years, driving the evolution of man. Even life itself seems to have started as a rock-life hybrid in magma-powered underwater springs.

Life shaped the Earth. From the beginning, life started to mold the Earth in its own image as "stromatolites." Sunlight-harvesting germs gave the world oxygen that caused the world to freeze, but they also made oxygenated minerals and ores, and saved our oceans. Life colonizing land changed weathering, the carbon balance, and climate. It generated more oxygen to support bigger animals that grew legs to walk on the green land. New plants that grew tall on the strength of wood became coal, while algae died to give us oil.

Rare, copious volcanic outpourings called "Large Igneous Provinces" punctuated evolution by producing global warming, ocean acidification, and oxygen-starved seas. They induced these climate changes by emitting vast quantities of CO_2 and Methane faster than the planet could safely absorb it, with devastating consequences for life at those times.

Now we live in a new geological epoch - the "Anthropocene."[427] Humans are just as much of an innovation to the Earth-climate-life system as the cyanobacteria that gave the world oxygen, or the worms that churned up the Cambrian sea bed and changed ocean chemistry. We are generating CO_2 at rates and quantities to rival those Large Igneous Provinces, dwarfing the CO_2 produced by volcanoes in recent millennia.[428] We can't expect the balance between climate, life and Earth to remain inert to this human-induced change. Rather, we *can* expect it to behave as it has done so many times before.

Part 2: Techniques of time travel

When you think about it, it is an act of breathtaking audacity to plot the story of Earth deep into the past, before history, before people, even before life. Yet it is the same intrepidly inquisitive instinct that put man on the Moon, sailed the unexplored oceans, or invented the airplane. The force that drove our ancestors to replace stone tools with metal ones, or to take control of their food supply by farming, is the same self-improving force that drives scientific inquiry. It is as human as our DNA.

"Your Life as Planet Earth" is a story revealed by some amazingly smart deductions from evidence gleaned through all branches of science, across all scales of observation from the microscopic to the cosmic. It is not fiction, and neither is it an embroidered creation over a thin armature of evidence. Every fact is backed by scientific evidence referenced to its source, and most of those sources are from respected scientific journals that employ a peer-review checking process before they publish the information to the world.

Some of that evidence is strong, some is more controversial. The deeper recesses of Earth's history – the first 2 billion years or so – are fraught with difficulty, for instance. Of course, to describe every piece of evidence and to flesh-out every argument would take as much space as a large university library, so I have focused on a few key areas of evidence: cosmic origins, a dynamic planet, evolution of life, clocking time, and sampling ancient climates.

New research is performed all the time, so fresh insights are likely, and some conclusions are bound to be proven wrong at some point. That's an essential aspect of science – its conclusions can be tested and either confirmed or disproved. Yet the basic skeleton of facts tends to remain over time, being fleshed-out and brought into ever-sharper focus with each new research result, even if the finer details change.

1. Origin

What souvenirs remain of the dark beginning of our Solar System?

The oldest Earth-formed specks (zircon crystals from Jack Hills, Australia) are too young - only 4.4 billion years old – as are the oldest complete rocks at 4.2 billion years old. That leaves the first 400 million years (or your first 8 years of Your Life as Planet Earth) without Earth-rock evidence. Fortunately, we do have rocks older than that. We have space rocks – meteorites and lunar samples - and they tell us a great deal about the origin of the Solar System and the Earth.

Cosmic sediments

Dating the birth of the Solar System

The date for the birth of the Solar System is measured from a kind of mottled meteorite called a "CI chondrite" and on basalt-like meteorites called "angrites." Chondrites are essentially cosmic sediments[6] composed of grains and sooty specks that clumped together in space at the birth of the Solar System. The proportions of chemical elements in CI chondrites closely match the proportions in our Sun[6] so they are thought to represent the primitive composition of our Solar System as a whole. They also contain a kind of granule called a CAI (calcium-aluminum-rich inclusion) which, due to their chemistry and high melting point, were probably the first minerals to condense from the solar nebula. The age of CAIs is therefore taken as the *de facto* age of our Solar System, and they, together with angrite meteorites, yield dates of 4.5682 billion years give or take 400,000 years.[429] [6]

Planet formation – from Enlightenment to Space Age

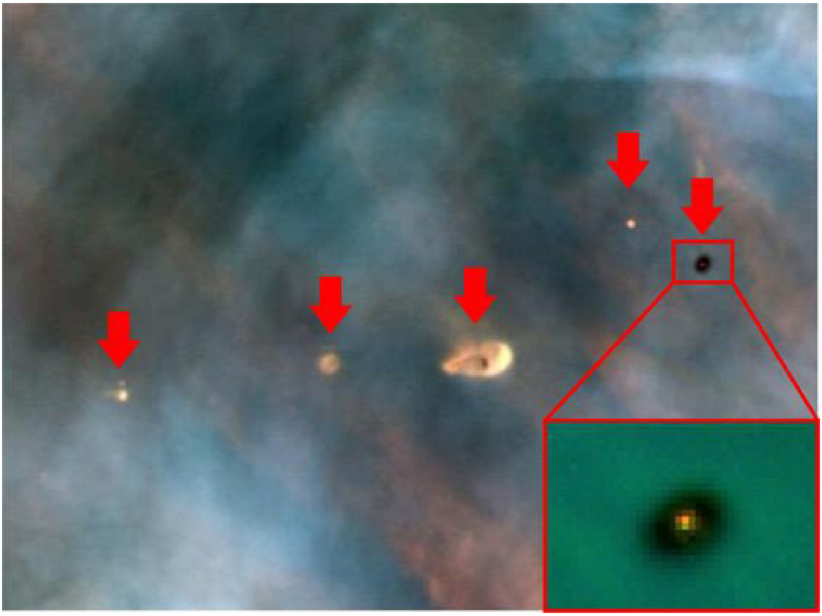
Any plausible explanation of the formation of our Solar System must be consistent with some present-day observable facts: (1) the planets contain most of the 'angular momentum' (rotating force) in the Solar System, (2) all the planets orbit the Sun in the same plane, which is also the Sun's equator, and (3) most planets rotate in the same direction, and most have their equator parallel to the Sun's. [6]

The "Nebular Hypothesis" for the formation of our Solar System actually predates the space-age by a long way. Originally suggested by the German Enlightenment-era philosopher Immanuel Kant in 1755, then refined by Laplace in 1796, [6] it has since been refined by space-age scrutiny. Telescopes like the Hubble, Spitzer and Herschel Space Telescopes have revealed "stellar nurseries" in huge clouds of gas and dust (nebulae), with thousands of young suns burning within them. In some, like the Orion and Trifid Nebulae, astronomers have photographed young stars at their earliest stage of formation, in the center of disks of dust, just like that inferred for our early Solar System. [430] [431] The light emitted by these disks reveals their composition of water ice, silicate rock, methanol and carbon dioxide, [432] similar to our own Solar System.

> "Earth must have been like Vesta in its infancy"

NASA's space probe visit to the asteroid "Vesta" backs this up. The spacecraft measurements matched Vesta with meteorites found on Earth, and revealed it to be an embryonic planet formed from chondrite meteorites, preserved today as it was in the early days of the Solar System.[433] Earth must have been like Vesta in its infancy.

The laws of physics (specifically the 'conservation of angular momentum') dictate that as these discs of dust are drawn inwards towards their embryonic stars by gravity, the contracting mass is forced to spin faster (just the way an ice skater spins faster as they contract their arms) and so the particles collectively flatten into to a disk[6] rather than a sphere or any other shape. In this way planets form in the same plane as the Sun's equator, spinning the same direction as the sun.



15 Embryonic solar systems: Hubble Space Telescope image of the Orion Nebula showing 5 young stars surrounded by gas and dust disks that may go on to

develop planets. Inset: close-up of a young star under a million years old within a protoplanetary disk about 7 times larger than our solar system. Credit: C.R. O'Dell/ Rice University; NASA

Moon formation

The "Giant Impact Hypothesis" is one of several ideas that have been put forward to explain our Moon, but it matches the evidence best and a broad consensus of scientists accepts it. [6] The evidence for the Giant Impact comes from the chemical composition of the Moon and Earth, their physical structure, and the constraints imposed by the present orbit of the Moon.

Chemical twins

Lunar rock brought back by the US Apollo and Soviet Luna missions are remarkably similar to the Earth rocks anorthosite and basalt. Of course there are differences due to the harsh lunar environment – lunar samples are pitted by microscopic meteorite impacts, altered by cosmic rays, and show internal signs of shocks from asteroid impacts. [434] They are also totally dry and have not been oxidized. [434]

These samples reveal that the Moon and Earth are compositional twins. Proportions of isotopes (meaning the same elements but with fractionally different masses, such as those of titanium,[435] tungsten, [8] oxygen [6 8] and hydrogen[436]) in these rocks are exactly the same in the Earth and the Moon, yet there are large chemical differences with other Solar System objects.[8] This tells us the Moon and the Earth formed together from a largely shared source.

Tying down the date of that impact is helped by the fact that uranium-to-lead ratios can be graphed back to an event of major loss of lead from Earth's crust and mantle roughly 100 million years after the formation of the Solar System, when it and other heavy elements sank to the core through a magma ocean created by the Giant Impact.[437] This timing coincides neatly with a rubidium-strontium radiometric date for the Moon, which is 70-100 million years after Solar System formation.[8] The conversion of iodine to xenon by radioactive decay also points to a huge loss of xenon from the Earth at around 100 million years after formation.[8] [2]

Interestingly, the Moon's relative lack of volatile elements, like sodium, potassium, [6] and light isotopes of zinc, [438] dovetails with the missing xenon. Their loss is explained by the searing heat of the Giant Impact which drove our primordial atmosphere and lighter elements of rock vapor into space. [8] [2] It also makes sense of Earth's relatively thin atmosphere today compared to Venus. [8] [4] Without the Giant Impact, the Earth may well have retained its primordial atmosphere and suffered the sterilizing runaway greenhouse conditions that Venus suffers from now.

Trojans and orbits

The Earth-Moon orbit,[8] Earth's tilted daily-rotation axis, and the Moon's slow recession away from us, are all explained by the Giant Impact. More evidence comes from our Moon's relatively large size compared to Earth, unlike the relatively small moons of most other planets in the Solar System,[8] which makes sense if it formed from an impact-mixture of another planet (Theia) and Earth debris. The Moon's core is proportionally much smaller than the cores of other terrestrial planets, as we would expect from its formation from impact debris around the more massive Earth, which would have captured more of the heavier particles after the impact. [6]

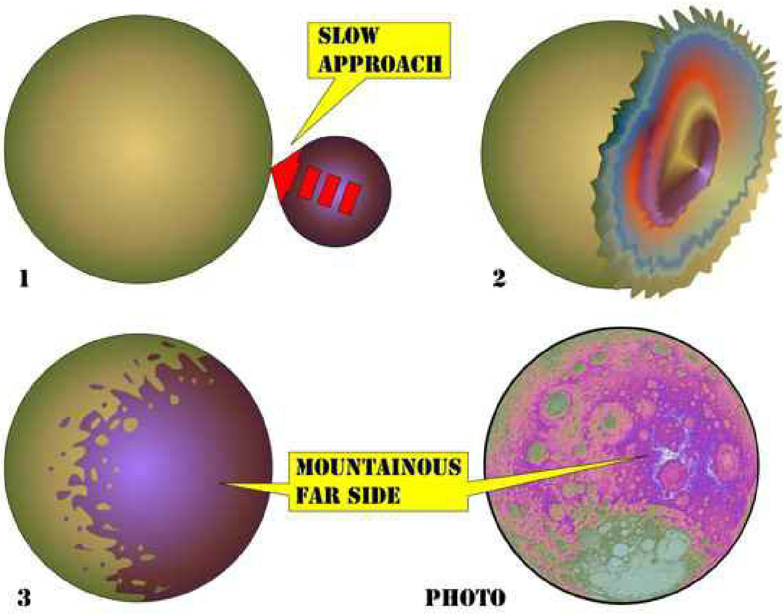
Computer calculations of giant impacts, using the laws of physics governing mass, gravity and angular momentum, show how a Moon-forming Giant Impact is a very feasible way to create our Moon. [6] But these simulations also suggest an intriguing possibility – that the Earth had more than one moon in its childhood.

Evidence for 2 moons

> "They found the highlands to be 12% less dense than expected"

Companion moons are a common outcome from such simulations, although most of their orbits are unstable, so they quickly impact or fly off into space. [10] However, if a companion moon forms at a "Trojan Point" (a point about 60 degrees ahead or behind our Moon but in the same orbit as our Moon) it can survive for tens of millions of years before crumpling slowly into the larger moon at sub-sonic speeds. [10] By that time the smaller moon would have solidified, but the larger moon would still be partly molten. The slow impact leaves a rubble pile over the larger moon, rather than blasting a high-energy, mantle-melting crater, and the added weight of that debris squishes the still-molten lunar mantle to the other side, the side we see from Earth.

Although not universally accepted, this conjecture neatly explains the lunar highlands on the far side of the Moon compared with the flatter landscape of basalt lavas that we see from Earth. Recent gravity surveys of the Moon support this idea They found the highlands to be 12% less dense than expected from the rest of the Moon (consistent with the rubble pile from a smaller moon), and found giant lava-filled cracks in the Moon's crust showing the Moon added 10km (6mi) to its circumference at a time after it was partly cooled.[17] [18] Satellite measurements of the composition of the far side of the Moon also confirm its rocks have not gone through as much chemical differentiation as the near side of the Moon, as would be expected from a smaller moon that solidified quickly.[19]



16 **The "Big Splat" collision of 2 moons to create our present single moon with remnants of the smaller moon forming the mountainous far side.** 1 to 3 redrawn

from computer simulations by Jutzi & Asphaug 2011, photo from NASA LRO

Other ideas and why they don't work:

At one time there were three main competing ideas for the Moon's formation. The first was that the Earth and the Moon formed next to each other at the same time. But the different densities of the Moon and Earth are not feasible if they congealed from the same part of the nebula, and it's very unlikely the neighbors would have avoided collision. [6] [8] The second idea was that the Moon spun off from the Earth, but for this to work the Moon would have to orbit Earth around its equator – which it doesn't. [6] The third idea was that the Moon was a passing planet that got captured into orbit around Earth. But this idea can't account for the chemical similarities between the Earth and the Moon, [6] and the vanishingly small chance that the Moon could approach Earth without either slamming into us or just deflecting into space again.

The lost elements – clues to Earth's childhood

Since the Earth is made up originally from asteroids and comets, you might expect the proportions of elements in Earth rock samples to be the same as those for meteorites (asteroids that fell to Earth). They aren't, and this tells us a great deal about what happened in the early childhood of the Earth.

Iron-lovers

I mentioned the loss of lead from the Earth's crust and mantle that helps tie the Giant Impact to about 100 million years after the formation of the Solar System. But evidence for the wholesale melting of a large proportion of Earth's mantle comes in the form of the abundance (or lack of it) of other metals such as manganese, nickel, cobalt, gold and platinum. These so-called "siderophile" ("iron-lover") elements dissolve in iron at the temperatures and pressures within the Earth. When you plot their abundance against their concentrations in meteorites, you see that they are strangely depleted compared to other metals. This is explained by iron, along with those other metals, sinking into the Earth's core through a "Magma Ocean" while the mantle was mostly molten after the Giant Impact. The quantities of these iron-lovers that remain in rocks near the surface (that we mine for precious metals) are paradoxically greater than you would expect after core formation. In fact there is some evidence (based on tungsten isotopes in some of the oldest crustal rocks) that our crust was 'topped-up' with these precious metals by asteroids that bombarded Earth after the core was already formed. [35] This "late veneer" of asteroid material seems to have happened everywhere in our Solar System. [439]

Rejected daughters

A clue for how quickly the Earth cooled after the Giant Impact can be found in isotopes of the gas xenon, which I mentioned above in dating the Giant Impact. Xenon is rejected during mineral formation, so it escapes into the atmosphere through volcanoes or a magma ocean. Isotopes, you may recall, are the same element but with fractionally different mass. The lighter isotope xenon-129 was produced by radioactive decay of short-lived iodine-129 which went extinct in the natural world a very long time ago. [30] The heavier isotopes xenon-131 to136 were produced by a different, longer-lived parent (Plutonium-244), which is also long-extinct. [30] And that's the clever bit – we can use these xenon daughters to infer what was happening to their parents while they were still around in those first few tens-to-hundreds of millions of years after the formation of the Solar System!

They show that more than 98% of the xenon offspring from the shorter-lived parent iodine-129 was lost to space from the hot atmosphere, but only around 70% of the xenon offspring from the longer-lived parent Plutonium-244 was lost. In other words, we lost much more xenon earlier, and much less later, [30] so the Earth's mantle must have cooled quickly in first 200 to 400 hundred million years after the Giant Impact. In fact it cooled by about 300°C, which is more than it has cooled in the entire time since then, much faster than the present rate of mantle cooling of about 40°C per billion years. [30] Such rapid cooling means that heat was lost from the mantle very efficiently through strong churning of a magma ocean, and precludes a thick, insulating crust.

This paints a picture of the Earth soon after the Giant Impact, covered by a mosaic of black and yellow, patches of bright liquid seething to the surface, crusting to black and sinking beneath the yellow glow of fresh lava, resurfacing the entire planet every million years or so, [30] in a scene resembling the surface of lava lakes in active volcanoes today (albeit on a much larger scale).

Freezing the mantle

There is considerable uncertainty in how long the mantle (as opposed to the crust) took to solidify after the Giant Impact and before the Jack Hills zircons. Estimates vary between around 1 to 5 million [30] [7] to 50 million [4] years to freeze the mantle, and then another 100 [7] to 200 [4] million years before radioactive heat remelted the mantle enough to allow it to move as it does today. But these studies do agree that the Earth cooled much more slowly once it was covered by a solid crust, just as the lid on a cooking pot keeps its contents warm.

Flaccid early crust - before plate tectonics

In "your first memories" I mentioned a type of very resilient mineral called zircon that constitutes the earliest trace of our Earth, from 4.4 billion years ago. Within zircons like these, extracted from the oldest rocks on Earth, there are measurable impurities of a chemical element called "hafnium" (Hf). One isotope of hafnium (^{176}Hf) is a product of radioactive decay, so its ratio to another isotope (^{177}Hf) changes over time. When that ratio is plotted against the sample's formation date, most rock samples plot along the straight line we would expect from continual melting and differentiating of the Earth's mantle from an original asteroid composition. But the most ancient rock samples (from Jack Hills in Australia and the Acasta Gneiss from Canada) plot along an entirely different line,[4] showing that they formed independently in crust that stayed stable for hundreds of millions of years. That is far longer than modern oceanic crust survives, and so it tells us that the world worked differently back then, without the plate tectonics of the modern planet.

In fact, some rocks from that time are of a type called "komatites" which have a high level of magnesium oxide in them.

These only form at temperatures about 350°C hotter than even the hottest basalt lavas of today. Scientists plugged these temperatures and rock properties into computer models that run equations for the physics of fluid dynamics, viscosity, buoyancy, stress, strain, and heat flow. The models showed that the crust was too weak back then to sustain subduction - the process of one tectonic plate descending into the mantle beneath another, which is necessary to sustain plate tectonics. [31] It took a long time before the crust cooled enough to gain the strength needed for subduction and the steady mantle circulation and cooling that goes along with it. Careful analysis of over 70,000 rock samples from across the globe backs this up. It shows the clear geochemical signal of long-term, gradual cooling in the mantle and crust starting roughly 3.2 billion years ago, consistent with the steady loss of heat through mantle convection [440] after subduction and plate tectonics was initiated at that time.

Last tango of Saturn and Jupiter

Dating Moon rock samples from the Apollo and Luna missions yielded a curious gap in impact craters older than about 4 billion years, and also showed that after about 3.5 billion years ago crater formation was at least 100 times less frequent. [441] [32] Since most of the samples were collected from impact craters on the near side of the Moon, it was reasonable to suspect the samples were dominated by a few major impacts, obscuring older dates. In fact samples from Apollo 16 and 17 were later found to be dominated by a single impact 3.9 billion years ago. [441] So scientists turned to bits of the Moon that fell to Earth as meteorites in places like Libya and Antarctica to supplement their data, but so far these have just confirmed the gap. [441] [32] Lunar geologists have also mapped the craters in lunar reconnaissance photos, building up a detailed sequence of crater formation. This allows them use the ages from the few lunar samples to bracket the ages of many other craters, and again shows that 80% of the Moon's surface was resurfaced by impacts between the formation of the Nectaris and Orientale basins[32] (3.92 to around 3.8 billion years ago, a duration of 120 million years). In other words there was a Late Heavy Bombardment of the Moon during the teen years in Your Life as Planet Earth. But the paucity of samples and dating uncertainties do allow for a more protracted bombardment potentially lasting more than 400 million years.[441]

> "direct evidence instead comes from microscopic glass spheres that form from condensing rock vapor"

The Moon retains its ancient cratered face, but all the craters from the bombardment on Earth have long since eroded away. Fortunately we can estimate what the bombardment was like on Earth by extrapolating from the Moon. The Earth was both a bigger target and more massive (with more gravitational pull) than the Moon, so it would have been hit about 20 times more often than the Moon. [11]

Since the craters on Earth have been erased, direct evidence instead comes from microscopic glass spheres that form from condensing rock vapor after an impact. These "spherules" have been recovered from dated sediments, revealing the frequency and size of ancient asteroid impacts. It shows that impacts big enough to spread molten rock droplets across the entire globe were frequent well after the traditional "end" of the Late Heavy Bombardment, only tailing off by around 2.5 billion years ago. [36]

The clues to the cause of this cosmic hailstorm came from peculiar orbits of objects in the Kuiper Belt, the distant cloud of asteroids that includes Pluto. Scientists found that some asteroids in the Kuiper Belt orbited in a regular dance with Neptune, orbiting the Sun either twice for every three, or once for every two of Neptune's orbits. Other objects in the Kuiper Belt have strangely elongate orbits, or orbits that take them well out of the Solar System plane, [442] and some have compositions that must have formed much closer to the Sun before finding themselves at the outer boondocks of the Solar system. [443]

Solving how the Solar System could end up in its current configuration, including the Kuiper Belt oddities, starting from a disk of dust and planetary embryos, has in large part relied on computer models controlled by the laws of physics concerning gravity and orbits. It turns out that to get to the current configuration from the earliest days of the Solar System, you have to start with a more compact distribution of the planets – like rewinding a video of a game of billiards. Fast-forwarding the orbits reveals a critical point at the beginning of the Late Heavy Bombardment when Jupiter and Saturn begin to resonate with each other in a kind of cosmic tango. This instability yanks Neptune and Uranus out of their stable orbits, which in turn scatters comets and asteroids throughout the Solar System, including towards Earth. [444] This idea is known as the "Nice

Model" (not because it's especially pleasing, but after the French city where it was discussed).

Armageddon?

Ever since we discovered that the dinosaurs were wiped off the planet by an asteroid, we have had a cultural obsession with impacts, resulting in more than a few disaster movies. But only recently have we begun to assess the *real* threat of an impact catastrophe. Tens of thousands of centimeter-sized objects burn up in our atmosphere yearly, as do a few meter-scale objects. [445] The fireballs they make are detected by monitoring satellites and ground-based sound recorders, or observed as "shooting stars."

It's the bigger objects, 50-100m (150-300ft) or larger, in orbits that come near us, which might pose a danger. NASA's estimate for the number of those is unsettling: roughly 5,000, of which only 30 percent have actually been located. [446] NASA maintains a watch on Near-Earth Objects it has identified, including a 325-meter-wide (1,000 foot) asteroid named Apophis which has a very small chance of an impact with Earth in 2068.[447] In fact we seem to be

> "NASA's estimate for the number of those is unsettling"

"buzzed" by a sizeable asteroid every few months, like "2012 DA14" that missed us by just 15 minutes on February 15 2013, on the same day that a 13,000 ton asteroid exploded in the sky above Chelyabinsk in Russia, injuring more than 1,000 people.[448]

To date some 185 impact craters have been positively identified on Earth, with new ones logged every year, [96] and estimates suggest there are another 700 or so that we haven't found yet. [445] To determine if a crater was caused by an impact rather than another cause (like a volcano, salt movement, or folding), scientists look for the fingerprints of a high velocity impact and its resulting shock wave. These include characteristic shock fractures in quartz grains, beads of glass cooled from vaporized rock (impact "spherules"), minerals like stishovite that only form under extreme pressures, abnormally high levels of the element iridium, evidence of melting, and crater-sized cone-shaped fractures.

And if the dinosaurs were wiped out by an asteroid impact, maybe the other mass extinctions like the Permian "Great Dying" were also caused by asteroids?

Not so fast.

Although there was an impact in Brazil about 3 million years before the Permian extinction (almost coincident given the date uncertainty), it was comparatively small so it can't explain the extinction and all the other documented environmental effects of that time by itself. It may have released a large amount of methane into the atmosphere by breaking up oil shales ("fracking"), which would have added greenhouse gasses to those emanating from the Siberian Traps eruptions.[177] An extensive search for a larger impact at the time of the Permian mass extinction failed to find the high levels of iridium, shocked quartz and impact spherules that would be expected, [449] and no "smoking gun" impact crater has been found – and it would have to be big! Instead, all indicators for the cause of the Permian Great Dying point to huge rises in atmospheric greenhouse gasses caused by immense volcanic eruptions. [176] [174] [180] [181] [178]

Even the Cretaceous Chicxulub impact, which is widely credited with the end of the dinosaurs, was not the only killer at the time. Indian volcanic eruptions around the same time undoubtedly did affect the climate, and began the mass extinction 150,000 years before the impact that finished off the dinosaurs. [245] [450]

Rapid climate changes induced by greenhouse gas emissions from the same class of immense volcanic eruptions that caused the Permian "Great Dying," have been consistently far more deadly to life on Earth than asteroid or comet impacts. [116]

2. The Terra Firma Illusion

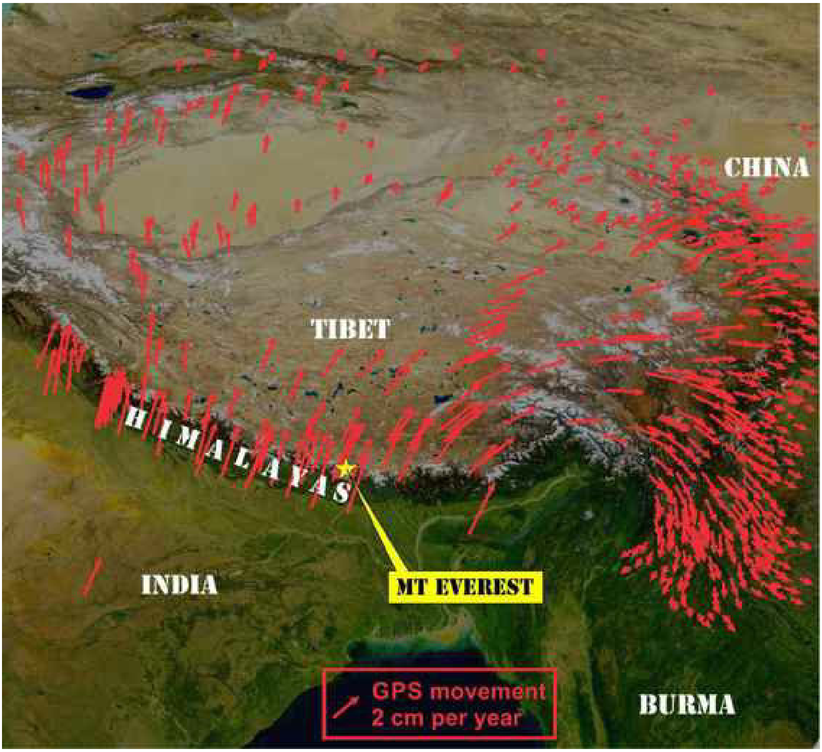
"Terra firma," "bedrock," "rock solid," "rock of ages"– they all convey solidity, constancy, reliability. For that reason rock is the brand image for many a bank and insurance company. And for the most part, on the scale of our normal experience, nothing is as solid as a rock, as permanent as a mountain, or as firm as the ground beneath our feet. But just as the stability of financial institutions sometimes proves illusory, so is the constancy of our Earth.

The "solid" Earth moves in many ways beyond our normal perception.

Drifting continents

It wasn't until the early 20th century that continental drift was surmised, and even then it took decades to be widely accepted, but these days it's not so hard to prove continental drift – we can just measure it.

The same GPS (Global Positioning System) that you us in your car or your smartphone is also used to measure continental drift, and NASA displays these data on their website [451] GPS measurements reveal ongoing plate movements today, such as the collision of India into Asia moving at 4cm a year (1 ½ in) on the Indian side, tapering off to very slow changes north of Tibet. They also show the Himalayas herniating towards China a around 2 cm (1 in) a year. [274]



17 **GPS measurements show tectonic movement**. Redrawn from Searle, et al, J. Geol. Soc. 2011 over MODIS image by NASA

Scientists supplement GPS measurements with "Very Long Baseline Interferometry" (using natural radio signals from quasars in deep space) and Satellite Laser Ranging (using pulses of laser light bounced off satellites). Together, these survey techniques have been crucial in plotting continental drift over the last few decades, but they are little help in working out what is going on below the surface to drive this process. For that geologists use a combination of field geology, calculations from earthquake signals, and highly sensitive measurements of the Earth's magnetic field.

Discovering drift

In fact, continental drift was discovered through just those techniques. The German meteorologist and explorer Alfred Wegner, when he first described the concept of continental drift back in 1912, [452] was convinced by the way continents fit together like jigsaw puzzle pieces, and by the matching distribution of plant fossils and rock types across now widely-separated continents. Wegner's ideas didn't gain widespread acceptance until decades later – it was counterintuitive that solid landmasses could drift, or that continents could *plow their way through solid rock*. And besides, what possible mechanism could drive such an epic process?

In 1962 Harry Hess, an American geologist, made the pivotal insight into both the process of continental drift and the mechanism that drives it. He knew that since the 1950s, surveys had identified underwater mountain chains all across the globe, forming a "Great Global Rift." He noticed that these mid-ocean ridges were always at the median line between continents, had very high heat-flow, and conducted earthquake waves strangely slowly, showing they were partly liquid. He deduced they must be zones where the mantle wells-up hot fresh magma. Noticing that ocean floors have relatively little sediment accumulation near mid-ocean ridges, he concluded that oceanic crust must be young. Putting all the evidence together he concluded that the mantle was convecting - circulating like a heat-driven conveyor belt - at around 1 cm (½ inch) a year, with mid ocean ridges marking the location of the rising part of the convection cycle. He realized that this mantle convection was moving continents *passively* around the globe rather than "plowing through" the mantle, and he realized that there must be descending parts of the convection cycle where oceanic crust gets destroyed in a "jaw-crusher" - as he called it - when it is shoved beneath continents. [453] So Hess had proposed the mechanism that drives continental drift, and further proof was soon to follow.

Magnetic zebra

In the 1920s a Japanese scientist named Motonori Matuyama established that the Earth had undergone switches in its magnetic field, flipping north to south and back again. This information became pivotal for our story the year Hess published his theories of sea floor spreading, as the ship HMS Owen conducted a magnetic survey of the Indian Ocean. When British scientists Drummond Matthews and Fred Vine graphed their magnetic measurements, they showed a regular pattern of alternating strong and weak magnetic field. They realized that these were a recording of the magnetic field flips that Matuyama had described, fossilized into the ocean floor like zebra stripes, whose pattern formed a mirror image either side of mid-ocean ridges. Other scientists found similar patterns in the North Atlantic and the Pacific Ocean, so it had to be a global phenomenon.

Vine and Matthews realized that their stripes were proof of Hess's theory of the continuous production of new crust along mid-ocean ridges. Fresh lava at the ridge is constantly cooling and freezing-in the magnetic field of the time, and is constantly separating as the sea floor spreads, with the gap filled by fresh lava in a continuous process. [454]

Jaw-crusher

> "the quakes are the rattle of Hess's 'jaw-crusher'"

The missing part of the puzzle was what happened at the other end of the sea floor to make room for all that spreading – Hess's "jaw crusher." That's where seismologists (earthquake scientists) came in. For some time they had noticed a distinct concentration of earthquakes around the Pacific Ocean. They found that the zone of earthquakes tended to plunge deeper into the Earth the further away from the ocean they occurred. They realized that the quakes are the rattle of Hess's "jaw-crusher" as oceanic crust plunges into the mantle in a zone of crust destruction called a "subduction zone."

The Canadian geologist Tuzo Wilson realized that these processes must have driven oceans to widen and shrink, and caused to continents to break apart and collide through geological time. He and many others refined the idea of continental drift into "plate tectonics" through the sixties and seventies,[455] and since that pioneering work, a host of new evidence, including videos of underwater eruptions and geothermal vents at mid-ocean ridges and geophysical surveys, has confirmed the theory. And to circle back to those GPS measurements, they do show Hess's deduced spreading at mid-ocean ridges, and his "jaw crusher" collision of plates at subduction zones.[451]

Realizing that our Earth is made of tectonic plates, dynamic at the rate of a fingernail's growth, has been the crucial epiphany for understanding so much about our planet. It explains earthquakes and volcanoes, building mountains and subsiding basins. It enables scientists to predict the locations of oil reserves and mineral deposits. In short, it is geology's unifying theory.

CAT scan results

Since then, advances in geophysics have enabled us to "see" into the Earth with increasing clarity to reveal structures within the crust and beneath, all the way to the core. This is an exciting time as satellite-based gravity[456] and magnetic surveys[457] vie with seismic imaging[458] for ever clearer and deeper views of our planet's tectonic engine-room. We've come a long way since Wegner.

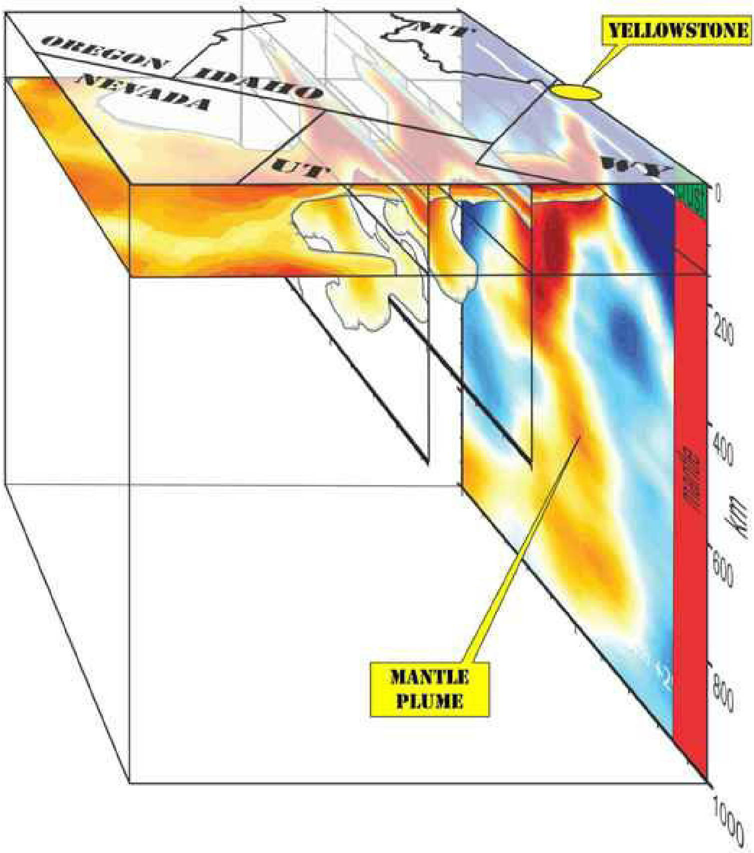
Scientists measuring the electrical conductivity through mid-ocean ridges have shown that the separation of tectonic plates is a passive process. Plates are pulled apart by mantle movement and sinking of the subducting edge of the plate. The pulling-apart lowers the pressure between plates, which causes the mantle in between to melt and rise, filling fissures that form as the plates tear apart.[459] Geothermal heat powers seawater through the newly-solidified, cracked crust until it jets into the ocean as hydrothermal vents or "black smokers," and this spreading zone is relatively buoyant, riding high as the mountainous chain of mid-ocean ridges.

Seismic imaging, using echoes from artificial shockwaves or from natural earthquakes, has revealed ever more information about the structure and processes of the deep crust, the mantle and even the core. As computing power and storage capacity increased, they permitted seismologists to record and process ever larger quantities of data. Seismologists now use hundreds of thousands of earthquake traces from hundreds of natural earthquakes across the globe, detected in monitoring stations distributed across large sections of the world.[316] They analyze the spectra of the earthquake waves and compare miniscule differences in the wave shapes recorded at different locations for the same earthquake, in order to assess the properties of the rocks that the waves passed through on their journey across the interior of Earth. In this way they build a 3-dimensional image, just like a medical CAT-scan or MRI, of the crust and mantle.

Seismic tomography shows the Pacific crust plunging to annihilation beneath Washington State and California. It reveals graveyards of broken pieces of subducted plate buried under the Pacific Northwest of the USA; a plume of magma extending from the hadean depths of the mantle feeding the Yellowstone Supervolcano; ancient crust that underpins the Great Plains and parts of the Rocky Mountains; and even gobs of crust "dripping" off into the mantle from under the Colorado Plateau.[316] It reveals finger-like plumes of hot mantle dotted all across the Pacific that are smeared into channels by the motion of the overlying tectonic plate. [458] These plumes also show up in satellite-based gravity measurements, corresponding with hot spots all over the globe.[456]

Mantle Plumes seem to protrude from enigmatic "Plume Generation Zones" - belts near Earth's core that appear to leak hot fingers of core-mantle magma towards the surface. These zones are like skirts enclosing two large mushy regions at the core-mantle boundary, one beneath Africa and the northern Atlantic nicknamed "Tuzo," and the other beneath the western Pacific, nicknamed "Jason." Both these regions, and the Plume Generation Zones around them, seem to have remained remarkably static over at least the last 500 million years, even as continents drifted high above them the way clouds drift over a landscape.[455]

Mantle Plumes are also linked to those catastrophic eruptions that caused global warming and extinctions in Earth's past, known as Large Igneous Provinces (LIPs).[178]



18 **Seismic tomography revealing a mantle plume beneath Yellowstone. Redder colors are molten/semi-molten zones that slow down earthquake waves.** Redrawn in 3D from 2D sections in Obrebski et al, Geophys. J. Int. (2011).

Large Igneous Provinces (LIPs) vs Volcanoes

We are some way from being able to predict volcanic eruptions reliably, but there have been some successes. In one example, US and Philippine scientists successfully forecast the 1991 eruption of Mount Pinatubo. Their forecast saved at least 5,000 lives and at least $250 million in property damage. [460] Hopefully we will see many more examples like this as new technology and research is brought to bear. For instance, satellite surveys using a sophisticated radar technique called "InSAR" can now reveal volcanoes swelling with magma buildup before eruptions, [461] and geophysicists have found characteristic "long-period" seismic waves can signal an imminent eruption. [462]

Volcanoes – a double-edged sword for our climate

Explosive volcanoes like Pinatubo and El Chichon usually occur above subduction zones where waterlogged plates plunge into white-hot mantle. They release CO_2 when they erupt, which combines with CO_2 from eruptions all over the world over many millennia to keep the planet from freezing. But violent eruptions also inject sulfur dioxide into the stratosphere where it converts to sulfate, which acts like sunscreen in the short term. Consequently we see cold periods lasting a few years after large eruptions like Laki in 1783, Tambora in 1815, and Cosiguina in 1835, El Chichon in 1982 and Mount Pinatubo in 1991.[463] Laki caused a severe winter in 1783/4 and a range of extreme weather across the globe, while Tambora caused a year "without a summer" in 1816. Earlier volcanic-induced cold periods are even documented in medieval Irish chronicles. [464]

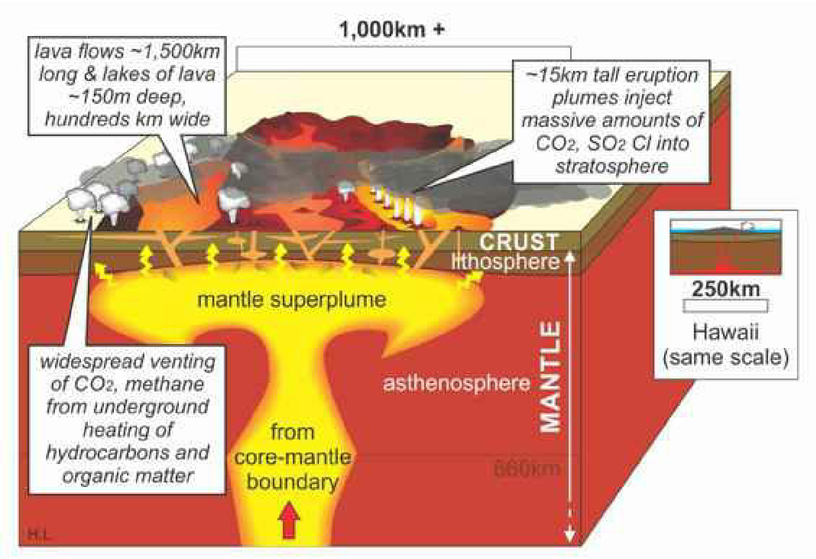
But other volcanoes occur away from subduction zones and spreading ridges, in the middle of plates. They seem to be associated with mantle plumes, like the one beneath Yellowstone. The plumes burn "hot spot" volcanoes through the solid crust above them, sometimes making long island chains, like the Hawaiian-Emperor chain. Usually these volcanoes are non-explosive, with hot, runny lava like at Hawaii. But sometimes local conditions can make even these volcanoes explosive, for

> "Volcanic-induced cold periods are even documented in medieval Irish chronicles"

example if the volcano erupts through a glacier (as was the case for the Eyjafjallajökull eruption that grounded European flights in 2010). And sometimes the plume magma is mixed with more explosive magma melted from continental crust around it – like at Yellowstone.

Large Igneous Provinces are not your regular volcanoes

Even Hawaii, Pinatubo, Vesuvius and Tambora are dwarfed by the epic outpourings of lava known as "Large Igneous Provinces" (LIPs). Every year there are something like 50 to 65 volcanic eruptions, but we haven't had a LIP eruption in 16 million years.[465] [272] LIPs are about 40 times larger than even our largest modern-day volcano (Hawaii) and seem to be caused by mantle plumes interacting with continental crust, injecting sheets of super-hot, very liquid magma through sediments underground, as well as smothering enormous areas of the Earth's surface under lakes of lava. They are a throwback to the eruptive incontinence of the pre-teen Earth, conducting heat and magma from the lower mantle to the surface. LIPs are concentrated at times when continents are fragmenting, and at places which occur over deep mantle Plume Generation Zones. As more and more LIPs are analyzed across the world, it's clear that the combination of their extraordinary scale (some cover 1% of the planet's surface) erupted over short time periods (geologically speaking) and their ability to release prodigious quantities of greenhouse gasses (directly, and also by baking the crust they erupt through), makes them so disruptive to the climate.[272][178]



19**A Large Igneous Province (LIP) eruption compared to the world's largest active volcano today.** Loosely based on Svensen et al EPSL 2009, Howarth et al Lithos 2014, Elkins-Tanton GSA Spec Pub 2005, Keller et al J Geol Soc India 2011, Li et al Nature Geoscience 2014.

Wandering poles

But what of the wanderings of continents in the deep past?

The evidence for that comes from the same kind of magnetic phenomenon that Vine and Matthews measured in the Indian Ocean. But rather than surveying vast swathes of crust, scientists measure the fossil magnetic field frozen into individual rock samples of different ages. As molten rocks cool, some crystals record the direction of Earth's magnetic field within them. In fact, rocks don't even have to be molten, they just have to be heated above their "curie temperature" which is much cooler (in the case of iron oxide it's less than half the melting temperature). So the magnetic direction of these minerals is set and reset any time they are heated above their curie temperature.

As any school kid knows, the Earth's magnetic field points outwards at the south magnetic pole and curves until it points inwards again at the north magnetic pole. So, knowing how steeply the magnetic field dips into (or out of) the ground tells you how far north or south you are. In this way, rocks can record their *latitude* of formation and it's often far from their present latitude. Unfortunately this doesn't help with their east-west location (*longitude*) but with enough samples these studies of fossil magnetism (or "paleomagnetics") plot a continent's journey through time, and show when different parts of a continent came together. [466] There are now sufficient data to plot the wandering continents back hundreds of millions, even billions of years ago. [466] [117]

Ghosts of continents past

It seems improbable that there could be any trace left of a piece of Earth's crust after it has been through Hess's jaw-crusher, descended into the hellish temperatures and pressures of the mantle, melted and conveyed through the planet's interior, and then erupted in some new location on the surface. And yet, like a suspect's DNA left at a crime scene, chemical traces of long-ago-lost crust can be revealed through exquisitely sensitive geochemical measurements.

They say "diamonds are forever" and perhaps they are right. The timing of the beginning of subduction was hotly debated until a recent study of some remarkably resilient diamonds was published. The scientists dated microscopic impurities locked in diamonds that had been dragged from deep beneath ancient continental roots by more recent volcanic eruptions. Impurities in the diamonds that were more than 3 billion years old were made of peridotite, a kind of olivine-rich rock that makes up the upper part of the Earth's mantle. But a different impurity – eclogite – only showed up in younger diamonds. [55] Eclogite is created by the ultra-high pressure cooking of slabs of oceanic crust during subduction. The switch in the type of impurity told scientists that the "Wilson Cycle" - rock recycling through subduction - started roughly 3 billion years ago, consistent with the change in mantle cooling rate at that time, that I mentioned in the last chapter (those "rejected daughters" and that "flaccid crust").

Even oxygen-free traces of sediments that were subducted into the mantle before the Great Oxidation Event (Earth's mid-life crisis) can be detected in volcanic glass from recent eruptions at some mid-ocean ridges today – a recycling that took more than 2.5 billion years to complete. [467] Subducted sediments can also leave tell-tale variations in isotopes of hafnium trapped in resilient little zircon crystals like those we spoke of as Earth's first memories. [468] These hafnium isotopes are "ghosts of sediments past" because they indicate the *kinds* of sediments that lay on long-vanished seabeds before they disappeared during an ancient continental collision, millions or billions of years before they were recycled into the crust again as fresh igneous rocks.

Starting subduction

There are chemical fingerprints for both the onset of subduction and the steady cooling of the mantle since then. Those hafnium isotopes I just mentioned also reveal the beginning of subduction through a marked change in the growth rate of continental crust around 3.2 billion years ago, in line with the appearance of those subduction-flagging diamonds.[56] [57] [55]

On top of that evidence, statistical analysis of over 70,000 rock samples has also found the tell-tale chemical signature of long term crust recycling, mantle churning, and progressive cooling. Lava at mid ocean ridges and other volcanoes fed by mantle magma show a decline in concentrations of nickel, chromium and magnesium, but an increase in sodium and potassium, over the last 3 billion years or so. This change reflects the reduction in the proportion of mantle that's actually molten from about 30% 3 billion years ago, to about 10% in today's cooler mantle. [440] Continental rocks have changed too. Ratios of indicator elements like sodium/potassium, lanthanum/ytterbium and the proportion of europium to other "Rare-Earth Elements," have progressively reduced over the last 3 billion years or so, reflecting the continued evolution of a repeatedly melted, maturing continental crust. [440]

Amasia – the next supercontinent?

So, in the century since Continental Drift was first posited, a great accumulation of evidence has confirmed and refined the theory into Plate Tectonics. Multiple lines of evidence narrate the story of wandering ancient continents, their collisions and the building of mountain chains, their inevitable break-up and renewed journeys until our present-day geography is arrived at. And in knowing this, it is clear that today's globe of seeming permanence is just a snapshot, a moment of illusory stillness on a continuum of change, which will eventually lead to the assembly of a new supercontinent - dubbed "Amasia" - probably near the North Pole in roughly 200 million years' time, [469] which will in turn break up, its parts destined to drift in cycles of supercontinent assembly and breakup in perpetuity, or at least until our planet is engulfed by our dying Sun, which is a very long way off.

The plumbing of Hades

The chemical symbol for lead is "Pb" from the Latin "plumbum" which is also the origin for the English word "plumbing." That's ironic because lead is at the heart of the chemical evidence for the origin, movement and connections of magma throughout the mantle. It begins with a problem known to geochemists as the "lead paradox," and the solution to that problem reveals fundamental information about the way the innards of the planet work. [437]

Experiments have shown us that as the mantle melts and recrystallizes over time, it should expel more uranium than lead into *crustal* rocks, leading to a decrease in uranium levels in the *mantle*. And since uranium decays radioactively to become lead, the mantle should have more of the lead from the origin of the Solar System, and much less of the type of lead that is made by the decay of uranium. But samples of lavas at mid-ocean ridges and oceanic islands like Hawaii show the opposite. [437] And that's the "lead paradox."

Plum pudding and marble cake

> "a residue of very heavy minerals (the anti-crust, if you will)"

The solution was expected to lie in the fact that slabs of uranium-enriched crust are constantly subducting, returning uranium and its decay-product-lead to the mantle. But there's a hitch – the recycled crust can only explain the lead levels found in ocean island basalts if the subducted slabs are kept isolated in the mantle for between 1 and 2 billion years (like plums in plum pudding), for their uranium to decay to more lead, before being mixed in with erupting basalts. But convection in the mantle (that drives plate tectonics) should smear and mix the recycled crust with low-uranium mantle (like the chocolate layers in marble cake, and not like plums) to an extent that conflicts with those lava samples. [437] The paradox remained unresolved.

A rare piece of lower crust that got transported to the surface in the Himalayan mountain-building train-wreck finally tipped the balance in favor of both marble cake and plums! The Pakistani rocks showed that as fast as melting over a subduction zone generates new, buoyant continental crust, it leaves a residue of very heavy minerals (the anti-crust, if you will). These dense, low-uranium 'plums' of matter preferentially lock-away the kind of lead that was formed at the origin of the Solar System (as distinct from lead created by the decay of uranium). They drip slowly to the lowermost mantle near the core, where they resist mixing with the mantle. That leaves the rest of the mantle 'cake' – with its marbling of recycled old crust – to erupt as basalt in volcanic islands or mid-ocean ridges, enriched in uranium-derived-lead. [470] This elegant combination of geology and chemistry showed us the connectedness of crust formation, subduction, mantle circulation, and mid-ocean volcanics predicted by Hess's continental drift all those years ago.

A source near the core

Evidence for ocean island volcanoes being plumbed into a layer near the core comes from isotopes of osmium. Osmium-186 is the product of radioactive decay of platinum-190, which was strongly concentrated into the core early in Earth's development. So high levels of osmium-186 in Hawaiian lavas and in Permian basalts from the Noril'sk area of Siberia strongly hint at magma interaction with the core before either of these lavas erupted. Ocean-islands' magma origin from a near-core reservoir of magma is reinforced by their high levels of nickel, helium-3 and neon, all indicators of a "primordial" or near-Earth's-core source. [471] [437] [472]

Seismic proof of the pudding

This geochemical evidence has since been backed up by seismic images that show semi-liquid areas at the core-mantle boundary, and revealing that the volcanic islands of Hawaii, Kerguelan and Tristan da Cunha lie at the edges of these zones. [473] The chemical variation in Hawaii's lavas shows that some of the Hawaiian volcanoes (Mauna Loa and others on the southern side of the chain) are more plumbed-in with this core-boundary source of magma, and some (Mauna Kea and others on the northern side of the chain) have more recycled crust. [473] Seismic studies show that even the Yellowstone supervolcano is fed by a mantle plume originating from near the core, which fits with high core-associated helium-3 values measured in Yellowstone's lavas. [316]

Did the Earth move for you too?

Of course the motions of Earth's plates have a far more immediate relevance than just being the conveyor of planetary change through deep time. According to the World Health Organization, plate tectonics is responsible for almost as many deaths as all other natural disasters (storms, floods, drought, wildfires, heat waves and cold) put together. [474] The Haiti earthquake in 2010 alone caused the death of 222,500 people, and on average tectonics claims over 100,000 lives a year through earthquakes, volcanoes and tsunamis. [474]

Earthquakes and instant gold

If you have never experienced an earthquake, nothing can fully convey the stomach-icing panic you feel when the solid ground shakes, when buildings that should be rigid and protective sway and crumble. Since infancy your body has understood these things to be hard, constant and unmoving. An earthquake feels as if the laws of physics were just revoked, and thrusts those unconscious assumptions into vivid fallacy. As the walls shake and gaps appear, you experience raw animal terror.

Plate tectonics makes sense of the pattern of earthquakes around the world. It explains why quakes are generally concentrated along plate boundaries by the juddering, stuck-unstuck scraping of one plate against another, or by one plate bulldozing over another, sending it to annihilation in the mantle. Each quake (even those too small be felt by people) is picked up by seismometers and accelerometers which measure shaking in all directions, and are networked together across the globe to allow a precise triangulation of the location of the quake. Seismologists can even calculate the 3D orientation of a fault plane deep underground from the precise wave attributes.

Forecasting quakes

> "nothing can fully convey the stomach-icing panic you feel when the solid ground shakes"

And if you look at the patterns of quakes on the USGS website, it immediately becomes apparent that a real-world plate edge such as the one in California is a much more complicated affair than a simple fault "line." In fact it is composed of many individual faults and fractures in a complicated 3-dimensional honeycomb. A closer look at any one of those fractures on the scale of a road cutting, for instance, reveals its own internal fracture structure, and so on down to the microscopic scale of individual fractured grains of rock. Sometimes rock conditions lubricate fractures, allowing them to creep past each other without generating earthquakes, but this creates knock-on stresses and strains on all the nearby fractures. Add-in varied rock-types, fluctuating groundwater pressures and temperature changes at depth, and it is no wonder that predicting earthquakes is so hard!

We still are a long way from forecasting earthquakes the way we do the weather, but seismologists are able to generate maps of earthquake risk and predicted shaking strengths, to aid the design of quake-resilient buildings. Monitoring before, during and after major earthquakes helps identify where stresses have moved and therefore where the next large earthquake might reasonably be expected. This has revealed some surprises, such as the way plates go through a slow-motion rebound lasting years after major earthquakes [475] and how earthquakes on one fault can raise the chance of an earthquake in some areas, and yet cast "stress shadows" that reduce the chance of quakes in other areas. [476] It has even revealed how earthquakes can create gold veins in an instant by causing sudden pressure drops in underground fluids![477]

The formation of a new plate boundary isn't that frequent on geological timescales, so it's all the more remarkable that we can witness the start of one today. 2 huge earthquakes in April 2012 were the earliest cracks heralding the breakup of the Indo-Australian plate, beginning a new plate boundary in the Indian Ocean, triggered by the Tsunami-producing Banda-Aceh earthquake in 2004.[478]

Earthquakes and volcanoes are such well-worn topics, covered in a myriad of other books and TV programs, so I won't take up more space with them here. However, there are other, more surprising ways the Earth moves that few people know about. The most common but least known is the phenomenon of Earth tides.

Earth tides and SQUIDs

Everyone knows the sea level rises and falls twice a day in tides. But few people know that the solid Earth itself rises and falls with the orbit of the Moon, imperceptibly but measurably. The ground beneath your feet moves up and down by as much as 30cm (12in) twice a day. You don't feel it because the effect is evenly distributed over a wide area.

GPS systems have to account for Earth tides when calculating positions [479] as do astronomical measurements, and large physics experiments like the Large Hadron Collider at CERN [480] have to be designed to allow for them. Scientists measure Earth Tides using exquisitely sensitive instruments like "Quartz Tube Extensometers" (to measure the stretching of Earth's surface), liquids in tubes (to measure tilt), and "SQUIDs" ("Superconducting Quantum Interference Devices") to measure the tiny gravity variations.

Earth Tides are a rare example of Earth movement that is not caused by plate tectonics, but they do have an influence on tectonics. They can be sufficient to push an already expectant volcano into erupting [481] [482] and may be the 'straw that breaks the camel's back' in triggering some earthquakes. [483] Tidal kneading of our planet's interior creates heat. Currently this amounts to about 0.2 Terawatts of energy [484] - about 150 times less than heat generation by natural radioactive decay (about 30 Terawatts) - but in the early Earth when the Moon was closer, it must have been a more significant contributor of internal heat. [11]

How fast does a mountain move?

When Mount Everest was first surveyed, its height was calculated by Babu Radhanath Sikdar to be 29,002 feet (8840m). This figure was revised as surveying became more accurate and stands at somewhere between 29,017ft (8844.33m) [485] and 29,035ft (8,850m) [486] at rock level. Or rather it did in 1999 – right now it is probably a little higher – it is rising about 4mm (about 1/8 in) a year [486] - and has moved northeastwards by about 10 times as much. [274]

Mountains everywhere, not just Everest, are on the move, victims of three competing forces: plate tectonics, erosion, and an effect known as "isostacy."

Pressure-cooker

The higher a mountain range grows, the deeper its crustal roots sag into the mantle beneath, like a heavily laden ship sits lower in the sea. That's called "isostacy." The roots of mountain chains are pushed to such depths and temperatures that the rocks they are made from are pressure-cooked into new kinds of rock: mud becomes slate; slate cooks into flakey mica schist; sandstones become quartzite, and eventually granite-like gneiss. If the cooking continues long enough, the rocks become overcooked and melt completely to form granite.

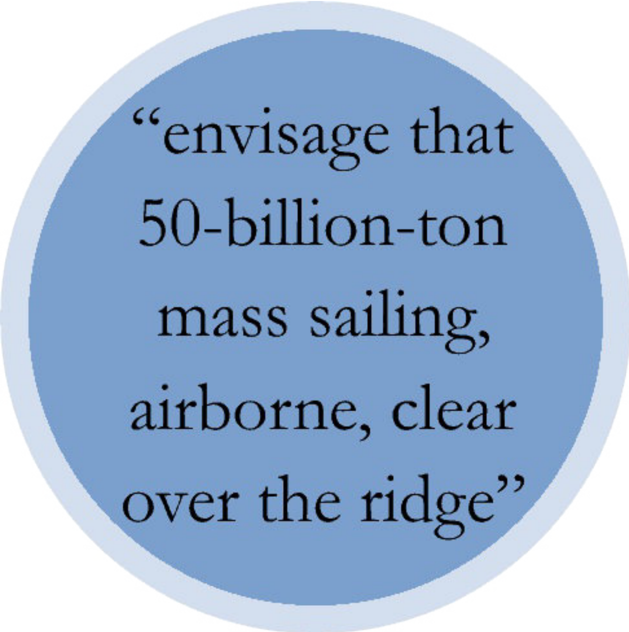
If you have driven through a mountainous area you may have noticed loops and swirls of folded rocks in road cuttings. It takes the immense pressures and temperatures found in the roots of mountains to fold rock, play-dough-like, into such forms of fluid beauty.

The flip-side to all this machismo mountain-building and forceful folding is the slow slaughter of mountains by erosion, and the dumping of their bodies, grain-by-grain, as sediments in river beds, lakes and oceans. Almost as fast as mountains build skywards they are assaulted by a barrage of frost and rain to erode them down, and once tectonic pressure relents millions of years later, erosion wins, diminishing mighty mountains to no more than a range of hills made from the cooked remnants of mountain roots.

Erosion can be assessed by monitoring the sediment load in rivers, and it can be faster than 10mm (½ in) a year or as slow as 0.5mm (1/64in) a year. [487] [488] But erosion doesn't have it all its own way – as the ground washes away, it lightens the load on the mountain roots, which slowly rise like a ship being unloaded (isostacy again), which is why mountain chains formed even hundreds of millions of years ago are still hilly today (like the Scottish Highlands and the Appalachians).

Landslides

It turns out that mountain erosion is far more dramatic than just the Zen-like rain-erodes-mountain-one-grain-at-a-time. Landslides are the most potent mountain-killing force.[489]



The word “landslide” probably recalls TV footage of an unfortunate property slowly departing down a hillside. And of course those do happen from time to time, but they are at the extremely wimpy end of the landslide scale.

To get an idea of the real power of landslides, imagine miles of mountains collapsing in an instant, dropping 50 billion tons of rock into the valley below, which races up the opposite side of the valley before soaring, airborne, clear over the ridge and into the next valley! A flying wall of rock 14km (9mi) wide, travelling at such speed it can glide into the next valley sounds impossible, but it happened in the Zagros Mountains, Iran, some 10,000 years ago,[490] in just one example of many all across the world. Others include the Flims rockslide in Switzerland, which dumped 12 cubic kilometers (2.9 cubic miles) in the path of the River Rhine, a landslide in Alaska in 1958 that triggered a tsunami taller than the Empire State Building, and it was a landslide that triggered the Mt St Helens volcanic eruption in 1980.

The speed of these phenomena is astonishing. In 1970 an earthquake in the Ancash region of Peru triggered an avalanche that turned into an 80 million cubic meter (105 million cubic yard) slide of water, mud and rocks that moved at 340kph(about 200mph) - as fast as a Formula 1 racing car! The speed was enough for it to ride over hills140m (460ft) high, hurling huge boulders into the air that landed up to 1km (½ mi) away! [491] Tragically, it buried a city and part of another with a loss of over 18,000 lives.

Fast-moving slides like these have a special name – "Sturzstrom." They move with such velocity that they can melt the ground they pass over, leaving a distinctive rock called "frictionite," which has been found across the globe, including in the Himalayas. [492]

But perhaps we should be more concerned about the mortal threat posed by landslides beneath the waves. The "Storegga Slide" was an undersea landslide that started off the coast of Norway about 8,000 years ago. The scale of this mass migration of rock is staggering – it spread across a large area of the Atlantic seabed, reaching halfway to Iceland! In doing so it triggered a tsunami that deluged Norwegian and North Sea coasts with waves up to 20m (65 feet) high in the Shetlands and up to 3 meters (10 feet) on the coasts of the Netherlands and eastern England. This devastated stone-age populations living there who were already at the mercy of rising sea levels at the end of the last ice age, probably wiping out any remaining inhabitants of "Dogger Land" (a now drowned island in the North Sea) and finally separating Britain from continental Europe. [493] Similar giant submarine landslides have been identified across the world, for example off the western coast of Africa (which flowed 1500km, (900mi) or the same as the distance from New York to Orlando),

[494] and in the deep waters off Hawaii. [495]

> "could generate a trans-Atlantic tsunami that would arrive on the American coast 7 hours later"

These events are not consigned to ancient history, either. The 1929 Grand Banks landslide off the coast of Nova Scotia killed 28 people and left 10,000 homeless, and a 6m (18ft) tsunami of mysterious origin affected the British Isles and Denmark on June 5 1858. [496] Today, some scientists suggest that the eastern seaboard of America is at risk from a tsunami that would result from an underwater landslide in the Canary Islands. Studies of the Cumbre Vieja volcano on the island of La Palma suggest its flank is primed to collapse at some point – nobody knows when. If it does, some calculations predict it could generate a trans-Atlantic tsunami that would arrive on the American coast 7 hours later with waves as high as 3 to 8 meters (10 to 20 feet).[497] This compares with the storm surge that accompanied Hurricane Katrina in New Orleans in 2005, and could cause extensive damage to major coastal cities like New York, Boston, Washington DC and Miami. Many scientists consider this disastrous scenario unlikely,[498][499] but research continues in an attempt to get a better handle on the threat[500][501] and similar-scale submarine slides have been found elsewhere in the Canary Islands, the Cape Verde Islands, and the Caribbean, suggesting the threat is plausible.

Volcanoes of mud and salt

Lava and volcanoes go together like... well, they just do. But there are 'volcanoes' that spew mud or even salt instead of lava.

On May 28 2006 a drilling rig was going about its routine business of exploring for oil in the island of Java, Indonesia. The drill bit was grinding its way to a target nearly 3,000m (9,000ft) below the surface when water, steam, and the smell of rotten eggs started erupting from the ground 150m (500ft) away from the rig. Soon hot stinking mud began to vomit from the orifice and flow all around it, spreading further and further with each passing day. 180,000 cubic meters of mud erupted daily, swamping surrounding farmland, homes and villages leaving 13,000 people homeless.[502] Dubbed "Lusi," it's still erupting and is likely to continue for years to come![502]

Lusi and mud volcanoes like it are no less a consequence of tectonic pressures in the Earth than their fiery counterparts. Waterlogged clays buried deep underground as plates collide are under intense pressure, ready to escape through any fissure they can find. An earthquake (or in the case of Lusi, a drilling rig) can be the kick they need to open a channel to the surface. Around a thousand natural mud volcanoes have been identified on land, and a similar number has been identified offshore, spread all across the globe from the Niger and Amazon deltas to the Caspian Sea to the Mediterranean, Black Sea, Burma and the islands of Indonesia. Along with mud, they also vent large quantities methane (a powerful greenhouse gas) into the atmosphere.[503]

Salt can make its own 'volcanoes' in a very slow-motion equivalent of mud volcanoes. Layers of salt from long-buried salt pans become more buoyant than the sediments above them, so they flow. They rise as blobs that disrupt the sediments they push through, sometimes reaching the surface like huge pus-filled boils, kilometers wide and hundreds of meters high.[504] Such salt mountains can even spawn salt glaciers ("namakiers") that slowly descend their briny slopes. There are hundreds of these in the Zagros Mountains of Iran ("namak" means salt in Farsi).

Salt movement is a boon for industry. Underground disruption by salt movement often creates traps where oil and natural gas can collect in sufficient quantities to make extracting them worthwhile, for example in the North Sea and the Gulf of Mexico. And the tendency of underground salt to flow may aid disposal of radioactive waste. Simulated canisters of radioactive waste were placed in a German salt cavern and left there. In just 8 years the seemingly-solid salt crept until it had completely entombed the waste containers.[505]

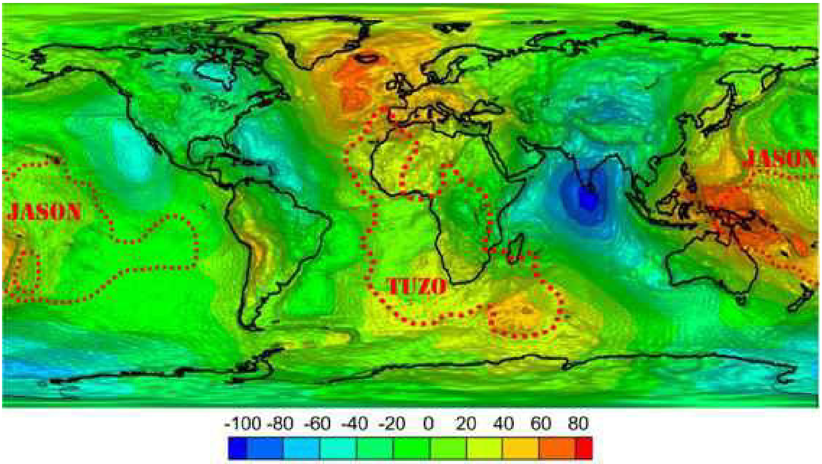
In touch with your inner mantle

The mantle shows itself through the crust in subtle ways, the way a lost toy is betrayed by a lump in a rug.

> "the way a lost toy is betrayed by a lump in a rug"

We are now beginning to appreciate that the motions of the mantle show themselves in the broadest scales of our continental landscapes. Where hot mantle mushrooms up under the crust it elevates the land over thousands of kilometers, like the high plateaus of the American West, [316] and the highlands of East Africa (the "African Superswell Structure").[313] As a kid in a high-altitude school in equatorial Kenya, I never imagined that the thin air and occasional night frosts on the soccer fields were a direct result of a swollen mantle! But the African Superswell is small compared to the largest inflammations on the planet.

As kids we are taught that Earth is a sphere, and to a gross approximation it is. But if you exaggerate the highs and lows of our planet's shape (the "Geoid") it is more like a potato than a ball. Two broad inflammations of the Geoid at opposite points on the globe have been mapped by satellites, one corresponding to Africa and the northern Atlantic, and the other across the western Pacific. These swellings correspond to those regions at the core-mantle boundary (nicknamed "Jason" and "Tuzo") associated with Plume Generation Zones. [455]



20 "Jason" and "Tuzo" superimposed on the "Geoid" (Earth's shape). Color scale shows how the actual Shape of the globe differs from a slightly flattened sphere (in meters). Jason and Tuzo at the core-mantle boundary correspond to swellings in Earth's shape at opposite sides of the globe. Source: [Burke, Annu. Rev. Earth Planet. Sci. 2011](); Geoid ©ESA – GOCE High Level Processing Facility

The mantle is far too deep beneath the crust to drill into. It's around 5 to 10 km (3-6mi) beneath the deep ocean floor, and 30 to 60km (20-40mi) beneath the surface of continents, whereas the deepest hole ever drilled was in Russia and it reached just 12km (7½ mi) [506] after nearly 2 decades of drilling! So scientists have relied on lumps of it brought up in volcanic eruptions, or indirect geophysical or geochemical analyses to learn about it. But recently scientists discovered an area where the mantle actually pokes through the crust at the Marion Rise in the Indian Ocean. This unusually buoyant piece of mantle is probably left over from the Karoo volcanic eruptions associated with the Toarcian extinction event in the Jurassic, and the Cretaceous eruptions as Madagascar separated from India. [507]

Rebounding from the ice age

During the last ice age Scandinavia and North America were covered in a great thickness of ice – more than 2.5 km (1.5mi) deep.[508] [509] This ice mass was heavy, so heavy in fact that it depressed the crust into the mantle (isostacy again), and the displaced mantle ebbed away from the dent, causing land for hundreds of miles around the edges of the ice to bulge. The ice-depressed crust lowered the altitude of the ice, making it easier to melt when solar warmth returned, generating rapid collapses of the ice sheets many times in the last 400,000 years.[343] When the ice melted, that weight was lifted, allowing the mantle to flow back again. But the mantle flows very slowly, so the crust is still rebounding even now, some 8,000 years after the last ice sheet melted.

Evidence for this lies in shoreline deposits well above today's sea level, and in data painstakingly gleaned from plant and animal remains in Scandinavian lakes that were overrun by sea and then reemerged. Dating these remains shows that in Scandinavia the land rose at between 1 and 1.6 cm (3/8 to 5/8 in) per year at the end of the last ice age. Then rising sea levels overtook the rising land, drowning freshwater lakes with salt water containing marine mollusks and algae.[510] When sea levels stabilized, the rebounding land re-emerged and its lakes contained fresh water again. Elsewhere in Scandinavia the presence of marine sediments miles inland, and freshwater lakes that once were part of the Baltic Sea, and ancient seaside settlements that are now miles from shore, are all vivid signs of the rebound after the last ice age.

GPS measurements confirm that Scandinavia is still rising by up to 1.2cm (½ in) a year, and surrounding areas are sinking by 2mm (1/16in) per year. Computer modeling of these movements shows that it is putting the crust under considerable strain[511] and this sometimes triggers new earthquakes on ancient faults.[512] It also opens those old fractures up for fluids and gasses to leak through them.[513]

Of course, the extreme example of ice depressing a large area of land is Antarctica. Airborne radar, seismic surveys and satellite altimetry allow us to "see through" the ice and plot maps of the sub-glacial landscape. They show that in some parts the Antarctic ice has depressed the ground up to 2.5km (1.5mi) below sea level, and entire mountain ranges with 3km (2mi) high peaks are submerged under a kilometer of ice![514]

Bottom line:

The Earth is dynamic across scales and timeframes beyond our everyday experience. Our landscapes and our atmosphere today are a consequence of these ongoing changes, which have been revealed by a myriad of scientific techniques, ranging from CAT scans through the interior of the Earth using earthquake waves, to exquisitely sensitive measurements of chemical variations. These data have shown us that the seeming permanence of our Earth is just an illusion. Our planet has been moving, changing and evolving since its birth, and it continues to do so today and it will into the future.

3. Proof of Life

When Darwin first suggested the evolution of species through natural selection, he was troubled by a dilemma:

> "... it is indisputable that before the lowest Cambrian stratum was deposited long periods elapsed, as long as, or probably far longer than, the whole interval from the Cambrian age to the present day; and that during these vast periods the world swarmed with living creatures... **To the question why we do not find rich fossiliferous deposits belonging to these assumed earliest periods prior to the Cambrian system, I can give no satisfactory answer**."[515]

In the mid to late 1800s, in the very early days of paleontology, it appeared as if a myriad of species just appeared, spontaneously, at the beginning of the Cambrian period (541 million years ago, or aged 88 in Your Life as Planet Earth). That and the lack of fossils catching creatures "in the act" of evolving from primitive species into modern ones (birds, amphibians, humans), were serious obstacles to the acceptance of evolution. As Darwin said:

> "Why then is not every geological formation and every stratum full of such intermediate links? Geology assuredly does not reveal any such finely-graduated organic chain; and this, perhaps, is the most obvious and serious objection which can be urged against the theory. The explanation lies, as I believe, in the extreme imperfection of the geological record." [515]

He was right, of course. The geological record is imperfect. But this was the infancy of Earth science, a time when

Darwin himself grappled with the span of geological time.[515] He and his peers were apparently still unaware of Mendel's theories of genetics (published at around the same time as later editions of his "On the Origin of Species"), and of course this was well before radiometric dating and a century before plate tectonics was understood. This was the time of the American Civil War and the Crimean War, before the source of the Nile had even been discovered.

Things have moved on over the inervening 150+ years, and Darwin's dilemma has been resolved. Not only have fossils been found going back 3 *billion* years (long before the Cambrian), but also fossils of intermediates for many species have been found, including precursors to whales, horses, birds, amphibians, and even humans.

> "the evidence for evolution is overwhelming. It is as proven as a round Earth and the Sun-centered Solar System"

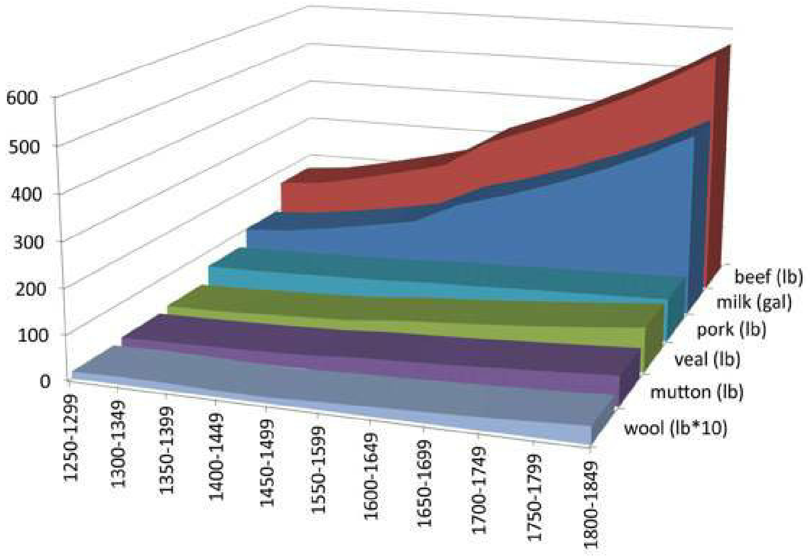
As we stand today, the evidence for evolution is overwhelming. It is as proven as a round Earth and the Sun-centered Solar System. Yet a surprising number of people just do not believe it. [516] [517] So it's worth exploring the fascinating and powerful evidence for evolution, which flows from 3 different areas of science – the fossil record, the biological record, and laboratory and field observations of evolution happening before our eyes.

Before I do, it's worth pointing out that evolution as *fact* is accepted by practically all scientists, and is the stated position of scientific institutions like The American Geophysical Union the Geological Society of America, the Geological Society of London (the oldest learned society for the Earth sciences in the world), and The National Academy of Sciences of the United States of America (including many Nobel Prize winners).

The Geological Society of London states that evolution is a *fact* "long established beyond doubt." [518] Similarly the American Geophysical Union calls evolution "one of the most important foundations of the science enterprise," [519] and the Geological Society of America calls evolution "now well established as a well-tested fact." [520] The National Academy of Sciences states that "Biological evolution is one of the most important ideas of modern science. Evolution is supported by abundant *evidence* from many different fields of scientific investigation." [521]

Evolution before our eyes

Farmers and animal breeders the world over have long used selective breeding to produce all the different kinds of domesticated dogs, cats and farm animals we have today. They used animal husbandry (*human* selection) to evolve shapes as diverse as the Dachshund and the Great Dane, large cows with milk-production that would be considered miraculous a few hundred years ago, bulls for beef twice as large as their ancestors, larger woollier sheep, [522] and pigs tuned to the different bacon markets in Europe and America. For many years farmers have used knowledge of genetics to improve crop resistance to disease, pests and drought through plant hybridization. These same aims are now the driving force behind the production of genetically modified crops. It's inconceivable that *natural* selection pressures (like changes in available vegetation or competition from other species), applied to generation after generation over millions of years, would have any less effect.



21: **Human selection causing evolution in farm animals: Historical Yields *per Animal* in Britain and Holland.** Based on Apostolides, et al, Univ. Warwick, 2008.

Evolution has been directly observed in the laboratory, for instance within fruit flies,[523] [524] bacteria,[525] wheat,[526] and even Bird Flu.[527] It has also been observed outside the lab, for example the increasing prevalence of drug-resistant malaria, antibiotic-resistant "Methicillin-resistant *Staphylococcus aureus*" (MRSA) and the SARS microbe. The process of natural selection causing evolution is surprisingly rapid: scientists working in Trinidad watched fish evolve in response to environmental change in as few as 20 generations (a guppy generation is 3-4 months, so that's 5-6 years).[521]

That doesn't mean there's nothing left to learn about evolution – far from it.

As the complete genetic codes (genomes) of more and more species are mapped, we are learning some surprising things. At the time of writing over 3,000 species have had their genomes mapped, including humans, bonobo apes, tomatoes, grape vines, mice, rice, yeast, corn, sorghum, some viruses and bacteria, some fungi, the turkey and even the puffer fish,[528] [529] and over 12,000 more species are in the works. These genome "maps" enable sections of genetic code that are the same in different species to be identified, and so ancestral trees can be defined from matched genes.

In the early stages of mapping the human genome, it appeared as if most – 98% - of our genetic material served no purpose, so it was dubbed "junk DNA." But since then this "junk" has been found to have many functions, from defining proteins to marking landing spots for proteins that influence genes, to switches that turn off bits of our chromosomes.[530] A portion of the "junk" is not human but actually viral DNA mixed in with our genes, creating populations of "endogenous retroviruses" that we pass on to our kids in just the same way we pass on the color of their eyes! It turns out that humans - and most mammals - carry DNA from viruses inherited over millions of years, going back to the age of the dinosaurs![531] Some of our genes have also been found to be "fossil genes" that gave us immunity to long-forgotten diseases deep in our evolutionary past, but which we still carry with us.[532]

The technological revolution in gene sequencing that made genome-mapping a practical endeavor has also triggered new movements in biology like "epigenetics," and the overlapping field of "evo-devo." They are starting to illuminate how our environment may switch on or switch off genes that we inherit, and the way a gene is expressed in an embryo alters the shape of an animal, like a bird having a longer beak than normal. This refining understanding of genetics holds promise for improved treatments for cancer and other diseases.

So evolution through natural selection is proven in the laboratories, field studies and medical experience of today. But that's not much help in narrating the play of life from its earliest origins. For that we turn to the fossil record, as well as the trail of clues contained within the cells of living organisms today.

Not your grandfather's fossils

When I say "fossil" you are probably picturing a dusty piece of rock with a curly seashell protruding from it. That's the kind that Darwin and his contemporaries were familiar with, but the fossils we can detect today are beyond the wildest imaginings of those 19th century collectors. Paleontologists now study fossils ranging from the microscopic to the size of an entire forest. Using techniques as diverse as rock-dissolving acids and CAT scans. They can even learn about ancient life when there's nothing left but a stain, or a burrow, or even just an imbalance between atomic isotopes.

Bear in mind that it's actually quite hard to preserve a dead creature as a fossil. It requires a series of happy accidents, like being covered by low-oxygen sediments soon after death to avoid rotting away, compaction of those sediments into rock, tectonic upheaval, exhumation millions of years later, and finally a chance find by a paleontologist. This means that the oldest fossil of a plant or animal is unlikely to be the first individual of that species, and the last recorded fossil may well predate the actual extinction of the species (this is known as the "Signor-Lipps Effect").

"it's actually quite hard to preserve a dead creature as a fossil"

Elusive earliest life

It would be great if we could find tangible fossil traces of LUCA – the first life on Earth - but it's hard to see how we could tell a fossil LUCA vent from any other ancient submarine vent. In the absence of fossil evidence for LUCA, we have to resort to biological clues to her existence later in this chapter.

For hard, fossil evidence of the earliest life we turn to microscopic traces in some of Earth's most ancient rocks. Claims were made in the 1990s for fossil traces of life as old as 3.8 billion years, in rocks located in the inhospitable wilds of western Greenland, but they have since been refuted. Other scientists painstakingly picked-apart the complicated rock structure and found that, sadly, the rocks with the putative life-traces weren't as old as first thought, and that they were formed as underground magma intrusions "wholly unsuitable for the discovery of primordial traces of life."[533]

It's hard to overstate how difficult it is to find and date unambiguous traces of microscopic life over 3 billion years old, in rocks that have been squeezed and folded and heated many times until even establishing the original rock type is not trivial. Unlike seashells, skeletons, teeth or even the imprint of a fern frond, the traces of early life are miniscule and barely different from their surrounding rock. It is not even enough to find traces of carbon associated with microscopic fuzzy bits. The carbon must be derived from kerogen (which is also found in petroleum and coal deposits) and must have reduced levels of the isotope carbon-13 which is depleted by biologic processes. [534] In fact the earliest traces of life on Earth are just such carbon deposits. [37]

We begin to see clearer traces of early life in the Barberton Greenstone Belt in South Africa, in the form of microscopic tubes on the rims of 3.5-billion-year-old lavas that bear uncanny resemblance to microbe-formed structures on the skin of modern submarine lavas. The clincher is that traces of carbon within these tubes have the right proportion of carbon isotopes to indicate they were created by life. [48]

In the first part of this book I described the humble stromatolite – basically a mound created by layers of slimy bacteria trapping and precipitating sediments. The ancient rocks of Western Australia contain an entire 3.43-billion-year-old reef of stromatolites. [46] The distinctive domes, cones and egg-crate shapes are proof of early slime-life, further confirmed by the superb preservation of clusters of microscopic cells, tubes, threads, films and spindle-shapes. The diversity of fossil microbe shapes suggests that even back then there already was a veritable community of microbial life. Better than that, scientists found tiny crystals of "fools' gold" (pyrite – or iron sulfide) associated with the fossil cells, which have a sulfur isotope ratio that is a dead giveaway that they were formed by microbes extracting energy from sulfur chemicals in the water. [47]

Those sulfur isotopes are an example of another kind of "fossil" that Darwin could not have imagined: chemical fossils.

Chemical fossils

Amazingly, scientists today can detect signs of ancient life even when there is nothing left but a slight stain between grains of ancient rock.

For instance, the first evidence for the more complex kind of cell that led to you and me shows up as little more than a chemical trace. [24] Our cells, like the cells of all eukaryotes (animals, plants, fungi, amoebas and some other single-celled critters) use a class of chemicals called "sterols," an important difference from non-eukaryotes like bacteria and archaea. [24] Sterols are necessary for the biochemistry of our cell membranes (cholesterol is a sterol). So finding sterols in ancient rocks would be a great clue that eukaryotes rather than more primitive bacteria or archaea were present. Unfortunately sterols degrade over time but the good news is that they degrade into steranes, which are much more resilient chemicals capable of hanging around for a couple of billion years or more. In fact, scientists joke that after you are dead and buried, the last trace of you will be your cholesterol! [535]

Traces of steranes have been found in rocks approximately 2.5 billion years old from Canada, Gabon and South Africa. In some locations there is uncertainty that the steranes date from the formation of the original sediments rather than from fluids that seeped in over eons since, but for now the balance of opinion is that they remain the earliest, if tenuous proof of eukaryote life – our distant ancestors. [24]

> “chemicals known as ‘2-methylhopanes’ are all that remain of the first cyanobacteria”

Similarly, the first traces of cyanobacteria – those first producers of oxygen that gave Earth its mid-life crisis – are chemicals. A small group of chemicals known as “2-methylhopanes” are all that remain of the first cyanobacteria. As was the case with steranes, there has been some debate over how reliable these oily hints are, but again recent work tends to confirm them as a valid trace for those special oxygen-producing creatures around 2.7 billion years ago. [24] [536]

Interestingly, eukaryotes need oxygen to make sterols [535] – something they had to rely on cyanobacteria to provide, and it may be no coincidence that both innovations in life show up at broadly the same time. But the steranes show us that eukaryotes were around some 300 million years before oxygen had built up significantly in air and water, so scientists were scratching their heads about that for a while. Thankfully, recent experiments have shown that primitive eukaryotes don't need much oxygen to produce sterols – trace amounts are enough,[535] and that's all that was available from those first cyanobacteria until the rocks and oceans were done absorbing all the oxygen they could.

At the other end of the timescale, sterols in sewage have been put to work to track the spread of human settlements after the ice-ages. Some sterols (5β-stanols) are only found in human and livestock feces, and above certain levels they are a sure indicator of human settlement. By analyzing the fine layers of sediments for these fecal markers in a lake in northern Norway, scientists were able to date the first human settlements there to 2,300 years ago.[537]

Chemical traces also provide important clues to the first colonization of land by early plants and fungi in the Cambrian period. Analysis of fossilized soil from that time reveals a pattern of aluminum, silicon and phosphorous levels that show it was treated by organic acids – which are naturally produced by plant roots in soils to this day. A phosphorous mineral called apatite is missing from the top layer of the soil (plants absorb phosphorous, depleting it from soil, which is why you add it to lawns and gardens in fertilizer). In addition, the clays in the soil show that calcium ions were plentiful. These clues together are a tell-tale "biosignature" of specialized fungi that live in symbiosis with plant roots, called "mycorrhizal fungi."[538] Because these fungi rely on plants for essential nutrients, evidence for them is also evidence for plants on land at that time, bolstering the first tenuous evidence for liverwort-like plants in the fossil record.[81]

Chemical fossils are far more than arcane tools for specialized paleontologists. The oil industry has been using chemical fossils ("biomarkers") for decades to appraise rocks that may have been the source for oil. They can choose from a menu of several hundred different chemicals with exotic names to discover what kind of life led to the formation of a sample of oil, and in many cases the kind of environment that it lived in. [539] For instance, a class of chemicals made of a chain of carbon atoms, called "alkanes," betrays their origins in the number of carbon atoms they contain. Alkanes with 15, 17 or 19 carbon atoms come from lake or marine algae, whereas those with 27, 29 or 31 carbon atoms originated as land plants. [539] "Pristane" and "Phytane" are all that remain of long-decomposed chlorophyll from plants, and "Bicadinane" tells us the rock once contained the resins from conifer trees. [539] Still others like "Oleananes" and "lupanes" originated from flowering plants, [539] whereas "dibenzothiophene," "dibenzofuran" and "biphenyl", can indicate where woody plants were buried but have long since decomposed. These last three tell us about the amount of vegetation washing from land into oceans. A big drop in these chemicals tells us there was probably a big reduction in vegetation on land, such as happened at the Permian "Great Dying."[540]

One of the most important traces of life, and yet maybe the subtlest, relies on subatomic differences in carbon isotopes. Most carbon in the world – in the air you breathe, the food you eat and the fuel you burn – is made up of the isotope carbon-12 (^{12}C). Only around 1% is made up of the fractionally heavier carbon-13 isotope (^{13}C). And it is this miniscule difference in mass that can tell us if life produced a carbon sample. Life generally prefers the "regular" ^{12}C variety of carbon. This means organisms concentrate ^{12}C within them while ^{13}C is shunned and builds up in the atmosphere and oceans. Even the earliest traces of life show up as 3.7 billion year old carbon deposits that are depleted in ^{13}C. [37]

Fossil fuels like coal, oil and methane have the same high ^{12}C proportions of their plant origins. If a vast amount of fossil fuel is burned or natural methane is released into the air, this shows up as a big increase in ^{12}C levels (and a corresponding negative shift in ^{13}C), such as happened at the Permian Great Dying, [181] the Triassic, [195] and the "PETM." [262]

So in myriad ways chemical traces can serve as "fossils" of life for which no other evidence remains. But subtle variations in chemicals can tell us other surprising things about ancient life, even ancient behaviors.

Tooth tales: ancient migrations and diets

The idea that dinosaurs underwent seasonal migrations over several hundred kilometers, like modern wildebeest in East Africa, is beguiling. But how can we possibly know? We can't track their footprints very far, and the fossil bones lie where the creature died – like a death-mask that can't tell of its living travels. Establishing the behavior of extinct creatures is fraught with difficulty, so it would seem impossible to prove the wanderings of individuals some 150 million years ago. Yet scientists have done just that by some ingenious work using fossil teeth from giant, long-necked *Camarasaurus* dinosaurs.

They analyzed the growth layers in the fossil dinosaur teeth for variations in isotopes of oxygen. They were then able to link those chemical traces to the water that the creatures drank, using the oxygen isotopes in sediments at different places across Utah and Wyoming. In this way they showed that several *Camarasaurus* individuals migrated from lowlands in the east to spend the summer dry months in western highlands before returning to the lowlands. [541]

> "it was the custom of our very early ancestors for brides to leave their homes and live with their husband's family"

A similar study on our pre-human ancestors was just as revealing. Scientists used fossil teeth from 2-million-year-old South African *Australopithecus africanus* and *Paranthropus robustus* specimens. By comparing the strontium isotope variations within the teeth of males and females with natural strontium levels in locations near where they were found, they were able to show that males tended to live in one area all their lives, whereas females were generally born elsewhere. In other words, it was the custom of our very early ancestors for brides to leave their homes and live with their husband's family![542]

Oral hygiene in our primitive ancestors was not up to our modern standards – which is a good thing for science. By picking at the dental plaque preserved on the teeth of *Australopithecus sediba* (a 2-million-year-old pre-human) scientists were able to find microscopic traces of what they had been eating still stuck there. Specifically they collected "phytoliths" which are microscopic silica crystals formed naturally in plant cells. These have characteristic shapes depending on the species of plant, so the scientists were able to tell that *sediba* ate mainly woodland leaves, fruits and bark. The scientists also used lasers to vaporize tiny pits into the enamel of the teeth ("laser ablation") and analyze the isotopes of carbon in the vapor. This showed that throughout their growth, these individuals had preferred a forest diet. [543] Thank goodness they didn't floss!

Realm of the tiny

Although Darwin was aware of microscopic fossils (he referred to them as "infusoria" and "rhizopods") [515] advances in microscopy since his time have revealed a cornucopia of tiny fossils that have played an important part in our understanding of changes in Earth through time. Even when rock might appear barren of fossils to the naked eye, modern microscopy - especially the electron microscope - allows us to zoom into the realm of the tiny where we can find a cast of thousands waiting to be read like a book to reveal ancient climates, water conditions and biodiversity.

Phytoliths, for instance, are not just used to reveal the dietary choices of our ancestors and other extinct creatures. [238] They are resilient enough to survive in rocks when all other traces of the plant that formed them have disappeared, and they even survive the journey through an animal's gut to be preserved in fossil poop (more delicately referred to as "coprolites"). [238] These allow us to trace the spread of grasslands across the globe, [237] and to build a picture of the flora that inhabited an area at a particular time. [543]

Spores and pollen – heralds for land plants

Crucial evidence for the evolution and spread of land plants comes from fossil pollen and spores. These tiny reproductive particles have distinctive shapes and textures that are characteristic of the types of plant that they originated from, so in finding the spore or pollen you have evidence for the plant that produced it. Spores or pollen are more likely to be preserved than their parent plants because each plant produces them in large numbers, they are made of resilient materials, and are small enough to be blown or washed into lakes or seas where sediments will preserve them even if the parent plant lived on some eroding hill slope doomed to disappearance.[81]

The earliest tentative evidence for land plants shows up as microscopic "cryptospores" and enigmatic tubes in the deep recesses of the Grand Canyon and Tennessee.[81] These are over 500 million years old, about 100 million years older than whole-plant fossils in the Scottish "Rhynie Chert." It's uncertain if those cryptospores come from a kind of liverwort or from algae, but they do resemble younger liverwort spores[81] and they are only 40 million years older than confirmed land plant spores from Argentina.[118] Considering recent evidence for the kind of fungi that are associated with plant roots ("mycorrhizal fungi") in 500 million-year-old Cambrian soils,[538] the case for the rise of early land plants around 500 million years ago looks increasingly plausible.

Not long after those cryptospores appear, we start finding "Trilete spores" – a kind that bears a Y-shaped dent. These are linked to plants that had evolved stems ("vascular plants"), like *Cooksonia*, hornworts and mosses. They first show up in the early Devonian, around 450 million years ago, again well before the whole-plant fossils for these plants are found, placing the arrival of vascular plants at a time of significant atmospheric, climate and evolutionary changes.[119] [129] [90]

With the advent of seed plants, pollen grains begin to show up in rocks. Pollen is as diagnostic of its originating plants as spores are for more primitive plants. This is tremendously helpful in plotting the spread of conifers, [164] and then (in the Cretaceous) flowering plants,[225] and is invaluable for revealing the traumatic changes at major extinction events such as at the end of the Triassic, when forests were devastated and replaced by ferns. [196] Pollen is also useful in narrowing down the time period rocks were formed in, especially in fresh water sediments where marine fossils normally employed for this job are missing. [544]

These tiny plant fossils are just a small part of the wide palette of microfossils that scientists use to correlate different rock layers, to establish their dates, and to reveal ancient environments.

Temperature-telling teeth

Perhaps the most bizarre are tiny, spiky tooth-like fossils called "conodonts," which were used for decades to match up different strata without anyone really knowing what kind of animal they came from. Then in the early 1980s a fossil of a big-eyed eel-like creature was found in Scottish oil shales with these "teeth" intact, revealing that they were indeed a kind of feeding apparatus. [545] Aside from defining various geological time zones, they can show how hot the rock containing them became during its sojourn underground. The phosphorous-based mineral that conodonts are made from changes color based on the temperature it has been heated to, from pale brown, to brown, black, and finally white (around 80°, 140°, 480° and 550°C respectively). [546] This information helps calibrate how deep rocks have been buried in tectonic upheavals, and tells oil explorers what grade of oil or gas they can expect to find. Conodonts first appeared in the Cambrian and they succumbed in the Triassic mass extinction 200 million years ago. [544]

The Swiss Army Knife of fossils

> “their shells give a measure of the water temperature they lived in”

Fortunately there is another group of tiny marine creatures who outlived the conodont animal - the foraminifera, or “forams” as most people prefer to call them. They are amoeba-like blobs which have the advantage (for us) that they make a durable skin with a huge variety of shapes ranging from simple balls to elaborate seashell-like structures, spirals, bunches of grapes or even vases, depending on the species.

Forams have so many uses you can think of them as the little Swiss Army Knives of micropaleontology! Being only about half a millimeter big means that even a single borehole can recover a useful sample of fossils. They are widespread in many environments and they underwent rapid evolutionary bursts, which allows precise matching to other locations across the globe. [544] Oxygen isotopes in their shells give a measure of the water temperature they lived in, and different foram species that live in different habitats reveal ancient ocean temperature, salinity and depth profiles. [544]

22 A diversity of forams from a single beach in Burma. The photo is just 5.2 mm (2/10 in) across. Source: Wikimedia Commons/Psammophile

… and many more…

Even Swiss Army Knives have their limits. In deep waters where the calcium carbonate of foram shells is dissolved away, scientists can turn instead to the silica-based skeletons of "radiolaria." These perforated balls and y-shapes are only about 1/10 of a millimeter big, but can be used much like forams. They are especially handy in rocks that have undergone intense changes in continental collisions. Their tiny flinty skeletons preserved in bands of chert are often the only fossils that survive in those rocks, providing a unique insight to conditions in long-departed seas.[544]

There is a host of other useful microfossils that I don't have space to discuss here, like Acritarchs (a catch-all name for a range of planktonic creatures, cysts and embryos from the early days of life to the present), chitinozoa (resembling small vases), ostracods (tiny leggy crustaceans in clam-like shells), diatoms, coccolithophores (whose bodies make up chalk) and dinoflagellates.[544]

So by delving into the realm of things too small to be seen without a microscope, scientists have been able to trace the evolution and global spread of different plant groups, learn about the diet of extinct animals, uncover the thermal history of rock strata, reveal ancient ocean temperatures, salinities and depths, and even match up disparate rock layers. But what about the other end of the scale - fossils so *big* they can't be appreciated wihout a bird's-eye view?

Realm of the really big

Fossil forests

We often talk of "not being able to see the wood for the trees" but in the Earth sciences this can be both a figurative and a literal problem. Much can be deduced from a single fossil – an isolated leaf impression, a shell or a tooth for instance – but inferring how different life forms coexisted in a

"like the ruins of Roman Pompeii"

community, based on isolated specimens, is fraught with difficulty. Just occasionally we do uncover fossils of such size and quality, and from a single instant, that they capture an entire ecosystem frozen in time. They are a bit like the ruins of Roman Pompeii where human bodies and artifacts lie preserved in the moment they were overrun by volcanic ash in AD 79.

The Pompeii analogy is particularly apt for the fossil Permian forest discovered at Wuda in Inner Mongolia, China, where over 1,000 square meters of forest has been found preserved in volcanic ash, just like the unfortunate Romans. This exceptional preservation has allowed scientists to plot the locations of thousands of individual plants in the actual spots where they lived 300 million years ago in their swamp, and so to reconstruct the ancient forest of long-extinct plants – trees, ferns, undergrowth and all.[547]

Perhaps the best known example is the Joggins fossil forest preserved in the tidelands of Nova-Scotia. This has over 60 separate levels [548] of fossil forest, which made a profound impression on Sir Charles Lyell and Sir William Dawson (two founding fathers of geology), when they visited the site in 1852. Along with fossil tree-trunks standing today where they grew in the Carboniferous, they discovered fossil amphibians, reptiles, millipedes and snails preserved where they hid in the hollows of those trees.[163] Dawson returned in 1877 armed with explosives to uncover more, and collected over 100 fossil amphibians and reptiles! The Joggins fossil forest influenced Darwin's theory of evolution and helped resolve the debate about the origin of coal.[163]

There are over 60 Carboniferous-era fossil forest sites that have been uncovered across the globe so far, [548] including a 310 million-year-old rainforest in Ovčín, in the Czech Republic, preserved in Pompeii-like ash, allowing paleontologists to distinguish the ground cover and understory plants from the creepers and the forest canopy.[548]

Bone beds and trackways

One of the most impressive fossil sites I have seen is the Dinosaur Quarry at the Dinosaur National Monument in Utah USA. It is a warehouse-sized, bone-strewn slab of rock upon which the contorted skeletons of dozens of dinosaurs of different species, young and old, lie as they were buried in their mass grave 150 million years ago. The quarry is just one part of the Morrison Formation which has yielded many dinosaur fossils across the western USA, including a huge collection of dinosaur footprints in southeastern Colorado. This "dinosaur trackway," with the footprints of more than 100 different dinosaurs, shed light on their gregarious behavior and also on the ratio of predators to prey species (which turned out to be similar to the ratio in modern species).[549] There have been similar finds around the world including in Yemen [550], France [551], China [552] and Arkansas.[553]

It's not just dinosaurs and coal forests that are preserved on a big scale. A 15 km (9 mile) area in California's San Joaquin Basin is home to a "bonebed" dating back to the Miocene, some 15 million years ago. It is just crammed with shark teeth, bones of dolphins, seals, whales, turtles, camels, horses, and teeth from the extinct giant shark called *Carcarodon megalodon*, which was much larger than a modern Great White shark.[554]

So paleontologists do occasionally get their hands on fossil sites that help them get the big picture of what an ecosystem was like at a given point in time and space. But sometimes they are blessed with discoveries that are special for another reason - they reveal much more than bones, shells and tree trunks. They reveal the delicate soft tissues that normally rot or are scavenged away before a fossil is safely locked-away in sediment.

Soft Stuff

If you think of your own body, there's much more to you than your skeleton, and yet for the most part if a fossil is preserved at all, only the hard parts – bones, teeth, shells, spores and woody trunks – get preserved. Forensic scientists could make a reasonable reconstruction of what you look like if all they had were your bones, but think about all those creatures who have no hard parts to speak of – the jellyfish and worms of this world. And even those that do have bones or shells –what did the animal that owned the bones, or inhabited the shells, really look like? Without soft tissues you have a very impoverished sampling of the real diversity of life at the time.

And that was essentially Darwin's dilemma, since in his day fossil collecting had not yet encountered those rare and precious fossil sites known as "lagerstätten," where soft parts of creatures are delicately preserved. All they knew of were fossils from after the evolution of the seashell. Lagerstätten have fleshed-out (pun intended) the diversity of life before the seashell first appeared in the Cambrian, and since.

Gunflint and Bitter Springs

It wasn't until the 1950s that the first convincing evidence for Precambrian life was discovered in the 2.1 billion-year-old Gunflint Chert (a 'banded iron formation") on the shores of Lake Superior, Canada. A geologist named Stanley Tyler took rock specimens and ground them into thin, translucent microscope slides. The flinty, striped rock was found to contain a wealth of cells and filaments, even preserving the internal structure of some. [555] The silica in the waters where these microbes lived had permeated their bodies and entombed them in rock hard enough to resist the ravages of 2.1 billion years of continental drift, burial, exhumation and ice ages. The silica preserved such detail that the fossils were unassailable evidence for early Precambrian life, at around the time of the planet's "mid-life crisis" that I described in the first part of this book.

Before long, other discoveries of petrified Precambrian life were discovered. At Bitter Springs in central Australia, more filaments and chains of cells were discovered in 820 million-year-old chert. These have been identified as cyanobacteria, algae, possible fungi and other microbes. [555]

Jellyfish and embryos

In 1947 geologist Reginald Sprigg announced his discovery of fossil "jellyfish" and other soft-bodied animals he had found on a mineral prospecting trip at Ediacara in the Flinders Ranges, South Australia. He assumed they were Cambrian, but they were later found to be Precambrian – from around 560 million years ago. [555] His discovery of fronds, disks and other shapes in sandstones bore witness to diverse soft-bodied-animal life at the end of the "Slushball Earth" period.

It sparked a search for similar fossils around the world, and since then exquisitely preserved fossils of this period have been found at Doushantuo in China, Mistaken Point in Canada, in Namibia, the White Sea region of Russia, India, and Shropshire in England. [556] [557] The fine detail preserved at some sites has even allowed scientists to study individual cells. For example, the Doushantuo fossils include tiny animal embryo cells, [558] seaweed, sponges and relatives of jellyfish. [49]

> “the fossilized brain of an ancestor to insects, spiders and crustaceans”

Reaching up into the Cambrian (aged 88 in Your Life as Planet Earth), we find more examples of extraordinary preservation, like a crustacean with every delicate strand of its filter-feeding mouthparts preserved in fools’ gold, [559] or the fossilized brain of an ancestor to insects, spiders and crustaceans![560]

The 510-million-year-old Canadian “Burgess Shale” is a spectacular location for Cambrian soft-bodied fossils. If you have ever discovered a bug flattened between the pages of an old book, you have a reasonable idea of the fossils there. Taking the place of pages are layers of shale, and the squished bugs are a wide range of arthropods, mollusks, worms and the earliest precursors to vertebrates. [49] The preservation is so good it even includes the guts of some creatures! [559] There are other Cambrian sites with similarly excellent preservation in Greenland, Örsten in

Sweden, Emu Bay in Australia, and Chengjiang in China.

Spiders from Scotland, feathers from Germany

Moving forward in time there are other lagerstätten sites scattered across the globe and the geological timescale, each filling in more detail of the anatomies of ancient creatures.

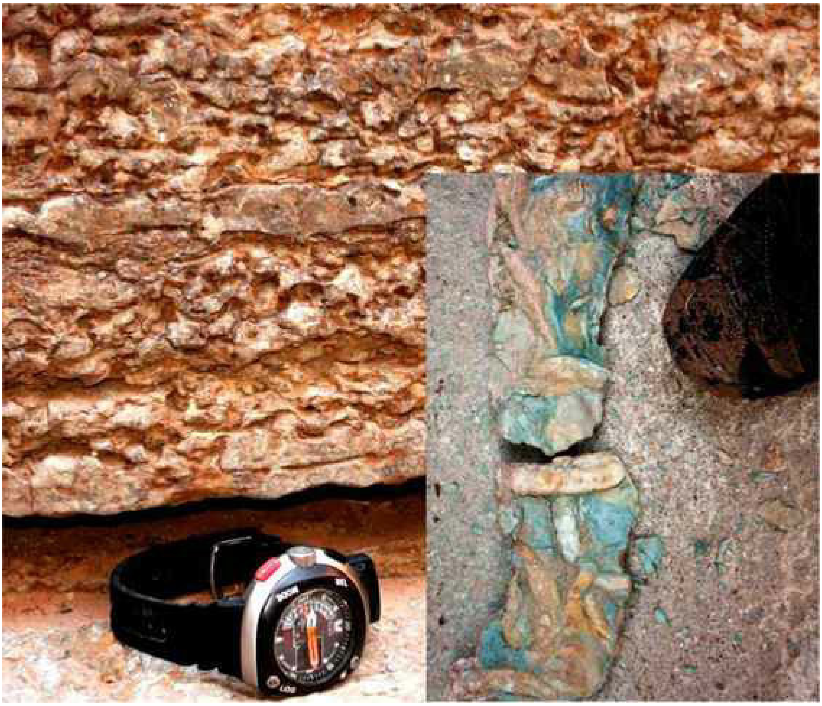
The Scottish "Rhynie Chert" is one. It shines a spotligh on the earliest days of land plants and the fungi, microbes, spiders, insects, mites and centipedes that lived among them. This Devonian community lived near volcanic hot springs that periodically engulfed them in silica-rich fluids that petrified them, down to the cellular level[49] 410 million years ago (aged 91 in Your Life as Planet Earth). The Solnhofen limestone quarry in Germany is another example. It preserves Jurassic creatures including the early bird "*Archaeopteryx*" as well as pterosaurs, dinosaurs and fish. The first Solnhofen "*Archaeopteryx*" specimen had clear impressions of feathers as well as a reptilian tail and clawed fingers. Its announcement just 2 years after Darwin published his first edition of "On the Origin of Species" was greeted skeptically at first, but eventually it was accepted as an intermediate between dinosaurs and birds.[49]

If lagerstätten are the Rolls Royces of fossil sites, it tempting to think of the next kind of fossil as more like a Ford transit van – utilitarian but indispensable.

Burrows and footprints

A rafting trip through the Grand Canyon, aside from being one of the most awesome experiences possible, is a backwards recital from the pages of time. Starting at Lee's Ferry surrounded by dinosaur-era strata, you regress through Carboniferous strata replete with marine fossils, until towards the end of the second day you reach the Cambrian "Tapeats Sandstone." Here the canyon walls look like they were assaulted by rioting pastry chefs!

Millions of finger-like blobs and smears bear witness to the feeding of creatures who tunneled in the sea bed some 525 million years ago, devouring anything before it had a chance to become a fossil, but leaving their burrows behind instead as "Trace Fossils."



23 **525 million-year-old worm burrows in the Tapeats Sandtone, Grand Canyon.** Watch and shoe for scale, photo by the author.

Trace Fossils are the burrows, tracks and footprints left behind by life. The blobs in the Tapeats Sandstone are a kind called "*Trichophycus*" which aren't found in rocks before the Cambrian Explosion, a clear indication of the new kinds of life that emerged then. In fact, trace fossils provide the earliest clues to the emergence of complex creatures because backfilled furrows require a creature that has a distinct front and rear end ("bilateran"). Such trace fossils have also been found in possibly older rocks in Uruguay, but their age is still debated.[561]

You can find other trace fossils in the Tapeats Sandstone: rope-like trails snaking through the worm burrows are trilobite tracks (known as "*Cruziana*"). In fact we know from trace fossils like *Cruziana* that arthropods (the group that contains trilobites, crabs, spiders and insects) appeared at the dawn of the Cambrian, millions of years before the oldest trilobite fossil itself,[562] just like the fossil spores that predate their parent plant fossils as I described in "The Realm of the Tiny" above.

Careful recording of trace fossils can tell scientists about the environment they were made in, its biodiversity,[563] the relative oxygen level, whether sea levels were rising or falling at the time, and even changes in salinity.[564] In fact the dinosaur trackway I mentioned in "Realm of the Really Big" above is also a trace fossil, revealing gregarious animal behavior. In the case of the largest dinosaurs, there are relatively few skeletal fossils, but their footprints are much more common. This allows scientists to use statistical analysis on the patterns of dinosaur footprints to tease out evolutionary changes over time. One such study was able to show that dinosaurs became more specialized into different ecological niches as time progressed from the Jurassic into the Cretaceous.[565]

> “a poignant record of the crab’s increasingly erratic behavior as it asphyxiated”

Just occasionally a dead body lies fossilized at the end of its tracks, enabling scientists to make a firm link between the trace and the creature that made it. In one example, from Solnhofen in Germany (where that famous *“Archaeopteryx”* bird fossil was found), a horseshoe crab lies at the end of a 10 meter (11 yard) death-march preserved as tracks in the stone. Its footprints are a poignant record of the crab’s erratic behavior as it asphyxiated in an oxygen-starved lagoon 150 million years ago.[566]

So trace fossils are a valuable part of the fossil record, which can record the communities that lived together, their environment, and even their behavior. But these days paleontologists also have high-tech tools to “see through” rock and extract even the most delicate, complicated fossils.

CAT scans

You or someone you know may have had a CAT scan in hospital. The "CAT" stands for "Computer Aided Tomography," a range of techniques widely used outside medicine, including in paleontology. Often fossils are so inextricably bound in their rocky tombs that any attempt to extract them would destroy them, so scientists use advanced CAT scanning technology to extract those fossils intact, albeit virtually, to reveal the tiniest of details.

In one example, every microscopic hair of a diminutive fly trapped in amber was revealed, and pollen grains on its back shown with enough detail to identify the species of plant the fly was pollinating. The 1mm (1/32 in) thrips were scanned at facility known as the "European Synchrotron Radiation Facility" – ESRF in France, which accelerates electrons close to the speed of light in a synchrotron the size of a stadium, generating exceptionally bright beams of x-rays. [567] This is a modern upgrade of the technique used to reveal the double-helix structure of DNA employed by Franklin, Watson and Crick in the 1950s. In those days they used x-ray films but in the case of our thrips, the scattered x-rays were measured by electronic detectors. Software then calculated the internal structure of the specimens from those measurements, revealing a 3-dimensional computer image of the pollinating flies. This was more than a visual joy-ride, as the results showed that the thrips were specialized pollinators of cycad plants 110 million years ago. [568]

A similar project revealed hundreds of tiny ants, flies, spiders, and even snails in opaque lumps of 100 million-year-old French amber[569] and the same technique has uncovered delicate feeding structures in ammonites that prove they ate plankton, [570] provided clear images of the inside of Ediacaran embryos, [571] and revealed the growth of teeth in 160,000 year-old humans. [572] It is also ideal for getting inside fossils without breaking them apart, which is how we know the brain shape of our pre-human ancestors Sediba and Toumaï.[356] [324]

Stadium-sized synchrotron facilities are dotted sparsely across the world, but X-ray scanning is getting smaller, and it is now possible to get comparable images from equipment the size of a large fridge-freezer. It was such equipment that uncovered some of the oldest multicellular fossils from Gabon,[71] and revealed a tiny mite hitching a ride on a 45 million-year-old spider.[573] Neither do the images have to remain on screens. They can be fed into 3D printers to manufacture enlarged plastic versions, accurate to the tiniest detail, for paleontologists to examine in their hands.[574]

Using X-rays this way comes with a bonus feature. The spectra of the x-rays from the specimen diagnose its chemical makeup. This has, for instance, allowed scientists to infer color patterns on the feathers of long-extinct birds.[575]

In some cases where the fossils are the faintest of impressions in sandstone, a different kind of scanning technique can be used. An offshoot from construction survey technology, 3D laser-scanning tracks lasers across a specimen, recording every bump and crevice. The results are fed into a computer and "rendered" in 3-dimensions. This technique has revealed previously unappreciated growth patterns in Ediacaran fossils, and has challenged ideas about feeding and evolutionary relationships between these enigmatic creatures.[576]

So fossils that were unimaginable in Darwin's day, and too small, fragile, or subtle to study even in the 20th century, are now yielding to the technologies of the 21st century.

Missing links – found!

One of the early criticisms of evolution was the lack of fossils of intermediate links between species that were thought to have evolved one from the other. By the beginning of the 21st century most of those missing links have in fact been found in the fossil record, and it's worth mentioning some.

Fish - from fins to legs

We now have fossils of most of the intermediate stages of the evolution from fish to tetrapods (4-legged animals) during the Devonian and Carboniferous periods. They show a progression of reducing "fishy" characteristics and increasing land-adapted characteristics through specimens including *Kenichthys,* [142] *Gogonasus,* [144] *Eusthenopteron*, *Tinirau,* [142] *Panderichthys*, *Tiktaalik,* [145] [146] *Acanthostega, Ichthyostega,* [146] and a dozen or so other species. [142] This includes the progressive change from lobed fins and a finned tail, to feet with toes and finless tails; but it also involves the loss of bony gill covers, a reduction in the size of "postparietal bones" and a lengthening snout [146] as they adopted air-breathing and changed feeding habits. The evolution of the ear is also recorded in this progression of fossils. In fish we start with the fish spiracle (a small gill slit) and hyomandibula (a bone supporting the gill cover). In *Panderichthys* the spiracle is widened and the hyomandibula is shortened. In *Tiktaalik* the spiracle is further widened, and these changes continue until both the spriracle and hyomandibula form the middle-ear in tetrapods. [146]

There is a minor wrinkle to resolve in this progression. A recent study of *Ichthyostega's* hips show it couldn't walk the way later tetrapods do [577] and so it must have been another, hitherto undiscovered creature that left its footprints (trace fossils) on the tidal flats of middle-Devonian Poland. [147]

For a while in the 20th Century it seemed that there was a 30 million year gap in the fossil record between the primitive quasi-fish tetrapods like *Ichthyostega*, and clearly land-adapted, lizard-like tetrapods in the Carboniferous. This became known as "Romer's Gap" after the scientist who described it, but since then the gap has progressively shrunk. [578] With the discovery of tetrapod fossils in Scotland (including *Whatcheeria* and *Pederpes*),[578] the gap has shrunk to about 10 million years (about 2 ½ months in Your Life as Planet Earth), and it seems likely that further fossils will be found for the intervening time period.

So the general progression from fish to tetrapods (thence to reptiles and onwards to mammals and us) is well documented and supported by the fossil evidence.

Dinosaurs to birds

The evolution of birds from dinosaurs is partly about the evolution of feathers, and partly about the development of flight.

> "fossil record of variously stubbly, fuzzy, shaggy or plumed dinosaurs"

As more and more dinosaur fossils have been found it has become clear that feathers, or things like them, first appeared very early in dinosaur evolution, by the early Jurassic. [206] In fact so much has been learned in the last two decades that the scaly, lizard-like velociraptors depicted in the movie "Jurassic Park" are now known to have been feathered! Even the leathery-winged pterosaurs were apparently covered in downy filaments. [207] The extensive fossil record of variously stubbly, fuzzy, shaggy or plumed dinosaurs shows a general progression from fuzzy filaments, to filaments branching from a central quill, to the types of feathers found in modern birds. [207]

But feathers alone are not necessarily evidence for flight. They probably served a variety of purposes before flight: display [208] or insulation for instance, and it is only late in their evolution that they show the structures that enable modern birds to fly. [207] Scientists have been debating whether flight evolved from ground-dwelling creatures taking to the air, or from tree-dwelling creatures gliding to the ground or other trees. Others say this isn't the way to look at this at all – what matters is how birds developed the "flight stroke" – the powerful flying wing-beat that keeps a bird in the air. [207] Either way, the debate continues, with one side linking the development of flight to how young birds "flap-run" along the ground to climb over obstacles, [210] while the other side refers to climbing adaptations like the clawed fingers on the wings of early birds. [209]

Whichever theory is correct, it seems that flight itself was gained gradually, starting as a kind of speed boost ("flap-running") [210], or as a parachute [209] to break a fall. As flying developed, early birds like *Sapeornis*, *Confuciusornis*, *Cathayornis*, and *Yanornis* used their legs as well as their arms as wings (like biplanes) [211] but some scientists have suggested these early birds' feathers and muscles were still too weak for flapping flight. [210] [579]

What matters here is that a number of transitional fossils have been discovered showing the succession from dinosaur-like animals to creatures with feathered tails and small wings to more comprehensively feathered creatures with leg feathers, and eventually to unmistakable birds. We also see the loss of fingers on the wing and the loss of teeth,[207] [212] [213] the development of a wishbone, a backwards-pointing toe, and the enlargement of the breastbone to the keel-like breastbone of modern birds. This wasn't a simple sequence of replacement, since in China 125 million years ago the spectrum from fuzzy dino to actual flying birds (like *Jeholorinis*) coexisted.[207] They each must have had a viable niche for survival.

Snakes get legless

The evolution of snakes – essentially legless lizards – was a puzzle, but scientists recently uncovered several fossils of creatures in transition from lizard to snake.

One example from eastern Wyoming is called *Coniophis precedens*.[227] This Late Cretaceous creature had a snake-like body and a lizard-like head, with a skull that was intermediate between snakes and lizards.[227] Its lizard-like vertebral spines also showed that snakes evolved from burrowing lizards.[227] Another example, *Dinilysia patagonica* from Argentina also has a skull with a mixture of lizard and snake characteristics.[580] One early snake fossil, the Lebanese *Eupodophis descouensi*, even had vestigial legs that were discovered using synchrotron X-ray tomography.[581]

Whales – from legs to fins

Enormous progress has been made over the last couple of decades in uncovering the evolution of whales and dolphins (collectively "cetaceans"). The earliest cetaceans split from a common ancestor with hippos around 53 million years ago[582] and fossil examples include *Himalayacetus*, and *Pakicetus* from the Himalayan slopes of India and Pakistan. *Himalayacetus* still had a land-adapted ear and walked on legs, although its teeth show it ate fish and foraged mainly in fresh water.[582] Then we find

Indohyus, a 48 million-year-old raccoon-like creature that has the beginnings of the specialized adaptation to underwater hearing, and dense bones to help it with neutral buoyancy. [583] Soon after, we find *Ambulocetus,* a large, furry, web-footed creature, with those same underwater hearing adaptations. [49]

Early whale fossils from the next 10-15 million years are found in marine sediments and begin to show up outside the India-Pakistan area into North Africa, Europe and North America Over this time the fossils show that whale ancestors severed their ties to the land and became completely aquatic creatures. [582] For instance, in *Rodhocetus* and *Georgiacetus* we see the pelvis separating from the backbone, and vertebra there which are fused together in humans and most other mammals, becoming separated. These adaptations allow for more powerful swimming but would make walking on land difficult to impossible. [582] By 40 million years ago we have completely aquatic cetaceans like *Basilosaurus,* [582] which resembles a modern whale in almost every respect, except it still has vestigial hind legs. [582]

Modern whales evolved at the Eocene-Oligocene boundary (about 34 million years ago) at a time of major changes in ocean circulation and climate. [582] By that time we already see the split between baleen whales (filter feeders) and toothed whales. [582]

Humans

There are something like 24 [325] [359] ancestral human "species" in the fossil record from the 7 million years between the most archaic creatures that first separated from the chimpanzee lineage, to me and you. This wealth of evidence is not always straightforward. It is complicated by often fragmentary fossils and relatively few complete (or near complete) skeletons, [325] and it's clear that several "species" coexisted during much of our evolution. [325] [359] The emerging view is that some of those *anthropological* "species" are really just regional variants, or variants from different times, or even just individuals who looked different, within far fewer actual *biological* species (*biological* species cannot interbreed with other species). [584] [585] We know from genetics that human ancestral groups sometimes interbred fusing separate branches of the evolutionary "tree" back together again, so the pattern of evolution pattern is more of a braid or a tangled thicket than a tree. [584]

Anything that dies on the African plains, if not immediately eaten by the predator that killed it, is usually picked to pieces by scavengers from vultures to hyenas to insects, before its bones are bleached to dust under the African sun. So we are lucky we have the specimens we do for this relatively short period of terrestrial history. The remains we do have paint a clear picture of the gradual development of human characteristics, like walking upright on 2 legs, dexterous hands with thumbs, changes in pelvis and skull shape, and increases in brain size.

Because a surprising number of people still believe humans were created in the last few thousand years looking as we do now, [517] I want to walk you through the evidence that this just isn't so, being open about the uncertainties but also being clear about the strong evidence that we do have.

The ape-human split

It's not correct to think of us as descended from chimps, rather we and they had a common ancestor that was neither human nor chimpanzee. [326] Unfortunately the only archaic chimp fossils are a handful of teeth from about 500,000 years ago, [326] and the only fossil putative gorilla ancestor is *Chororapithecus* from 10 million years ago. [586] That's a time when we find a diverse collection of apes including *Dryopithecus* in Europe and *Sivapithecus* (the ancestor of orangutans) in Asia and *Kenyapithecus*, whose teeth, face and elbow begin to resemble our pre-human ancestors, in Africa and the Middle East. [320] [587]

> "It's not correct to think of us as descended from chimps"

There are fossils of 2 creatures that must be close to that last ancestor we share with chimps. They are each candidates [325] for our ancestor, but we don't know for sure if they are in a direct line from apes to us, or on some ancient side branch of our evolution. Interestingly, the dates of these fossils falls into the time period shortly after the separation of chimps and humans calculated from genetic data, of 7-8 million years ago. [588]

Sahelanthropus fossils date from around 7 to 6 million years ago. We have a skull (nicknamed "Toumaï"), some lower jaws and some teeth, but no bones from the rest of the skeleton.

[325] Its skull and teeth don't fit well with chimps & bonobos, but it is the shape of its brain (revealed by synchrotron X-ray tomography) and the location of the spinal column at the base of its skull, that most clearly places it in the "hominin" line as our upright-walking ancestor. [324] *Orrorin* is another. There is a fragment of a lower jaw and some thigh bones, 13 specimens in all from the Kenyan Rift Valley. [325] It lived 6 million years ago and, given the few bones we have, there's no surprise we know very little about it. It appears to have been able to walk upright, but its teeth are distinctly ape-like. [325]

And then there's *Ardipithecus*, or "Ardi" for short.

We have 2 skeletons of Ardi, one which has part of the skull and good preservation of the hands and feet, [325] and we have parts of an estimated 35 other individuals like Ardi. [327] We also have pieces of skull, teeth and bones from an older and slightly different *Ardipithecus*. [325] All the fossils were found in Ethiopia in rocks dated from about 6 to 4.4 million years ago. Ardi's hands and feet are ape-like [325] but her pelvis and skull suggest she walked upright [327] and her wrist suggests she couldn't have knuckle-walked or even swung from branches like chimps. [327] Her brain was only slightly larger than a chimp's, but her face and teeth are a little more human. The totality of the evidence has convinced many scientists that Ardi is our next oldest relative after Toumaï, but this is still a matter of debate. [325] [327]

Archaic humans

Soon after *Ardipithecus* we find a variety of prehumans in the genus *Australopithecus*, including the famous "Lucy." There are a skull and bones from caves in South Africa, a lower jaw from Tanzania, and a number of sites in Kenya, Ethiopia and Chad which have yielded a well-preserved skull, bits of other skulls, many lower jaws, teeth, and a number of limb bones. Although there are differences between the various species of *Australopithecus (anamensis, afarensis, africanus, bahrelghazali,* *prometheus,*[589] and the closely-related *Kenyanthropus platyops),*[325] if we focus on "Lucy" (a specimen of *afarensis*) as being representative, we can see that in many ways she makes sense as the next step on the ladder after Ardi on the way to us.

> "'Lucy' is about 25% of an adult female skeleton found in the Afar region of Ethiopia"

The actual skeleton that was dubbed "Lucy" is officially labeled "AL 288," and is about 25% of an adult female skeleton found in the Afar region of Ethiopia.[325] At 3.2 million years old she's from the middle of the *Australopithecus* time range. Her short legs and pelvis shape show she was capable of walking upright on 2 legs better than Ardi,[327] but not for great distances like us,[325] and there are several contemporary trails of fossil footprints in Tanzania from a Lucy-like prehuman that support this idea.[325] Her brain size is similar to Ardi's, but her teeth are more human.[325] Evidence that she still spent significant time climbing in trees comes from a fossil juvenile found in Dikika, Ethiopia. Specifically, the shoulder blade of that fossil has important ape-like climbing characteristics.[335]

So Lucy has attributes that are closer to humans than Ardi is. Moreover, it is during the reign of *africanus* that we begin to see the first simple stone tools known as "Oldowan" tools,[353] although exactly who made them is uncertain.

"Sediba" is the next superstar on this evolutionary tour. She's more closely related to the southern African *Australopithecus africanus* than eastern African *afarensis* that includes Lucy,[590] and she dates to a much more recent age of 1.977 million years ago.[356] There are 2 partial Sediba skeletons (possibly mother and son) that were found encased in rock inside caves at Malapa in South Africa[591] along with a leg bone from a third individual,[590] and more remains have been found through X-ray scanning of rocks from those same caves.[592]

We have a nearly complete wrist and hand of the adult female, which is partly *Australopithecus*-like (a climbing-adapted upper arm and powerful forearms for climbing trees[590]) and partly *Homo*-like (a long thumb and short fingers for precision gripping and, *possibly*, stone tool production).[355] Sediba has a human-like ankle, foot arch, and Achilles tendon, yet her foot is also partly ape-like, with a thinner heel and a bigger inside ankle bone than humans.[354] She walked awkwardly, with her foot rolled on its outer edge rather than our modern flat-footed gait,[590] a condition that some runners and high-heel wearers suffer from today. Her brain is about the same size as other *Australopithecus* brains, but its shape shows its structure was closer to a modern human brain than other *Australopithecus* brains.[356] Interestingly, genetic studies suggest there was a crucial mutation roughly 2.4 million years ago that duplicated the human brain-gene called "SRGAP2,"[357] which fits well with the emergence of a more human-like brain at this time. Her teeth are also intermediate between *Australopithecus* and *Homo*,[590] rounding out the pretty convincing evidence for Sediba being a transitional species linking *Australopithecus* to the *Homo* genus that includes us.

But if Sediba is the ancestor of the later *Homo* species – including you and me – then there is a problem with her timing. At 1.997 million years ago, she is more recent than the first putative *Homo* fossils at around 2.4 million years – so either she is a relic of a group that gave rise to *Homo* much earlier, or maybe the older *Homo* fossils are dubious, or a bit of both. It turns out that that the oldest reliable specimens of *Homo* are around 1.9 million years old. [356] The older assumed-*Homo* fossils are fragmented or isolated bits of skull and teeth, which are tough to assign to any species with confidence, or whose date is suspect. [356] So the upshot is that the timing still makes sense for Sediba to be transitional between *Australopithecus* and *Homo*.

At around the same time as *Sediba*, we find fossils of weirdly robust prehumans called *Paranthropus*. Fossils of this genus have been recovered from South Africa, Tanzania, Kenya and Ethiopia. These creatures have a wide face, a distinct ridge along the top of their skulls [49] and massive jaws with large, fast-growing molars suggesting they were adapted to a great deal of chewing, and analysis of their teeth reveals that they did indeed graze on large quantities of grasses and sedges. [358] Their hip joint is like most *Australopithecus'* suggesting *Paranthropus* did walk on 2 legs but not exclusively, [325] and curiously their brain is slightly larger than that of their *Australopithecus* cousins. [325] Some scientists lump *Paranthropus* in with *Australopithecus,* [593] but their anatomical features don't survive into *Homo*, suggesting that *Paranthropus* was a side branch of our evolution that died out.

Ecce Homo

The group that succeeded Sediba and her *Australopithecus* relatives was *Homo* - which includes you and me (we are *Homo sapiens,* which is self-congratulatory Latin for "wise man").

The *Homo* genus is complicated and varied, with up to 5 different kinds of *Homo* living at the same time immediately after Sediba (around 2 to 1.6 million years ago). They were *habilis*, *rudolfensis*, *ergaster*, [325] and a specimen labeled "KNM-ER 1802," which has recently been attributed to a new, unnamed species. [359] They overlapped with *Paranthropus*, so it's clear that our ancestors in Africa were a diverse lot at that time.

These earliest *Homo* specimens can be seen as transitional [325] between *Australopithecus* anatomy and the kind of anatomy we find in later *Homo* species. Fossils for this group come from Olduvai Gorge in Tanzania, Koobi Fora in Kenya, as well as Ethiopia, South Africa and Malawi.[325] The famous "Turkana Boy" *ergaster* fossil is a nearly complete skeleton from Kenya, without feet and few finger bones. [49] The skulls and skull fragments tell us they had a brain size of around 600 cubic centimeters (37-48% of ours), which is a significant step up from the brains of *Australopithecus* and *Paranthropus*. [49]

Recent finds in Dmanisi in Georgia suggest that the variations between *habilis*, *rudolfensis*, *ergaster* and *erectus* are all just individual variation in early Homo, and so can all be lumped in with *Homo erectus*, but this remains controversial.[585] [325]

Homo erectus fossils have been found in rocks dated from about 1.8 million years ago to 30,000 years ago across the continent of Africa, in Georgia, and as far afield as China and Indonesia. [325] The fossils are mainly skulls, with some bones from the body but few hands or feet. [325] In most respects *Homo erectus* was quite like modern humans in height (with much individual variation), proportions, teeth, gait and stature. The differences are its substantial "monobrow," a pointed back of the skull, and a chin-less jaw that is thicker than in modern humans. [325] His limbs also had thicker bones than ours, but his hands were as dexterous as ours. [325] [594] Like us he had a flattish face with a pointed nose, a barrel-shaped ribcage, and his knee and thigh joints show he was just as adapted to upright walking or running as you and me.[49] His smaller teeth than *Australopithecus* fossils are probably the result of increasing use of tools to do the work formerly done by teeth,[49] and microscopic scratch patterns on his teeth show that he had a more varied diet than either *habilis*, *Australopithecus* or *Paranthropus*.[595] Tool marks on bones and isotope evidence show *erectus* had a generalized diet including meat.[584]

Still, the brain of *erectus* was not quite as big as ours (67-95% of a modern human brain)[49] which raises the question of how intelligent he was. Turkana Boy (*ergaster*) seems to have a smaller brain[49] than later *erectus* fossils, so there was some enlargement as *erectus* evolved. In fact the most recent mutation of our SRGAP2 brain gene happened around 1 million years ago in the middle of *erectus*' age range, before the appearance of later *Homo* species like the Neandertals and modern humans.[357]

> "to make fire without matches involves some sophisticated cognitive functions"

But the fact that by at least 1 million years ago (probably earlier) they had learned to use fire, [360] suggests that *erectus* was in fact pretty intelligent. If you have watched "Survivor man," "Man versus Wild," or even Boy Scouts try to make fire without matches, it's clear that it involves some sophisticated higher-level cognitive functions like problem-solving, preparation, learning, and communication. The strongest evidence for this comes from the Wonderwerk Cave in South Africa, in the form of burned bones and plant ash found in an ancient fireplace. [360] Fires were clearly a regular habit rather than chance events, and the quantity of burned bones strongly suggests *erectus* was cooking food. [360] Other, more tentative evidence for *erectus*' use of fire comes from sites in East Africa up to 1.5 million years ago, and more recent deposits in Israel. [360]

Cooking is vital for brain development, [361] because there just aren't enough foraging hours in a day for *erectus* to sustain the number of neurons in their brains on raw food! [361] Cooking supplied the calories needed by *erectus* and later humans, and it freed-up time for them to be social, make tools, and engage in other activities rather than grazing all day. [361] There is also tenuous evidence that *erectus* might possibly have had some form of language, based on the shape of the base of its skull and the timing of language-implying anatomy found in later species. [364]

Another sign of *erectus* intelligence is their distinctive "Acheulean" stone tools. These tools were clearly made with considerable care and skill, and they begin to show up in Kenya and Ethiopia 1.75 million years ago, right at the start of *erectus*' date range. [362] They are a variety of specialized tools that show refinement between the earliest and latest examples. [362] *Erectus* seems to have had tool "factories" for example at Konso in Ethiopia and at Kokiselei and Olorgasailie in Kenya, suggesting a degree of social organization akin to modern humans. The anatomy of *erectus*' waist, elbow and shoulder shows it was the first human capable of throwing weapons [363] - killing from a distance - so it can't be coincidence that at around the same time as the emergence of *erectus*, we begin to see extinctions of a number of large carnivores in Africa. [365]

The fact that erectus spread so quickly across the world, successfully exploiting environments quite different from Africa, shows that erectus was special, and entirely new. [585] They also lasted well into the era of *Homo sapiens*, and they seem to have evolved the later "species" of Homo.

floresiensis (nicknamed "The Hobbit") is an oddball. This diminutive creature was discovered in a cave on the island of Flores in Indonesia and may have evolved from *erectus*. 2 skeletons and up to 100 fossils have been found representing up to 10 *floresiensis* individuals. [325] It has a brain about the size of an *Australopithecus* in an early *Homo*-like skull, a unique pelvis and legs, [325] and in adulthood it is only the size of modern 4-year-old child.

Denisovans are a newly-discovered species from a cave in the Altai Mountains in southern Siberia. All we have of them sc far is a finger bone and 2 teeth, but the bone still has good quality DNA in it so scientists were able to sequence the genome of this Denisovan girl who lived between 50,000 and 30,000 years ago. [370] The DNA confirmed that the girl was not Neandertal bu was instead the product of a different migration out of Africa, and that her lineage had separated from that of Neandertals and us about 1 million years ago, [370] suggesting *erectus* as its tentative ancestor.

From *erectus* to modern humans

We have over 80 skeletal remains of *antecessor* representing some 7 individuals, including bits of skull, teeth, and a mandible, from Atapuerca in Spain. The fossils are found witł stone artefacts and are dated between 1.2 million years and 900,000 years old. [596] [597] *antecessor* seems to be an evolved European version of *erectus*, [598] and some consider it the ancestor of Neandertals and modern humans, but most scientists do not. [325] [598]

heidelbergensis is the earliest of our ancestors to have a brain as large as some modern humans, and is perhaps better thought of as "archaic *Homo sapiens*." [325] [599] We have fossils from Europe, the Near East, Africa, China and India dated betweeı 600,000 to 100,000 years ago. Some researchers classify Africaı *heidelbergensis* as a separate group called *Homo rhodesiensis*, and see those as the ancestors of *Homo sapiens*. [325] *heidelbergensis* skeletons are more robust than ours, with thick skulls, large eyebrow ridges [325] and a forward-projecting face [49]. Their leg joints are also large and adapted to long-distance travel. [325] *Heidelbergensis* evolved from *erectus*, developing an enlarged and more rounded back of the skull and a broader forehead enclosing a larger brain in the process. [325] They probably had speech, based on fossil hyoid bones from their throats, the nature of the middle-ear bones, and the size of certain nerve canals. [364] They evolved into modern humans in Africa, and into Neandertals in Europe, showing a gradation of characteristics over time into those species (for example many fossils at Sima de los Huesos in Spain). [325] *heidelbergensis* was an accomplished toolmaker and butcher, using fire-hardened wooden spears and a variety of stone tools to process animal carcasses. They also hafted stone tips to wooden shafts to make spears, [369] which involves tying a suitably-crafted spear tip to a shaft using some kind of twine and maybe glue. This suggests high level cognitive ability and communication to teach the skill to others, which adds more weight to the suggestion they had some form of speech. Evidence for this comes from excavations in South Africa, [369] England and Germany. [49]

> "They had a distinctive culture and they adorned themselves with feathers and eagle claws"

Neandertals were a highly successful group whose territory extended across Europe and the Near East and into western Asia from around 200,000 to around 40,000 years ago,[600][601] overlapping the age range of modern humans in Africa and *erectus* in Asia.[325] This age range assumes the older fossils at Sima de los Huesos are assigned to *heidelbergensis* and not Neandertals, which is still debated.[325][598] Fossils of more than 275 individual Neandertals have been found from over 70 sites, representing a strong fossil record.[49] They had distinctive low-browed skulls with large eyebrow ridges, big eyes, wide noses and a small-to-non-existent chin, and their bodies were stocky, robust and muscular, suggesting a very strenuous lifestyle.[325] Neandertal DNA has been recovered from several individuals and their genomes sequenced, showing that there was much less genetic diversity in Neandertals than in modern humans.[325] They did have brains as large as ours (actually slightly larger) and had at least one distinctive culture of tools known as "Mousterian." [602] They used ochre for paint, scratched symbols onto bones, [381] and they adorned themselves with feathers and eagle claws. [379] They also constructed 10m (32 feet) wide huts from carefully selected mammoth bones. [381] There is evidence that they had speech based on the shape of their hyoid bone in their throats, [49] the presence of the speech-associated variant of the FOXP2 gene in their DNA the shape of their middle-ear bones, the size of relevant nerve canals, their culture and their symbolic behavior. [364]

In other words, aside from appearance and stature, they were quite similar to the earliest modern humans and not the primitive, brutish creatures so often depicted in popular culture. In fact they appear to have been about as modern, culturally and behaviorally, as Anatomaically Modern Humans who lived at the same time as them. [603]

Improvements in carbon dating have now pushed back the dates for the last Neandertals from about 30,000 to about 40,000 years ago, [398] but the extent and nature of modern-looking humans' overlap with Neandertals is still debated, with the possibility of a later Neandertal outpost in Southern Spain. [398]

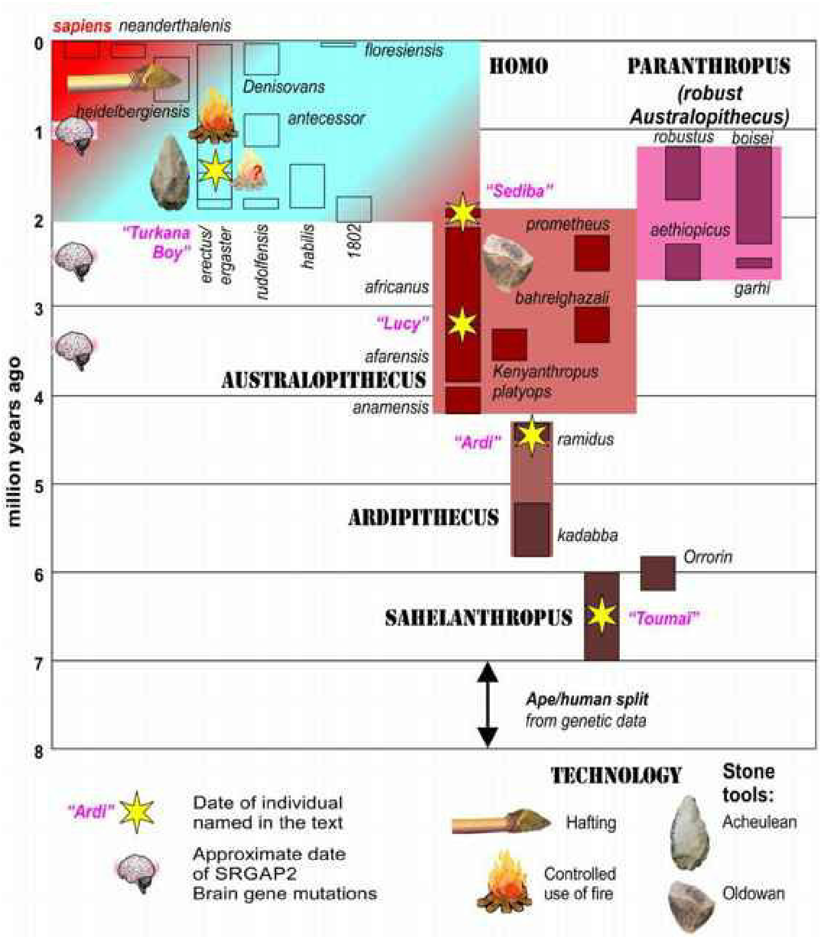
Anatomically modern humans emerged around 208,000 years ago in Africa, [372] and the oldest fossils are from Omo Kinish in Ethiopia. [325] Fossils of ancient *Homo sapiens* have been discovered on every continent except Antarctica, with the first discovery in 1822 in a Welsh cave, [325] and there are plenty of *sapiens* fossils in good condition. What they show is a gradation over time from archaic *Homo sapiens* with robust skulls and muscular bodies [325] to the lighter-boned modern humans of today. Early fossils also show a gradation between *heidelbergensis* and Anatomically Modern Humans, making the boundary hard to set [325] but supporting our gradual evolution from African *heidelbergensis* (sometimes called *rhodesiensis*). It was probably more complicated than that, given interbreeding between closely-related but distinct groups, and the high degree of individual and regional variability over time in archaic groups like *erectus*.

Direct fossil dates for modern humans in Europe are from around 44,000 years ago [399] but technology associated with modern humans begins to show up in Europe around 45,000 years ago, during a relatively warm and humid respite in the ice age known as MIS3.[398] That gives a protracted overlap with Neandertals in Europe of 2,600 to 5,400 years.[398] Interestingly, places like Arcy-sur-Cure in France show that Neandertals changed their "Mousterian" culture to a kind of hybrid culture ("Châtelperronian") once modern humans arrived in the region about 44,000 years ago, and then modern human "Protoaurignacian" and "Aurignacian" artefacts take over completely by about 41,000 years ago, suggesting the extinction of Neandertals at that location around that date. [604] [602] This transition occurs earlier in southern Europe, showing that the annexing of Europe by modern humans was slow and piecemeal.[604]

> "This is a hotbed of current research on all fronts: archeological, fossil, and genetic"

The traditionally-assumed single African exodus 60,000 years ago has now been superseded by evidence of older wanderings, and recognition of much more complexity to the migrations. [386] [584] This is a hotbed of current research on all fronts: archeological, fossil, and genetic; but it suggests a complicated pattern of dispersal, generally associated with warmer, wetter interglacials. [605] Considering that we are talking of a time period in excess of 100,000 years, this complexity is unsurprising, since in just the last 5,000 years we have seen many wholesale population migrations through Europe alone (Indo-Europeans, Hittites, Celts, Aryans, Greeks, Phoenicians, Persians Romans, Samartians, Goths, Huns and Mongols to name a few). [606]

So, to sum up, there is a wealth of fossil evidence for the emergence of modern humans from apes through a series of intermediate species. This is an exciting time of big steps in our knowledge brought about by improved dating and genetics, which I will cover in the next section. There are also new fossil finds that have yet to be spliced into this story, like those recently unearthed in the Rising Star Expedition in South Africa.[607] But it doesn't seem likely that the broad-brush picture of our journey from apes to modern humans will change fundamentally.



24 **Human Evolution Family Tree.** After Wood, PNAS 2010; Pickering et al, Science 2011; Leakey et al, Nature 2012; Krause et al, Nature 2010; Langergraber et al, PNAS 2012; Dennis et al, Cell 2012; Wilkins et al, Science 2012; Berna et al, PNAS 2012; Beyene et al, PNAS 2013; Clarke, The paleobiology of Australopithecus, Springer 2013; Herries, et al. The paleobiology of Australopithecus, Springer 2013; Lordkipanidze et al, Science 2013; Parés et al, J.Arch.Sci 2013.

Breadcrumbs of evolution

In the fairy tale of Hansel and Gretel, the children leave a trail of breadcrumbs so that they might find their way home after being abandoned in the forest. This is a good analogy for the way clues in our biology today can lead us back, like a trail of breadcrumbs, to our origins.

The genetic code in all organisms is based on a 4-letter alphabet representing the 4 different bases in DNA, and the patterns of these letters are amenable to computer processing, which can find identical matches of sequences and even close matches that aren't identical. Now that the entire genomes of many organisms have been sequenced, and with recent advances in computer processing, we can now parse these vast sets of genetic codes for matches between organisms, and we can rank the closeness of those matches.

This tool is known as "molecular phylogeny" and provides a new and powerful way to illuminate the evolutionary tree of life based on how similar creatures' genetic codes are. It is actually not restricted to genetic code – it can be applied to the makeup and structure of proteins too (the "proteome" - the protein equivalent of the "genome").

LUCA and the dawn of life

We can learn a surprising amount about LUCA – the Last

Universal Common Ancestor of all life on Earth – from these studies. For instance, one study concentrated on the proteins in 420 organisms spread across the 3 domains of life: archaea (simple single-celled organisms), bacteria, and eukarya (fungi, plants, animals). They ran their algorithms to identify proteins shared across all these life forms (therefore present in their common ancestor) and found 70 families of proteins that all other life has inherited in some way from LUCA. [608]

This primordial set of proteins sheds some light on the nature of LUCA (or the "urancestor" as the authors prefer to call it). It tells us that LUCA had enzymes for metabolism and for making a simple cell membrane of glycerol ether and ester lipids, and it had the ability to synthesize proteins. It also had very simple genetic replication using RNA rather than DNA.[608] LUCA had the simplest type of RNA called "16S rRNA,"[45] and its metabolism must have used the Krebs cycle and a process known as "chemiosmosis." [39] LUCA did not start life in an especially hot environment. The tolerance for high temperatures seems to have evolved after LUCA, requiring that wherever LUCA lived, the environment at that time was not far off modern conditions. [609]

Of course these are the characteristics of our last common ancestor (as in the one that could replicate itself and pass on genes to its descendants), and not necessarily the earliest prototype of life on Earth. The scenario for the origin of life on our planet as a kind of living rock in submarine vents [39] is speculative but plausible. [41] This subject alone is a book's-worth, so I can only touch on the highlights here. For a fuller account of the emergence of life from chemistry, see Nick Lane's book: "Life Ascending."[39]

> “we have discovered most of life’s chemical building blocks already exist in meteorites”

We have to bridge the gap between the LUCA revealed by those molecular phylogeny studies, and the chemistry that existed before life in the oxygen-less early Earth. Science has moved on from the famous experiments of the 1950s which suggested lightning could generate the chemicals of life. They were based on an assumed composition of Earth’s early atmosphere that we now know was wrong, and when you repeat the experiments using the more realistic atmosphere you just don’t get those protein building blocks we call amino acids. [610] More recent experiments suggest that you can get more amino acids from a realistic atmosphere if you add other chemicals, but it just isn’t necessary to invoke lightning now that we have discovered most of life’s chemical building blocks already exist in meteorites [34] [41] and so were readily available on the early Earth. The other source of essential life chemicals is the natural chemistry of deep ocean vents. Measurements of the chemistry at alkaline submarine vents today, such as the "Rainbow Hydrothermal Field" in the Mid Atlantic Ridge, have found they exude hydrogen, methane, and hydrocarbons with life-like carbon chain lengths of between 16 and 29 carbon atoms.[21]

The real problem is getting from those chemical building blocks to complicated life-chemicals like RNA. RNA is a string of ribonucleotides, and each of those is made up of a sugar, a phosphate group and a base (one of the 4 letters in our genetic code). Scientists have found that if you recreate the chemistry of the early Earth oceans, then ribonucleotides spontaneously form in that soup,[611] but they have not yet been able to go the next step and combine those ribonucleotides to make RNA. Once you do have strands of RNA, experiments have shown they spontaneously cooperate with each other and grow. More complex RNA networks grow faster than single molecules, so there seems to be an inherent bias for RNA-based chemistry to evolve the complexity of life.[612]

Life needs energy and so the earliest life needed some form of metabolism to extract energy from its environment. All life today has a metabolism based on a cycle of chemical reactions known as the "Krebs Cycle" and a process known as "chemiosmosis." The fact that these are shared across all life suggests we inherited them from LUCA.[39]

Archaea today use enzymes containing iron, nickel and sulfur to react hydrogen with CO_2 to produce organic molecules and, *crucially*, energy. The metallic cores of those enzymes are very similar to natural minerals in hydrothermal vents. The vent minerals react hydrothermal fluids with CO_2 - rich water to produce "acetyl thioester" (similar to vinegar), which in turn reacts spontaneously with CO_2 to produce "pyruvate," which kicks off the Krebs Cycle.[39] In other words, the natural geochemistry around ancient mineral vents spontaneously produces the chemistry to arrive at the Krebs Cycle.

Chemiosmosis is a chain of reactions to create a charge across a membrane, just like the electric charge between the "+" and "-" terminals of a battery. The fact that all life uses protons (hydrogen ions) for chemiosmosis, rather than any other kind of ion, seems to hark back to the natural proton gradient at hydrothermal vents (like the Rainbow vents) where alkaline fluids meet mildly acidic, carbon-rich sea water, producing a natural charge which can be exploited by metabolism. [39] [613]

Of course life on Earth today is not tied to submarine vents, so at some point our transition from rock chemistry to cellular life must have involved the development of cell membranes to package the chemicals required for metabolism and replication into an independent cell.

All cell membranes are composed of glycerol *phosphate* phospholipids and this, again, suggests LUCA had such a membrane. [41] It turns out that an iron–nickel phosphide mineral common in meteorites (schreibersite) reacts with sea water in early-Earth conditions (low-oxygen, mild temperatures) to produce those very membrane molecules. [42] Other experiments have shown that organic materials in meteorites like the Murchison meteorite will spontaneously make little bubble-like "cells" in water, capable of enclosing packages of RNA and other chemicals, and which grow and divide spontaneously. [41] So the fact that life emerged during the heavy bombardment of Earth by asteroids is probably no coincidence, as schreibersite probably also supplied the phosphorous required to make the essential life chemicals RNA and ATP. [42]

Interestingly, archaea and bacteria have their own variants of cell membranes, which implies that LUCA may have had a mixture of the two. [41] This difference also helps us understand how eukaryotes including us evolved (which I'll cover below). By the time LUCA left her rocky womb she possessed complex lipid membranes and the enzymes to make them. [41]

The great schism – the separation of the 3 domains of life

The protein study I mentioned above also mapped-out the family tree of life, supporting the fundamental split into 3 domains early on, and suggesting that archaea are closer to LUCA (and therefore more primordial) than bacteria. [608] That study not only gives us the *order* of evolution (who begat whom), but it also gives an idea of *when* those organisms first evolved (calibrated using dated fossils). This "molecular clock" places the split of eukaryotes (the kind of cell which gave rise to multicellular life including humans) from bacteria at about 2.9 billion years ago. [608] This is around the time when about 27% of all gene families in creatures alive today, across all forms of life, seem to have evolved. [609] These gene families are mainly involved in respiration, and that makes sense because this was around the beginning of the Great Oxidation Event (the mid-life crisis of the first part of this book) which would have allowed organisms to respire using oxygen for the first time.

Our genes involved in replication and making proteins are inherited from archaea, yet our genes for metabolism and cellular functions are essentially bacterial. [41] Our cell membranes are bacterial in origin, as are the membranes that surround the cell nucleus and mitochondria (the parts of eukaryote cells that generate energy). Mitochondria, in fact, have their own DNA which is kept separate from the rest of the cell's DNA and, unlike the rest of our genes, it is only inherited from mothers. This suggests that eukaryote cells originated as a hybrid of an archaeal cell and a bacterium, or possibly from a bacterium engulfing both an archaeal cell and another bacterium. Either way, the bacterium lived on as mitochondria,[41] resulting in more sophisticated, more energetic cells (eukaryotes) that paved the way for complex life, and eventually us.

Breadcrumbs of mammal evolution

It's remarkable that molecular phylogeny, a technique of sleuthing through our genes and proteins, agrees so well with the evolutionary relationships previously derived through many decades of painstakingly detailed fossil comparisons. It complements the fossil record, filling in gaps where the fossil record is sparse, and the "molecular clock" can improve our knowledge of when new groups evolved.

We also get two bites at the genetic cherry, as the technique can be used on both nuclear DNA and mitochondrial DNA. For example, by using both kids of DNA, scientists have been able to clarify the evolution of mammals, showing that a number of groups had already evolved before the demise of the dinosaurs, but that they only diversified in the 20 million years after the dinosaur extinction.[614] Another study using both kinds of DNA showed that a major radiation in whales coincided with the startup of the Antarctic Circumpolar Current around 31-34 million years ago,[615] the same event that triggered the Antarctic ice cap and our spiral into an ice-age climate. That study also found whale and dolphin diversification in the period of 13-4 million years ago, when the Tethys, the Indo-Pacific, and Panama ocean connections closed.

Scientists are now borrowing techniques from molecular phylogeny and applying them instead to physical characteristics ("phenomes") of living and fossil creatures. This technique was used to track the emergence of the first placental mammals (our ancestors) to very soon after the end-Cretaceous extinction.[252]

Evolution in humans revealed by genetics

Sequencing human genomes has led to an explosion of information about our evolution. Modern human genomes across the globe have shed light on patterns of ancestry, but ancient genomes from archaic humans have also been sequenced, including several Neandertals, a Denisovan, and a 400,000 year old *heidelbergensis*. As I write this, new genetic data are emerging every few months with fresh insights on our origins.

It is very clear from our genomes that about 2% [388] of our genes are Neandertal (for Europeans, Asians,[616] and North Africans[380]), and that some 20% of Neandertal genes are scattered throughout different human populations today. [617] Melanesians, Aboriginal Australians, Polynesians, Fijians, and some Indonesians have also inherited about 4% of their genes from Denisovans, who in turn inherited genes from an older, non-Neandertal group. [390] [389] [618] The genes of a *heidelbergensis* person from Spain turned out to be more closely related to Denisovans than Neandertals, despite its quasi-Neandertal skeleton. [619] The fact that some Asian populations have Denisovan DNA but others (like mainland East Asians, western Indonesians and some other groups) do not, means that any interbreeding must have occurred in Southeast Asia. This suggests that the enigmatic Denisovans had a vast range from tropical southeastern Asia all the way to frozen Siberia. [390] What all this tells us is that the migrations and interbreedings of Homo populations were much more complex – and interesting - than we previously assumed.

Neither were we a “final product” of evolution when we emerged in Africa 208,000 years ago. We continued to change in response to the unique environmental challenges we faced as we spread across different regions of the globe.

Genome studies tell us East Asians have evolved subtly different genes concerned with hearing and vision, blood pressure and metabolism, and West Africans have evolved specialized genes for disease immunity. [620] In Europe and Africa, life alongside domestic cattle resulted in evolution of adult lactose tolerance, [621] something that is switched off after weaning in other populations and all lactose-intolerant people. And Tibetans, who live at high altitude, have evolved differences from closely-related Han Chinese in genes associated with blood oxygen levels. [621]

Genetics tells us that the San people of southern Africa (sometimes called “Bushmen”) became a distinct population very early on at around 130,000 years ago, long before Eurasians began to diverge from African populations between 64,000 and 38,000 years ago. [622] They also tell us that America was initially populated by several distinct migrations from Siberia, and show how those populations spread south along the coast into South America, and east of the Rockies from Alaska. [623] [624]

These studies also tell us that there is far more individual genetic variation within our population groups than between them. [622] There is much active research on our genomes which will shed new light on our recent and distant past. Molecular clocks will be refined [625] and no doubt revisions will occur, but so far the genetic evidence has fleshed-out the story of our evolution that was previously only revealed by bones and teeth.

Shared anatomy

It’s not just our genes and proteins that bear witness to our evolution. Our very flesh and bones contain echoes of our ancestors.

Take your legs and arms, for instance, and compare them with the limbs of all 4-limbed creatures since our divergence from fish. We all have the same basic structure of a single upper bone in arms and legs, two bones for our lower limbs, and then a series of smaller (wrist or foot) bones before ending with 5 toes or fingers. This is true for humans, whales, dogs, cats, horses, bats, lizards and even frogs.

There are many cases where you can trace changing anatomy through a series of descendent species. We can see the sophisticated mammalian ear begin its evolution from the reptile ear. Small bones at the back of the jaw in reptiles began to separate in early Cretaceous "utriconodont" mammals, before eventually becoming the tiny bones of our middle ear in later mammals. [626] Jaws are another example. After some initial variation in very early fish, their shape settled on a design that stayed through fish and then the 4-legged creatures that moved onto land.[627]

Evolving embryos

Of all the 4-limbed animals, birds would appear to be the exception to the 5-fingered rule, because they have lost 2 of those 5 digits. But they do have those fingers as embryos when they are still in their eggs. Watching a bird embryo develop shows that it starts with 5 digits but then the "extra" digits stop developing and degenerate long before the bird hatches, [628] so they aren't an exception after all.

In fact the way embryos develop offers still more clues to the origins of species. Vertebrate embryos, including humans, all go through a similar development sequence which reveals vestiges of the ancient creatures we evolved from. At an early stage of development we all have a tail, gill slits, and gill cover.

As the embryo develops further some of these remain vestigial (like our tail) and some are repurposed, like the gills which become our parathyroid glands.[629]

Bottom Line:

Evolution is a *fact* accepted by practically all the world's scientists, because of the overwhelming body of evidence that proves it. The evidence for evolution and for the myriad creatures that existed long before us is writ large and tiny in rocks across 3.7 billion years of our planet's history. More than that, it is written in the very biology of living things today – their genes, their anatomy and their biochemistry. Evolution through selection has been observed in the lab, outside the lab and in the history of domestic animals. But more than that, we are increasingly understanding how the evolution of life has been an integral part of our planet's evolution.

4. The Clocks In Rocks

Sands of time

Throughout this book I have referred to events at specific times in the past - thousands, millions and even billions of years ago. Being able to nail events down to specific times, and so work out the order of events, is pivotal for working out the history of our planet. *How* we know those dates is therefore a cornerstone of our understanding of Earth's past.

From scripture to nature

In the 17th century, Bishop Ussher based his calculation of the age of the Earth on a literal reading of the Bible. He decided that the Earth was created in 4,004 BC,[630] and this date has become a fixation for Young Earth Creationists today. But the bishop had only ancient texts and family trees to go on, unconstrained by scientific measurements and observations from the natural world.

In the 18th and 19th Centuries, as geology moved from a collecting hobby to a science, observations of nature were brought to bear on the question. It was James Hutton who first articulated the idea that it must have taken eons to produce the landscapes of today. Hutton was part of the Enlightenment society that flourished in Edinburgh after the Jacobite rebellion. He travelled and made observations of the rocks everywhere he went, which convinced him that erosion leads to sediments that form rock. He also observed marine sediments high up in mountains, and deduced that the mountains must have been raised from the bottom of the sea.

After the first edition of his “Theory of the Earth” was published, he visited Siccar Point, about 50km (30mi) east of Edinburgh, where he saw red sandstone strata draped over upended layers of gray sandstone. That crystallized his understanding of the deep time required to explain what he saw: eons must have passed from the initial formation of the grey sandstone layers, to the time needed to petrify and upend them, then later to drape them in fresh red sands, for those also to petrify, and then the whole edifice to be raised, eroded and exposed before him. All that must have taken far longer than Ussher’s 6,000 years:

> “It is only in science that any question concerning the origin and end of things is formed; and it is in science only that the resolution of those questions is to be attained. The natural operations of this globe, by which the size and shape of our land are changed, are **so slow as to be altogether imperceptible to men who are employed in pursuing the various occupations of life and literature**.” [631]

Smith’s puzzle

William Smith came a little after Hutton. From his work building canals and coal mines, Smith deduced that sediments laid down at the same time had the same characteristics and, *crucially*, the same assemblage of fossils. [632] Armed with this knowledge, Smith was able to trace strata from one mine to another, and from one county to another, fitting them together like pieces of a puzzle. He labored many years single-handedly, mapping strata all across Britain, until he had produced the world’s first geological map in 1815. [632] Far more than an impressively-colored piece of paper, this summarized the entire geological history of Britain in a single, graphical document. By stringing together many individual successions of strata in their proper order of formation, he had multiplied Hutton’s eons.

Geologists follow Smith's mapping technique to this day, and still use fossil assemblages to correlate and date strata (although these days those dates are calibrated to radiometric dates which I will come to below). But it was a while before Smith's achievement was understood for its true significance, and he was treated shamefully in the interim – a tale deftly told by Simon Winchester in his book "The Map That Changed the World."[632]

So Smith had succeeded in defining the *relative* dates of strata (this layer came before that layer, and so on), and Hutton had shown us that the planet's history was played-out across the eons of deep time. Hutton's insights influenced scientists after him, from Sir Charles Lyell (who visited the Joggins fossil forest in Nova Scotia, in the "Proof of Life" chapter earlier) to Darwin. Darwin himself observed the slow rate of accumulation and erosion of sediments in British landscapes, and multiplied those times by the vast thicknesses of sands and clays exposed in cliffs, to arrive at timescales in the hundreds of millions of years.[515]

Yet *absolute* dates (exactly how many million years old a particular stratum is) remained elusive. So, at the end of the 19th and beginning of the 20th centuries, scientists turned to physics for answers.

To start with they were way off. In the 1860s Lord Kelvin attempted to calculate the age of the Earth by assuming it had cooled from a molten state. He came up with between 20 million and 400 million years. [630] He was profoundly wrong because he guessed a melting point for rock which was way too high, his value for how fast the Earth conducts heat was wrong, and crucially he did not know about the heat added by natural radioactive decay. He also did not factor in other heat sources like asteroid impacts and the heat generated by the planet's core. The heat balance of our planet is much more complex than imagined by Kelvin, [630] which is why his age of the Earth is far too young.

> "Lord Kelvin was profoundly wrong"

Fortunately, in the 20th Century, physicists like Rutherford and Boltwood began to measure radioactive decay, delivering a new technique for measuring accurate, absolute dates by radiometric dating.

Radiation-free proofs of an old Earth

Since radiometric dating is dismissed by Young Earth Creationists, it's worth touching on a few of the ways we know that the Earth is very old, even *without using radiometric dating*.

Measured continental drift

If we start with modern GPS measurements of the speed of movement of continents today, we can calculate how many years back in time you have to go to join continents like Africa and South America back together. Using the GPS-measured drift rate today of around 26mm (1in) per year, [451] multiplied by the distance between the continents of roughly 5,500km (3,400mi), it takes you back roughly 200 million years to join the continents together again. Lo and behold, that puts you at the end of the Triassic period, which is when geological and radiometric dating evidence does, indeed, have the beginning of the opening of the Atlantic. This crude calculation illustrates that we are dealing in hundreds of millions of years, not thousands.

And a similar exercise can be done with Hawaii. The "Big Island" of Hawaii currently sits over a mantle hot spot that has remained fairly fixed as the pacific plate drifted over it, like a blow-torch, melting a string of volcanoes into the seafloor to create the Hawaiian-Emperor seamount chain. GPS data show the plate is moving at about 70-90mm (2 ¾ - 3 ½ in) per year. [633] [451] That means the Midway Islands (around 2400 km (1500mi) away) should be roughly 28 million years old. Potassium-argon radiometric dates for the Midway Islands are around 27.7 Million years old. [634]

Erosion rates

Measurements have been made of erosion rates across the world's river basins, and as you might imagine, they vary. They range from averages around 0.5 mm per year (1/64in) across most of the world's rivers to around 5mm per year (¼ in) in tectonically active mountain ranges, to a few cm per year in volcanic areas. [488]

The point of this is you end up with a *minimum* of millions of years required to erode the miles-deep river valleys through the world's great mountain chains. And that's if you suspend geological reality by ignoring tectonics or isostacy (the unloading-a-boat effect), which just prolong that time in reality.

We do know for certain that they are eroding (from measurements of sediment loads in rivers, for instance), and we can measure with GPS the rate of their tectonic uplift (Mount Everest has been rising about 4mm (about 1/8 in) a year[486]). Once again, these are very simplistic calculations, but they force us to accept timescales of *millions* of years to explain such topography.

Tree rings

Everybody knows that each ring in the wood of a tree represents 1 annual growth cycle, so counting the growth rings gives you the age of the tree. Unfortunately it's not quite that simple because some trees have missing or false rings, so in reality counting rings from a single tree doesn't always yield very accurate dates.[635] But you can get around the idiosyncrasies of individual trees by counting the rings in many trees and cross-matching their thick-thin ring patterns like barcodes.[635] In this way an accurate master chronology can be built up, starting with living trees and going back many thousands of years.

> “unassailable evidence that the Earth is much older than Ussher’s six millennia”

Oak tree rings in Germany can be traced back over 9,000 years, and a combined Swiss-German pine tree record goes back more than 12,000 years.[636] The German oak chronology matches an Irish oak chronology as far back as the 3rd millennium BC. The North American Bristlecone Pine record goes back over 7,000 years[636] and several living trees of this species have been found to be over 2,000 years old.[637] Thousands of tree-ring chronologies from across the world and many tree types have been measured, and they can all be cross-referenced, albeit with minor error in some cases (there is apparently a 37 year error comparing the bristlecone pine chronology with the German pine chronology – or about 0.5%).[636]

This is further, unassailable evidence that the Earth is much older than Ussher’s six millennia.

Coral growth bands

Corals have annual growth bands much like trees, and they are used to construct chronologies in much the same way as tree rings. Cores drilled from coral reefs are photographed under ultraviolet light which makes the summer (tropical rainy season) growth bands glow. [638] These bands are traced, compiled, and cross-matched with other cores to produce a year-by-year count. In many cases variations in stable isotopes (not the radioactive kind) are logged along the coral record to help constrain that annual count. [639] Corals grow in more complicated shapes than trees, so it's harder to construct chronologies as accurate as the tree ring record, but despite that, scientists have been able to trace a year-by-year record that extends back around 130,000 years, with just a 2% error. [639]

Lakebeds

Some lakes have been quietly silting-up for thousands of years. Each year in summer they lay down a lighter colored layer of fine sand, and each winter a thin film of black clay drapes the lakebed. Drill-cores through these lakebeds reveal black and white stripes called "varves" – exactly one for each year, just like tree rings. Counting the stripes gives you the number of years it took to make the sediment in that lake bed.

Lake varves record the passage of up to 30,000 years in a single lake (Lake Suigetsu, Japan) and they occur all across the globe. [640] Many records begin today and extend continuously back, but others begin in the past so they have to be matched by other means to an absolute date. Matching different sequences from many lakes (using radiometric dating or volcanic ash deposits or magnetic data) creates a robust year-by-year timeframe going back tens of thousands of years, with errors calculated to be just 1-3%. [640]

Ice Cores

Ice cores are cylinders of ice bored from ice caps and glaciers by special drilling rigs. They are mainly from the deep ice caps of Greenland and Antarctica, and comprise a record of snows for millennia together with any trace impurities that were in the air at the time. The younger part of the record can be annually counted just like tree rings, coral bands and varves, but for the longer timescales we are interested in here, visual layer counting alone is insufficient. [639] The difficulties are many; including ice compression and diffusion that blurs the seasonal distinctions. [641] Nevertheless, detailed chemical sampling along the ice cores yields wiggles in the ratios of isotopes of oxygen and hydrogen (again, these are nothing to do with the isotopes used for radiometric dating) which reflect temperature variations at the time the snow was falling. These show a distinct up-down wave corresponding to summer-winter cycles – giving a timescale of 1 year per wiggle. To supplement the isotope wiggles, scientists also use analyses of dust levels (which vary seasonally) [641] and ash from volcanic eruptions to cross-match different cores. [639]

The upshot of all that is that we have ice core records that go back 800,000 years. [642]

Cave crud

We're all familiar with the spiky stalactites and stalagmites that build up in caves, if only from movies. Many contain annually-layered deposits which go back even further in time than ice cores. Their annual banding is related to seasonal variations in the amount of water percolating into the cave, and several can be traced back hundreds of thousands of years (a cave in Borneo goes back 600,000 years, and the "Soreq" and "Peqiin" Caves in Israel go back 250,000 years). Most of those older dates are based on radiometric dating, but a few younger caves have had stalagmite layers counted going back 6,500 years (the "Cold Air Cave" in South Africa) and others about half that age (eg Carlsbad Cavern, USA: 2800 years; northwestern Scotland: 3600 years). [643]

Some of these layer-counted "speleothem" records have also been radiometrically dated (eg the Carlsbad Caverns in New Mexico). The radiometric dates do indeed match the layer counted dates, validating the radiometric technique at least over the timescale of a few thousand years.[643]

25 Annually-layered rock 'clocks:' coral bands, lake varves and a stalagmite layers. Photos by:- corals: Rob Dunbar, Rice University / NOAA Paleoclimatology; Varves: Takeshi Nakagawa, suigetsu.org; Stalactite: Dr. Honglin Xiao, Elon College/ Department of Geology, University of Georgia

Physics of the Sun

Evidence taken, quite literally, from out of this world also corroborates an ancient origin for the Solar System. The age of the Sun can be computed from the proportion of hydrogen to helium in its core, because in a "Main Sequence" star like our Sun this hydrogen is converted to helium at a specific rate. The trick, then, is to find out what those proportions are. It turns out that the Sun, which is basically a giant hydrogen bomb, resonates with its nuclear reactions. The frequency of that vibration is very strongly related to the proportion of hydrogen to helium in its core. Scientists detect the vibrations using Sun-observing satellites like NASA's "SOHO" and "SDO"[644] and those "heleoseismic" measurements place the birth of the Sun between 4.6 billion years[645] and 4:57 billion years[646] – remarkably close to radiometric dates of meteorites which are used to date the birth of the Solar System (including Earth).

An old Earth even without radiometric dating

The last few paragraphs add up to a number of completely independent lines of evidence for the millions of years of Earth's existence. When compared they agree with each other, recording the same climate cycles. So even without recourse to radiometric dating, there is a mountain (pun intended) of evidence for the long timeframe of the planet conventionally understood by science. They also agree with, and therefore validate, radiometric dates.

Radioactive rock-clocks

Radiometric dating, using radioactive isotopes, allows us to read the natural 'clocks' in rocks. Unlike most of the methods above, radiometric dating isn't limited to a few specific situations (like trees or lake bottoms) or to the last few hundred thousand years. It can be used across the span of geological time and on many different rocks, making it indispensable for any practical understanding of our deep past.

It only became possible with the advances in atomic physics in the 20th century, and the development of an exquisitely sensitive technique for measuring minute quantities of chemical elements in a sample - the mass spectrometer.

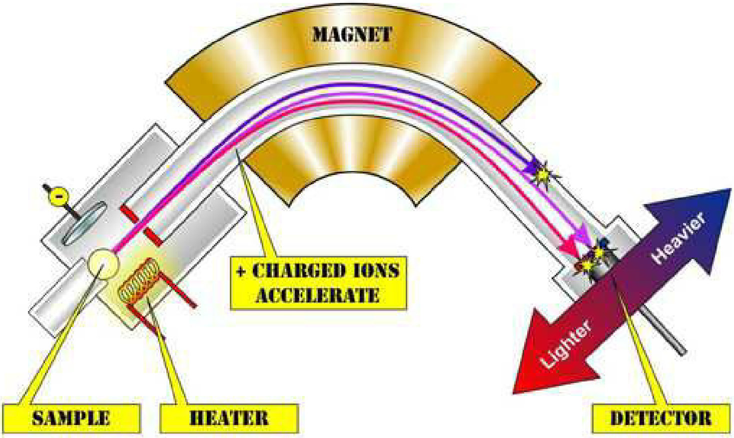
Atomic race track

The mass spectrometer sounds complicated but in essence it's very simple. It's basically a race track for atoms.

Imagine 2 racecars, one lightweight, the other heavily overloaded, racing around a bend. The lighter car makes the bend, but the heavy car smashes into the barrier. The mass spectrometer works just the same way – it separates atoms that weigh differently, no matter how slight that difference. A sample is heated to the point that its atoms lose their covering of electrons, leaving just atomic nuclei. The naked nuclei are then accelerated by magnets along a curved track and, just like our imaginary race cars, the lighter atoms make it around the bend but the heavier ones slam into the wall. Sensors record the locations of crashes, and a little calculation gives the weights of the atoms and their quantities.

There are many different kinds of mass spectrometers, including some that are coupled to particle accelerators (smaller cousins of the famous Large Hadron Collider), and some coupled to microscopes and lasers so that tiny samples can be vaporized from a single crystal or individual growth layers in a tooth. But they all work in essentially the same way, counting the amounts of atoms of different weights.

So what does atomic weight have to do with reading the 'clocks' in rocks?



26 **Atomic race track: how a mass spectrometer detects atoms of different mass.**

Moldy cheese

> “Radiometric dating works like moldy cheese”

Radiometric dating works like moldy cheese.

If you leave cheese out of the refrigerator, it goes moldy. The longer you leave it, the moldier it gets. With the exception of college students, we tend to throw that cheese away as soon as the mold appears, but if you were to leave it out for a few weeks it would eventually decay completely.

It’s basically the same with radiometric dating. Radioactive elements spontaneously decay to other elements over time. The atoms of the “parent” element and the atoms of the “daughter” element have different weights, so the mass spectrometer tells us the relative proportions of each. We use the ratio of parent (fresh cheese) atoms to the daughter (moldy) atoms, and the *rate* they convert (their “half-life”), to get a date.

“Half-life” just means the time it takes for *half* of the original parent to decay. If an element’s half-life is, say, 100 years then after 100 years half of the parent will remain, after 200 years half of that half will remain (¼) and after 300 years ⅛ is left, and so on in an ever-decreasing curve.

Skeptics of radiometric dating claim that there is no experimental proof of the technique (because humans haven't been around long enough) making the dates are unreliable. So it's probably a good idea to explain why such criticism is misguided by covering some of the ways that radiometric dating has been proven valid.

Time signal – checking the accuracy of the radiometric clock

Lab proof

Firstly, radiometric dating has been proven in the lab. As scientists began to understand radioactivity at the dawn of the 20th century, they realized that each kind of radioactive isotope decayed at its own set rate – its "half-life." Some decay fast, and others decay over billions of years, but experiments and theory showed they all decay in the same precisely-predictable *way*. In fact it is a "law" of physics that has been checked and rechecked many times over the last 60 years or so. [437] Still, we should prove its validity much further into the past than that.

Cross-checking with other kinds of rock 'clocks'

A good way to check radiometric dates is to compare them with other reliable rock 'clocks' like the tree rings, corals, cave deposits and varves I mentioned earlier. These have been used to calibrate radiocarbon and uranium dating to 50,000 years ago. [636] [647] Uranium dates have also been checked against annual layers in stalagmites from caves like the Carlsbad Cavern, USA (2800 years) and caves in northern India (about 700 years). [643] Carbon-14, lead-210, Cesium-137, lead-206/207 and Plutonium-239+240 dating techniques have been cross-matched to varves going back 15,000 years. [640]

So we have independent validation of radiometric dating going back tens of thousands of years, but we want to prove its reliability back into the millions and billions of years in the lifetime of Earth.

Orbital tuning and seafloor spreading

To address this, scientists matched dates of sea-floor lavas (using potassium-argon dates) with their expected age based on sea-floor spreading rates, going back several million years. They also used the pattern of magnetic pole reversals preserved in terrestrial basalt lavas. They successfully compared the radiometric dates of the basalts with the patterns of magnetic reversals going back around a million years. [437]

To validate radiometric dates further into the past, they made use of Earth's orbital wobbles. These orbital wobbles, which I described as the major cause of fluctuations in the ice ages, are known very accurately and can be projected with precision into the past. They can be correlated with temperature variations in ocean water revealed to us through oxygen isotopes in our microscopic fossil friends, the "forams." In this way, radiometric dates can be checked against orbital cycles – and they match all the way back into the age of the dinosaurs. [437] [648]

Ancient nuclear reactor

Beyond that we must reach into the deep past, to the weird natural reactor that occurred in Oklo, Gabon, around 2 billion years ago. First off, scientists can tell that a nuclear reactor was operating there because the profile of elements in the ground closely matches that in waste from modern nuclear reactors, and the isotopic abundances of several elements can *only* be explained by nuclear fission reactions (isotopes of neodymium, Plutonium-239 and uranium-235). This relates to radiometric dating because the proportions of those isotopes today are exactly as predicted by a *constant* nuclear decay rate operating over the last 2 billion years. In other words, the rate of radioactive decay has been constant, and therefore reliable for dating, at least since the time of Oklo, around 2 billion years ago. [437]

Immunity from temperature and pressure changes

But what if our 'clock' speeds up or slows in extreme conditions deep inside the Earth? It turns out that the dates are immune to extreme temperatures and pressures because the radioactive decay happens in the atomic nucleus, shielded from chemical reactions, which only involve electrons. Lab experiments have put radioactive samples through bomb explosions, frozen them to near absolute zero, taken them to mountain tops and down the deepest mines, spun them in centrifuges, fried them with electricity and put them in strong magnetic fields, all to no avail. Their decay constant remained just that – constant. [630]

There is one exception – a kind of decay called "electron capture." Experiments on Beryllium-7 showed that electron capture can be affected by extreme pressures – those found very deep in the mantle. Isotopes of rhenium and dysprosium also change their half-lives if their electrons are removed, but the conditions that would make that happen exist only in the interiors of stars! [630] In reality Beryllium-7 is not used for dating, and the related potassium-Argon (K-Ar) dating that should theoretically be affected, is not used under those conditions because rocks are molten at those extreme temperatures and pressures (so the radiometric clock is never 'set'). Nevertheless, a small error in the decay constant for K-Ar dates has recently been corrected, which I'll explain below. [648]

In the final analysis, there are dozens of different radioactive isotopes used for dating, who each have different chemistries and get incorporated into different rock types, and yet they *all produce consistent dates* compared to each other. [437] Moreover, dating is carried out routinely in hundreds of labs around the world with consistent results. [437] So radiometric dating has been proven in the lab and validated by cross-checking with a range of other rock 'clocks,' and between different radioactive isotopes. Radiometric dating is conclusively valid.

Errors and uncertainties

This doesn't mean that every radiometric age is infallible. As the geologist and author Brent Dalrymple put it: failures may be due to: "laboratory errors (mistakes happen), unrecognized geologic factors (nature sometimes fools us), or misapplication of techniques (no one is perfect)." [630] To mitigate these risks, scientists analyze multiple samples, use several independent techniques, and check the geology around the sample location. [630]

As better instruments become available and measurements more precise, some fine-tuning inevitably occurs, and occasionally new techniques supersede old ones. For instance, a small error in uranium dating was recently uncovered that affects dates of the most ancient rocks and meteorites, enough to reduce ages at the beginning of the Solar System by 700,000 years[649] – but still only a tiny error (0.015% or about 5 days in Your Life as Planet Earth). The electron-capture decay constant for potassium-Argon (K-Ar) dates is another example. Using values adopted in the 1960s and 70s, K-Ar and argon-argon (Ar-Ar) dates were generally younger[437] by around 2% compared to other dating techniques. [648] The K-Ar decay constant has since been corrected, and newer results (since 2010) are as accurate as uranium-lead dating. [648]

> "experiments put samples through bomb explosions, froze them, spun them, fried them and put them in magnetic fields, all to no avail. Their decay constant remained just that – constant."

It also doesn't mean the dates are exact to the day. A date of, say 2.024 ± 0.062 million years doesn't mean April the 24th, in the year 2,021,987BC. It just means it is most likely 2,024,000 years old but almost as likely to be any date 62,000 years younger or older than then. It's a spread of probability, with the quoted date in the middle of the spread the most likely.

Setting the stopwatch

Radiometric 'clocks' in rocks are really more like stopwatches. When rocks are forming there is a point when their chemistry stops changing, like when some magma cools into basalt. At the point that the rock is chemically static, the 'stopwatch' is set. And if nothing disturbs it, that natural stopwatch keeps ticking until scientists measure it in their mass spectrometer, like a timer in a swim race that keeps going until the swimmer touches the plate at the end of the race.

> "like a timer in a swim race"

Sometimes the rock can go through changes after its formation, like getting caught up in a continental collision. If the temperature and pressure rise sufficiently, they can make the minerals chemically mobile again, resetting the stopwatch. Scientists can exploit this by using different isotopes that are more or less susceptible to those changes, to learn what changes a rock has been through in its life, and when they occurred.

Spotting a faulty stopwatch

I don't want to get bogged down in math and graphs here, but the important thing to know is that scientists measure not just the radioactive parent and daughter isotopes, but also the quantity of a *third* element. This removes the need to know how much of the original daughter was present when the rock formed. It also makes the technique self-checking: if the radioactive clock has been compromised it will show up as scatter in the data points, so scientists would know not to rely on those dates. Even better, it allows scientists to calculate the initial quantity of the daughter isotope as one of the results, which can be useful for other purposes.[630]

Choosing the right clock – like choosing the right ruler

Because there are such a variety of environments that rocks form in (sediments, reefs, volcanoes, mountain belts, and so on), scientists must pick the appropriate 'clocks' that form naturally with those rocks. They must also choose different radioactive 'clocks' for different time ranges. It's just like choosing the right kind of ruler for measuring – you can choose anything from micrometers to tape measures, but you would never use a tape measure to make precise microscopic measurements, and you would never use a micrometer to survey a large plot of land. In just the same way, you would never attempt to use a short-half-life isotope like carbon-14 (the micrometer analogy) to measure dates in rocks billions of years old, and you would never try to measure the date of recently-erupted lava using the potassium-argon method (the tape measure analogy) which is useful between around 10,000 years to billions of years.

Dating humans

Carbon-dating with ^{14}C

In the most recent past, the time of modern humans, dates are measured using isotopes with relatively short half-lives, like carbon-14 (^{14}C). Carbon dating is the technique most people have heard of and it starts with cosmic rays bombarding our atmosphere. Every day some atmospheric nitrogen is transformed into ^{14}C by cosmic ray damage, and it reacts with oxygen to make CO_2, which gets incorporated into plants and then animals as food, or into seashells from carbon dissolved in seawater. ^{14}C decays back into nitrogen with a half-life of about 5,700 years, so provided an uncontaminated sample of wood, tooth, bone, etc. can be found, the amount of ^{14}C that has reverted back to nitrogen can be measured to give a date.

Carbon dating is used extensively in archeology, but its short half-life limits it to samples less than 50,000 years old, which is unfortunately right when modern humans were spreading across the globe. [650] Its cosmic origins mean that a correction must be applied for the variable rate that ^{14}C has was created in the past. To do this, a great many samples have been cross-referenced to dates from stalagmites, varves, [651] corals and tree-tings, creating a calibration curve going back 50,000 years. [636] A bonus that falls out of this wiggly curve is that it tells us about space weather in the past, which I will cover in the next chapter. Carbon dating of marine samples is a lot trickier because it takes time to mix the CO_2 from the atmosphere into the oceans, and ocean currents create variable reservoirs of ^{14}C, making marine carbon dates inaccurate. [636] [437] This does have a beneficial side-effect – it enables ^{14}C to be used as a tracer for ocean circulation. [437]

^{14}C false dates & contamination

> "scientists are busy reanalyzing specimens to correct their dates"

Since the 1970s, many ^{14}C dates were measured either on contaminated samples or on samples erroneously assumed to be the same age as nearby human remains. [652] The problem was so widespread that some scientists estimate up to 90% of middle to upper Paleolithic (Old Stone Age) dates are wrong.[652] In a 30,000 year-old bone, 98% of the original ^{14}C has decayed, leaving only vanishingly small levels that are easily overwhelmed by carbon that seeped into the bone from the surrounding soil over the ages. The problem stems mainly from collagen, a tissue in bones, which has an annoying preponderance for soaking up contaminants and throwing off date analyses. This issue is now being addressed by far more rigorous sample preparation to remove contaminated collagen, and scientists are busy reanalyzing specimens to correct their dates. In one example, a human jaw from the UK, which was previously dated at 35,000 years old, has now been shown to be more than 41,000 years old[652]. In another example, Spanish Neandertal remains were re-dated and found to be at least 10,000 years older than previously thought, limiting the time Neandertals and modern humans coexisted.[601]

Dating Sediba

When it comes to dating the bones of our ancestors like *Homo erectus* and *Australopithecus*, we have to reach past the range of ^{14}C. The work that went into dating "Sediba" is a great illustration of the way Earth scientists have to work with the real-world conditions they find, and employ a variety of methods to narrow-down the age of ancestral human remains.

The Sediba fossils were found in a dirt-filled cave in South Africa. Scientists began by identifying the sediment layers in the cave, then they collected over 200 fossils (from hyenas, saber-toothed cats, wolves, zebras, etc.) from those layers and identified them. Based on published dates when these animals appeared or went extinct, they could bracket the Sediba remains between 2.36 and 1.5 million years ago. No suitable samples for radiometric dating could be found in the layer with the Sediba fossils, so instead they sampled a layer of "flowstone" (basically horizontal stalagmite) from below the fossils. They sent those samples to two different labs for uranium-lead (U-Pb) radiometric dating. The two dates (2.024 ± 0.062 and 2.026 ± 0.021 million years) were identical within their error ranges and coming from the layer *below* the human remains they set a *maximum* age limit for Sediba.[653]

So, based on the combination of radiometric dates and the fossils, Sediba was between 2.047 and about 1.5 million years old – a big range in the context of human evolution. They had to narrow it down further.[653]

They turned to the international record of Earth's magnetic field reversals.[654] They analyzed samples from the flowstone and the sediments above it for the remnant ghost of Earth's magnetic field preserved within them from the time they formed. They found that the sediments where Sediba was found had *normal* polarity, so given the dates already established, they assumed the Sediba layer had to be in the normal-polarity "Olduvai Subchron," which lasted from 1.95 to 1.78 million years ago. So now Sediba was dated at 1.95 to 1.78 million years old - an uncertainty of 170,000 years.[653]

But they were wrong.

As they continued to excavate, they found a new layer of flowstone capping the layer that contained Sediba (so it was younger). The U-Pb date of the new flowstone was 2.19 to 1.9 million years old - straddling the Olduvai Subchron and an earlier magnetic reversal. Magnetic testing confirmed that the new flowstone had *reversed* polarity, so it had to be from *before* the Olduvai Subchron (so it was older than they thought). There was a very short switch to normal magnetic polarity at 1.977 million years ago, which only lasted 3,000 years, so Sediba had to be right in that magnetic time zone. This tightly-constrained the age of the Sediba fossils to 1.977 ± 0.002 million years old,[356] an uncertainty of just 2,000 years, or 0.1%.

Dating human artifacts

In exploring the earliest *Homo sapiens* culture and survival, scientists found pigments, stone "bladelets" and a quantity of seashells in a cave at Pinnacle Point in South Africa. Those workers needed to pin their discoveries to a date, and they used techniques that were different from those used to date Sediba. They used "Uranium Series" dating, which is good for samples that are too old for carbon-dating and too young for U-Pb dating, on a flowstone just above the artefacts.[437] The results gave a *youngest* age limit of 92,000 years. They then used a technique called "Optically Stimulated Luminescence" (OSL) on the sediments containing the artifacts, to come up with an age for the artifacts of 164,000 years. OSL requires samples to be kept in darkness from excavation to analysis, and it exploits dirt's ability to be a natural 'dosimeter' – the device on every nuclear power plant worker's coat that measures their radiation exposure. It works because while a sample is buried, it is constantly zapped by natural radioactivity in the soil, which causes microscopic damage to mineral grains in the dirt. The longer the burial, the more damage. When that sample is recovered and stimulated by light, it glows, and the strength of that "glow curve" gives the length of time the sample was buried! OSL is another technique for dating in the relatively recent geological past from 1,000 to 500,000 years ago. [650]

Dating at your local nuclear reactor

For older remains, like those of *Ardipithecus*, workers have used a technique which requires sticking samples inside a nuclear reactor! You may be surprised how many nuclear reactors are quietly working away on university campuses and other research facilities. [655] Samples are placed in the reactor to turn potassium-39 into argon-39 by being bombarded by neutrons. Once the samples have been radiated, they are then analyzed in a mass spectrometer. In the case of *Ardipithecus* they used this argon-argon (Ar-Ar) dating technique on volcanic ash deposits that sandwiched Ardi's bones, and came up with an age of 4.4 million years for Ardi. [656]

Dating fossils with SHRIMP

You may be wondering why they didn't just date the fossil bones themselves. As we saw a few paragraphs ago, radiocarbon (^{14}C) dating is sometimes used directly on bones, [652] but it's of no use on fossils older than about 50,000 years. Direct dating of older fossils is problematic because the process which preserves bones, teeth and shells as fossils usually messes with their isotopic 'clock.'

Living bone and tooth is made up of calcium-phosphorous crystals (hydroxyapatite), embedded in collagen fibers. When a body decays in dirt, the collagen eventually rots but the bone crystals exchange chemicals with groundwater and are gradually converted into fluorapatite, which is more stable and capable of lasting millions of years. The new crystals are as tiny as the original bone crystals, so they collectively have a large surface area in contact with groundwater. This means they continue to exchange isotopes with groundwater over thousands or millions of years, so the radiometric 'stopwatch' is never set. Dating these specimens typically gives dates that are far too young, sometimes half the true age, and with very large errors. [657] In contrast, mollusk shells have a tendency to absorb uranium from surrounding sediments, [437] which gives them an artificially *old* age.

This difficulty in establishing meaningful radiometric dates *directly* on fossils (as opposed to the strata enclosing them) has been a stick that Young Earth Creationists have used to beat radiometric dating as a whole. In reality, meaningful dates *can* be extracted for fossils when they have been isolated from chemical contamination. Examples include a 50-million-year-old shark tooth extracted from clay, a Jurassic dinosaur bone extracted from a clay-rich limestone, and conodonts (those mouthparts from ancient eel-like creatures). All these were dated using lutetium-hafnium (Lu-Hf) dating, and evidently the sediments that encased the fossils protected them from contamination.[657]

High precision dates have also been obtained from pristine samples of coral using uranium-thorium (U-Th) dating,[658] and microscopic shells of forams have been dated using strontium isotopes.[659] Uranium-thorium-lead (U-Th-Pb) dating has also been successful on Carboniferous and Silurian conodonts, and a Cretaceous dinosaur tooth.[660] These analyses used a microscopic probe known as a "SHRIMP" (Sensitive High Resolution Io Micro Probe) to zap tiny spots within samples, to find uncontaminated parts of fossils.

> "fossils *can* be dated directly in special circumstances"

Direct dating of fossils has also been used to shed light on early humans. Antelope teeth have been used to date ancestral human artifacts in South African caves using uranium-lead (U-Pb) dating,[661] uranium-thorium direct dating has been successfully applied to a Neandertal jaw bone from Spain,[662] and an important early *Homo sapiens* skull from Ethiopia has been dated directly using uranium-series dating.[663]

These examples show that fossils *can* be dated directly in special circumstances (so there's no fundamental flaw in the concept of dating fossils), but in most cases it's much more practical to date volcanic deposits or flowstones that bracket the strata were fossils are found, because they give a much more robust, tightly-constrained age.

Ages of lavas and granites

Potassium-Argon (K-Ar) is the most widely-used dating technique for lavas and other igneous rocks. It's good for rocks older than about 10,000 years, which contain potassium-rich minerals, like feldspar. [650] A variant of the K-Ar technique is the argon-argon (Ar-Ar) technique that we met when we were dating Ardi, above. The advantage of the Ar-Ar method is that by heating the sample in precisely-controlled steps, it can give the date of original crystallization (called a "plateau age"), screening out effects of any later part-resetting of the 'stopwatch.' [630] The Ar-Ar method gives very precise dates (precisions better than 0.1%) only matched by the uranium-lead (U-Pb) method,[648] and so is behind many of the key dates in the story of the planet between about 10,000 years and 66 million years ago. [648]

The other workhorse of radiometric dating is uranium-lead (U-Pb) dating, often using zircon crystals. Because of the long half-life of uranium, U-Pb dating isn't used on rocks much younger than about 40 million years old, [650] and it is the main method of dating rocks older than the age of the dinosaurs. [648] Zircon is a very resilient crystal which we met as the holder of your first memories in Your Life as Planet Earth. When it forms, it strongly incorporates uranium but not lead, so once the 'clock' is set it isn't easily re-set, which makes it a vital tool for dating old rocks that have been through complex histories. It's also a mineral that forms in a range of igneous rocks, so it is widely applicable. In some cases, zircon crystals can survive intact even when the rock around it is melted and later crystallized a second time. This allows scientists to measure the original age of these "inherited" zircons, and therefore to "see through" more recent events to older periods. [437]

For those most ancient specks of early Earth - the Jack Hills zircons – scientists used lead-lead (Pb-Pb) and lutetium-hafnium (Lu-Hf) dates to reveal their origin 4.4 billion years ago. [437] There's a range of other radiometric dating techniques for igneous rocks - like rhenium-osmium (Re-Os), and samarium-neodymium (Sm-Nd)[437] - but I'll spare you those details.

Dating sediments

If you think about what sediments actually are, they are mostly bits of older rock that have been broken off and washed into rivers, lakes and oceans. They are chimeras assembled from bits of diverse mountains and plains upstream. So with that in mind, what would it mean to date such a rock, other than to attempt to place a single date on myriad pieces of older rocks? [437]

Except, it turns out you can in some cases.

Firstly, some sedimentary rocks (limestone, salt deposits and the like) are *chemical* precipitates rather than grains of older rocks. So, provided they haven't been contaminated, it's reasonable to date those. Secondly, the very process that converts loose sand to sand*stone*, for example, involves the individual grains being cemented together, and this cement can be dated. It's not the same date as the moment the sand grains dropped out of the water, rather it is the slightly later date when the burial pressure and groundwater turned it to rock. [437]

There is an exception. Rhenium-osmium (Re-Os) dating has been used to date black shale from the age of "Slushball Earth." Both Re and Os become concentrated in low-oxygen muds on the seabed, and they get absorbed into decaying organic matter that will become the black in black shales once the mud has been compressed into rock. Because Re and Os come from the seawater they do indeed date the deposition of the mud, rather than a later rock-forming event or indeed the date of the parent rock that the muds were eroded from. [664]

Uranium-lead (U-Pb) dating can be used on marine limestones, cave flowstones (as we saw with dating Sediba), and even fossil soils ("paleosol calcite"). [437] Other dating techniques for sediments include uranium series dating (for young rocks with silica cement), [650] thorium-thorium, thorium-230 (with proctactinium-231 as a check), [437] and rubidium-strontium (Rb-Sr -

for marine sandstones that contain the mineral glauconite).[437]

So there are, in fact, techniques for dating the formation of sediments, but what happens to those dates when rocks are subjected to the temperatures and pressures of continental collisions and mountain building?

Cooking time – dating metamorphic rocks

Rocks that started out as sediments or igneous rocks, but which were subsequently changed by being squeezed and heated in continental collisions, are called "metamorphic." They are changed by the heat and pressure, growing new minerals to replace old ones, and they change their appearance. So in dating metamorphic rocks, what we are really doing is dating the metamorphic cooking event that transformed the original rocks.

> "like a holiday turkey in the oven, sizzling on its outside but defiantly raw in its middle"

A common way to do this is to use the argon-argon (Ar-Ar) method, to learn about the rock's "thermal history."[650] Many metamorphic crystals are zoned, with the outside of the crystal more "cooked" than its inside (like a holiday turkey in the oven, sizzling on its outside but defiantly raw in its middle). Lasers zap tiny spots across these zones, which are analyzed to reveal the equivalent of the oven temperature and when it was cooking.[437] This is usually combined with uranium-lead dating[650] (using zircon if it's available) to "see through" the metamorphic changes to the original rock, and sometimes with rubidium-strontium (Rb-Sr) dating[650] to learn about its cooling history after it was "cooked."

Some metamorphic rocks are studded with dark red garnets. These semi-precious gems form during the pressure-cooking of rocks, and they have high levels of lutetium, making them suitable for Lu-Hf dating of very high-pressure-formed rocks, such as in the Alps and similar mountain chains. [437]

So there are ways to date the cooking process that rocks have gone through, but what about rocks that were cooked in space rather than on Earth?

Antiquity of meteorites and impacts

The time between the formation of the first solids in the Solar System and the formation of the earliest protoplanet embryos was less than 10 million years. [429] This critical stage in our Solar System is crucial for understanding how our planet, our Solar System, and others like it evolved, but it's asking a lot to resolve dates at such high precisions from so long ago. [429] Luckily, lead-lead (Pb-Pb) dating does have this precision and, as we saw in Chapter 1, it has been used to date "Calcium-Aluminum-Inclusions" (CAIs) from meteorites like the Allende meteorite which fell to Earth in February 1969, and basaltic meteorites called "angrites." The CAIs and angrite meteorites yield dates of 4,568.2 million years give or take 400,000 years, which serves as the date for the origin of the Solar System. [429] [6] [630] [649]

Iodine-xenon (I-Xe) dating is another technique used on meteorites. It uses step-heating like the Ar-Ar method, to "see through" heating and shocks that happened in the long lives of meteorites between their formation and their discovery on the ground here on Earth. Measurement of the Allende, Bjurbole Qingzhen and Kota-Kota meteorites all cluster around the same early Solar System date of 4.56 billion years old. [437]

Rhenium-osmium (Re-Os) dating has helped tie down the timeframe of core formation in the earliest proto-planets in our Solar System. Measurements across different types of iron meteorites (shards from the cores of planets that were obliterated early in their lives) reveal an "osmium isotope evolution curve." The curve plots the earliest evolution of planets in our infant

Solar System, from the most primitive planets at around 5 million years after the start of the Solar System, to the most evolved (most complete core formation) around 100 million years later.[437]

There is even a way to date when a meteorite arrived on Earth. Asteroid fragments hurtling through space before they arrive on Earth are constantly fried by cosmic rays, which convert any aluminum in their minerals to aluminum-26 (^{26}Al). Once they land on Earth they are (comparatively) shielded from those cosmic rays and the ^{26}Al decays at a known rate, so measuring the level of ^{26}Al allows the calculation of the rough date of the meteorite's arrival.

Establishing the date of an asteroid impact on Earth is particularly challenging because the asteroid, and so much of the site it hits, are vaporized in an instant. Moreover, the instant melting and cooling hinders the proper setting of the radiometric 'clock,' resulting in ages that pre-date the impact. [665] In craters that have an impact melt layer, Rb-Sr, Sm-Nd, K-Ar and Ar-Ar dating can all be used. Fission track dating (see below) on glassy melts can also be used, and the dates can be compared to the record of magnetic reversals (like they did to date Sediba) for impacts in the last 200 million years or so. For debris flung from the crater, it's more complicated, but carefully chosen samples may yield Ar-Ar or fission-track dates. Young crater walls can be dated using isotopes generated in the rock surface by cosmic rays since they were first exposed to the sky. And finally, the glassy droplets of impact melt that fall far from the crater can also be dated using Ar-Ar or even U-Pb in zircons.[665]

The ups and downs of mountains

The ups

Fission-track dating is a little different from the other techniques described so far because instead of relying on the decay of a parent isotope to a daughter, this technique makes use of the natural damage radioactive decay (fission) inflicts inside crystals. Radioactive elements like uranium-238 eject high energy particles when they decay, which are like microscopic bullets that leave tiny 10-nanometer-wide (0.00001mm or about 3-millionths of an inch) tracks of destruction in crystals, which can be seen under an electron microscope.[437] The trails of destruction are so tiny that they can heal themselves given sufficient heat – 120°C for apatite, 200°C for zircon, and 300°C for sphene crystals.[650] What this means is that apatite crystals will not have fission tracks until they rise to within about 3km (2mi) of the ground surface (where the temperature reduces to less than 120°C).[650] The slower a mountain rises, the more fission tracks it will have, so scientists can calculate uplift rates over the last few million years. This technique showed that the eastern Alps have slowed their uplift, and the western Alps have sped-up, over the last few million years.[437]

The downs

And to get a handle on how fast those mountains are eroding away, you can calculate how long rocks at the surface have sat there, exposed to the atmosphere. Cosmic rays hitting rocks on the surface slowly generate chlorine-36 (^{36}Cl) from chlorine, potassium and calcium in the rocks' minerals. The cosmic rays don't penetrate into the ground, so the levels of ^{36}Cl are a measure for how long a rock has been exposed to the sky. This can also be used to date glacially-deposited boulders and even asteroid impacts![437]

Bottom line:

The take-away from this chapter is that the rock record is full of natural 'clocks' that get set – like a stopwatch – when they are formed or reheated. Scientists have an extensive menu of dating tools to apply to different situations, and several of these are often combined to bracket the age of a sample. Radiometric dating has been proven valid by comparing it with other dating methods, and by experiments in the lab, so we can be sure that the Earth is over 4 billion years old, and be confident in the dates that form the scaffolding of our planet's story.

5. Dipping a Toe in Ancient Seas, Breathing the Air of Lost Worlds

Throughout the story of Your Life as Planet Earth described the climates of those times. It's not as if we can time-travel to the Jurassic and set up a weather station, or sail Ediacaran oceans to take their temperature. And even if dinosaurs were alive today, you wouldn't want to take their temperature in the usual way! But Earth scientists do have ways to reveal the climates of the past, and even the body temperatures of extinct creatures.

Once again we have the mass spectrometer to thank for this. That versatile piece of lab equipment, which revolutionized the dating of our planet's history, also revolutionized our ability to probe the climates of millions and even billions of years ago. Through incredibly smart forensic science, we can use a variety of "proxies" that are preserved in rock or ice to tell us the temperature, atmospheric, and oceanic makeup going back to Earth's earliest days. Many of these proxies are isotopes, and the mass spectrometer serves to measure them in much the same way as radioactive isotopes used in radiometric dating (described in the last chapter). But the proxies for ancient climates are "stable isotopes" - they are not radioactive. And by learning about past climate changes we can get a handle on what to expect from our modern climate.

Thermometers for times past

Water as a thermometer

Water can be used as a kind of thermometer for ancient times. More specifically, isotopes of oxygen and hydrogen can. These are called "stable water isotopes."

You may recall that isotopes are flavors of the same element differing only in their mass. For instance oxygen comes in 3 isotope 'flavors': oxygen-16, 17 and 18. Almost all of the oxygen we breathe is oxygen-16, but it is always accompanied by a tiny fraction of the slightly heavier isotopes, including about 0.2% oxygen-18.[666] The ratio between oxygen 16 and 18 is widely used in a "thermometer" for ancient climates and goes by the moniker of "delta 18-O" or more correctly: "$\delta^{18}O$." Hydrogen in water also comes in the isotopic 'flavors' of hydrogen 1, 2 or 3 (usually referred to as hydrogen, deuterium (0.015%[666]) and tritium). The ratio of hydrogen to deuterium is another "thermometer" for ancient climates - "δD."

> "as the ocean temperatures rise, so do the levels of oxygen-18 and deuterium"

Stable water isotopes work as a thermometer because they get more concentrated or depleted through temperature-dependent changes like evaporation or condensation to rain or snow. Water made with lighter isotopes evaporates more easily than water with heavier isotopes, and heavier water (i.e. with oxygen-18 and/or deuterium) tends to condense into rain easier than lighter water.[666] So as the ocean temperatures rise, so do the levels of oxygen-18 and deuterium in the ocean, as more of the light water evaporates into the atmosphere. Stable water isotopes in marine fossils reflect the levels in the water they lived in, so they can tell us the ocean temperature when they were alive. The same is true for marine sediments. [667]

Stable water isotopes measured in corals, tree rings, lake deposits and ice cores have generated an annual (or nearly annual) record of temperature going back hundreds of thousands of years, from locations dotted across most of the planet. Going further back in time than those records allow, scientists have measured $\delta^{18}O$ in fossils and sediments all the way back to the early part of the planet's history. [52] Fossil mollusks, forams, diatoms, conodonts, [668] other marine invertebrates and even fish bones can be used to generate date-indexed records of ancient temperatures. [53] [669] [670] [671]

But the further back in time, the more uncertainties there are that the results reflect real temperatures, rather than some other intervening process like warm groundwater percolating through the sample at a later date. So climate estimates gleaned from Earth's earliest rocks, which tend to have been squashed and cooked multiple times over the last 3 billion years, are particularly challenging. Yet scientists have still been able to make reasonable estimates of Earth's very early climate, using a combination of painstaking sample collection, comparing results from different techniques, and advances in lab equipment.

Very careful geological fieldwork and sample screening can find small havens of relatively unaltered rock, and advances in lab equipment allow increasingly tiny spots to be measured from those samples.[53] Comparing the $\delta^{18}O$ in one kind of mineral (like phosphates) with those in another (like chert – a flint-like rock) allows scientists to triangulate a reasonable temperature estimate. For example, one study on rocks from South Africa deduced ocean temperatures 3.5 billion years ago (at the dawn of life on Earth) to be 26-35°C (79-95°F).[53] A different study using cherts from the same area and time concluded ocean temperatures were less than 40°C (104°F),[52] and a third study on older rocks (3.8 billion years old) from Greenland studied serpentinite – a product of reacting sea water with ocean crust – and concluded ocean temperatures were similar to today's. [20] So these 3 separate studies from 2 different parts of the world independently concluded the ocean temperature at the dawn of life was not very different from our own time. This was a surprise because the oceans were previously assumed to have been rather hot back then, at about 55 to 85°C (130-185°F).

But a couple of interesting things fall out of those temperature soundings of the deep past. The first concerns a surprising loss of our ocean water, and the second is a puzzle known as the "Faint Young Sun Paradox."

Water world

> "Based on δD values, oceans 3.8 billion years ago had 26% more water!"

Stable water isotopes tell us that the Earth has been losing ocean water since those early days. While the non-ice-age average value of $\delta^{18}O$ seems to have stayed the same for the last 3-plus billion years, [20] the deuterium component of water (δD) has not. It went through an increase, [20] which tells us that water has been lost – but where to? Since we know that the amount of continental crust has grown since then, and it contains a significant proportion of hydrated minerals, scientists can calculate how much water has been 'soaked up' by continental crust. But it's not enough to explain all of the δD increase. We know the planet is leaking hydrogen into space and has been since its early days. Hydrogen is such a light gas that its atoms bouncing around in the upper atmosphere can exceed their escape velocity and fly off into space, never to return, and nevermore to bond with oxygen to make water. The planet leaked more hydrogen when the atmosphere had more hydrogen,[13] and again when it had more methane, because sunlight breaks methane down in the upper atmosphere, freeing hydrogen. Based on the δD values, scientists calculated that oceans 3.8 billion years ago had 26% more water than today![20]

Faint Young Sun Paradox

And this is important because our Sun (a "main sequence" star) was about 30% less bright back then,[4] [11] which means the planet should have been frozen solid. But we know from stable water isotopes, the Jack Hills zircons[26] [27] [29] and from marine sediments formed at that time, that it wasn't frozen. There were oceans of liquid water, and temperatures were balmy. For a warm climate to exist under a faint Sun, there must have been a thick warm blanket of greenhouse-gasses in the atmosphere. There was, but it doesn't seem to have been quite dense enough to explain the balmy temperatures alone.[672] So scientists think that the extra warmth came partly from Earth being darker-tinted than it is today (it had a "lower albedo," as they say),[673] and partly from the peculiar combination of gasses in the atmosphere back then. A less-bright Earth absorbs more sunlight, the way an asphalt driveway will melt snow cover long before a lawn. And the early, oxygen-free and low-methane atmosphere seems to have absorbed more heat by the interaction of hydrogen and nitrogen molecules, in a manner similar to Saturn's moon Titan today.[13]

So even if there wasn't a super-dense atmosphere of CO_2, the extra warmth to keep the Earth temperate was provided by a combination of a hydrogen-nitrogen atmosphere, [13] 26% more ocean (which is low-albedo) [20], and small continents devoid of mountain chains (no reflective snowy peaks) because subduction hadn't started yet. [55 56 57] Moreover, in a volcanically-highly-active, basalt-covered, oxygen-less world with no terrestrial life, any dry land would be much darker than today, and so would absorb more sunlight. There may also have been fewer clouds due to less dust and biological particles in the atmosphere. [673] Add-in the occasional ocean-boiling asteroid impact and throw in tsunami tides (from a closer Moon and shorter days[22]) for good measure, and you may well have enough heat to compensate for the "faint young Sun paradox" and explain why the Earth wasn't frozen solid. It is also possible that the Sun was slightly bigger (by maybe 5%) [674] in its youth, which would have delivered more energy to the Earth despite a faint Sun, but it is fair to say there is some mileage left in this paradox. As one scientist put it: "it is a very complex problem, with very few non-controversial limits that can be placed on it."[675]

Complicated thermometer

Unfortunately $\delta^{18}O$, although a "common currency" [667] for ancient temperature measurement, is not a simple thermometer. To solve the equations that give you temperature you have to know the oxygen isotope proportions of the water that your sample (fossil, sediment, etc.) formed in. [676] In ocean waters this depends on the volume of water locked up as ice, so it is different in ice ages than warm phases. As far back as the most recent ice ages, this value can be measured directly from water trapped in sediments, [676] but further back in time an assumption must be made for this value, within the limits of what is physically reasonable. [667]

Working out the initial $\delta^{18}O$ in land deposits is harder than for oceans, as land values are affected by altitude, latitude, distance from the coast and amount of precipitation. [666] It is a little simpler at high latitudes, but even there it can still be skewed by long-term changes in atmospheric circulation or rainfall.[667] In tropical latitudes it is more a record of the rainy season, which means that in, say, Hong Kong, the $\delta^{18}O$ record may have the opposite relationship with temperature than we find in, say, Switzerland.[677]

Scientists deal with these shortcomings in three ways. Firstly they get a handle on the processes affecting stable water isotopes across the globe today, and use this information to calibrate ancient temperature readings. Second, they repeat measurements across a range of different substances and locations, to build a consistent picture. And third, they try to use alternative temperature proxies if they are available.

We now have a detailed understanding of how stable water isotopes correlate with temperature, latitude, rainfall and geographic location today because they have been monitored since 1961 at more than 800 locations across 101 countries, and on the world's oceans, by the International Atomic Energy Authority (IAEA) and the World Meteorological Organization (WMO),[677] along with precipitation, pressure, and temperature. These results can be used to calibrate temperatures measured from ancient samples.[667]

When they use fossils to measure the stable water isotope temperatures, scientists also have to correct for the creatures' metabolic effects on the isotope levels. Calibrations are based on laboratory measurements on a range of different species that are both alive today and found in the fossil record. Care is also taken to ensure only pristine fossils are sampled, and that enough samples are taken that the results are statistically valid and not just a sampling artifact.[245] In addition, scientists screen out any temperatures that have been compromised by ground fluids, by analyzing trace metals in the samples, which betray such effects.[676]

In the final analysis, when stable water isotope temperatures are compared with instrumental records (which only go back 130 years), they do match, even when tropical and land-based stable-water isotopes are included,[678] which suggests they are indeed reliable thermometers. But to be sure a temperature is valid, it's a good idea to also use alternatives from the growing toolchest of proxy thermometers.

A toolchest of thermometers…

There are many other ancient temperature-measuring tools in the scientific toolchest, including microbe membrane chemicals (TEX86),[679] Silicon isotopes (δ^{30}Si),[680] microscopic bubbles of brine in ancient salt crystals,[681] magnesium-strontium levels in seashells,[682] [683] lipid chemicals in peat ("MBT-CBT"),[684] crystal orientations in mother-of-pearl,[685] and even worm poop![686] Atmospheric temperatures going back a few hundred years ago can even be measured by logging the temperature profile in boreholes up to 600m deep.

One of the more widely used temperature proxies is a class of chemicals extracted from dead algae. We try to avoid saturated fats in our diets, but it turns out that saturation is the important temperature proxy in algal chemicals called "alkenones." *Coccolithophores*, those algae whose chalk skeletons make up the White Cliffs of Dover, change the saturation level in their alkenones depending on the temperature of the water they live in - when it's warmer they make more-saturated alkenones. The "alkenone saturation index" is abbreviated to the symbol "$U^{K'}_{37}$," and tracks the temperature of the ocean at its surface because the algae live in near-surface, Sun-illuminated waters. Alkenones happen to be resistant to breakdown in sediments, so rocks going back millions of years may be analyzed for their alkenone saturation index to derive sea surface temperatures for those times. Even in sediments 4 million years old, they remain a very sensitive measure of the ocean temperature at that time, having precisions as good as 0.2°C (0.4°F).[683]

This range of proxy thermometers in the scientists' tool chest builds confidence when different proxies agree on the temperatures in the same environment for the same time period. But they all require their own calibrations, and their use becomes problematic for extinct creatures and physical conditions outside the limits of their calibrations.

Capable clumps

One new technique stands out as it seems to give valid temperatures without having to know the starting isotopic makeup of the waters in which the sample formed, and it seems to be oblivious to the different organisms it forms in.[676] Called "Carbonate Clumped Isotope Thermometry," which is a mouthful to be sure, it is exploits the fact that the isotopes ^{13}C and ^{18}O in carbonates bond together in a mathematical ratio that depends on temperature, and apparently nothing else.[676] It seems to have problems in cave deposits and in samples formed close to the freezing point of water, but apart from that it shows great promise as an independent and versatile verifier of temperatures in times past.[676]

It has already been applied to ocean temperatures during Ordovician ice ages about 445 million years ago,[132] the most recent ice ages, and in East Africa at the time of our *Australopithecus* ancestors about 4 million years ago.[676] But perhaps the most intriguing use of this new technique has been to measure the living body temperature of extinct animals like dinosaurs.

Taking the temperature of dino blood

Carbonate Clumped Isotope Thermometry can be used on fossil bones and teeth to work out the body temperature of land vertebrates.[687] Scientists used this technique on the teeth of large dinosaurs from the Jurassic and discovered their body temperature was 36° to 38°C (97-100°F).[688] Human body temperature, by comparison, is a very similar 37 °C (98.6 °F). This was a surprise, because previous calculations had estimated a higher body temperature around 41 to 44 °C (116-111°F) based on the sheer size of the creatures, so dinosaurs must have had a way to cool themselves down.[688]

The technique has also been used to measure the body temperature of ice-age woolly mammoths, and Miocene rhinos and alligators (from about 12 million years ago).[687] To check the technique was accurate, scientists tried it out on modern teeth from a rhino, elephant, crocodile, alligator and a sand tiger shark, and found the technique gave an accurate body temperature for the modern creatures. The Miocene rhino body temperature of 36.6°C (97.9°F) agreed well with the modern rhino temperature of 37°C (98.6°F), and the woolly mammoth samples suggested a temperature of 38.4°C (101.1°F), slightly higher than a modern elephant temperature of 37°C.[687]

Plant thermometers

Leaves are remarkably good thermometers too. You may already be familiar with the fact that cold-climate leaves are often toothed whereas warm-climate leaves tend to be smooth-edged. It turns out that a number of other properties of leaves (size, shape of the tip, shape of the base, shape and spacing of the teeth, type of lobes, and so on) vary with climate too. Because leaves are the food-engines of plants, they are very sensitively tuned to their environment. For example, the leaves at the top of trees tend to be smaller and thicker than leaves that are shaded further down the canopy. [689] A tree will vary its leaf properties in its lifetime in response to changes around it, for example if surrounding trees are felled. Rigorous sampling of leaves and a statistical process applied to their characteristics called "CLAMP," yield not just mean annual temperature, but also warm month mean temperature, cold month mean temperature, length of the growing season, growing season rainfall and even altitude. [689]

CLAMP can be applied to fossil leaves so long as there are many of them, from different species, and they are preserved with sufficient clarity to meet the strict CLAMP standards. When these results are compared with other proxy thermometers like $\delta^{18}O$ they generally agree, [689] which increases confidence that they reflect real climate values.

Land temperature and rainfall changes in the past can also be estimated from plant pollen records. Pollen is extracted from lake sediments and the species it comes from is identified. Then scientists count the abundances of different species and construct ratios (for example: (birch+spruce) / (oak+Hickory)), [690] calibrated to different modern climate zones, to yield values for summer temperature and annual rainfall. They plot the pollen ratios for the sediments layer after layer, covering millennia, to reveal the advances and retreats of different woodland types in response to changing climates.

So, as wild as the idea first sounds, scientists do in fact have forensic techniques to tell the temperature of past oceans and even the body temperature of extinct creatures. But as we try to get a handle on modern climate change, one archive of temperatures and atmospheric gasses is particularly important – ice cores.

Ice cores

> "They contain an annual record of atmospheric gasses, temperature, and impurities going back 800,000 years"

Sticks of ice drilled from ice caps and glaciers are an incredibly detailed record of climates of the past. Being ice, they are obviously limited to cold locations – ice caps and glaciers. Most come from polar regions like Antarctica or Greenland and other Arctic islands. But some are extracted from glaciers across the globe, including places like Tanzania, Kenya, Peru, the Altai Mountains, China and Tibet.[642]

They contain an annual record of atmospheric gasses, temperature, and impurities going back as much as 800,000 years (EPICA Dome C in Antarctica),[642] 400,000 years (Vostok in Antarctica), [691] or 123,000 years (North Greenland Ice Core Project).[641] Outside Greenland and Antarctica, age ranges are more modest, ranging from a few hundred years to roughly 5,000 years.[642] Collectively they preserve a meticulous record of Earth's climate from today through roughly one third of the Pleistocene ice age, covering 19 glacial-interglacial cycles.

Frozen temperatures

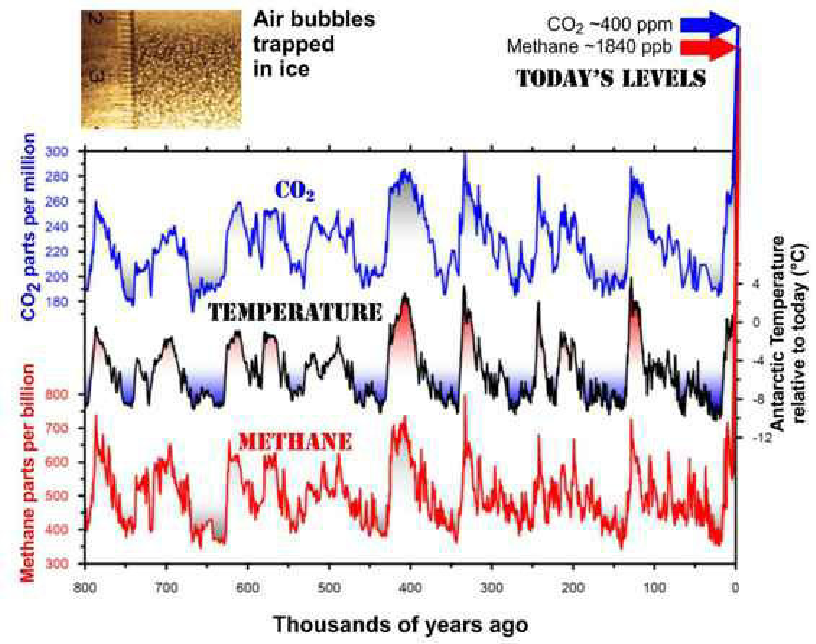
Stable water isotopes in polar ice cores record not just the seasonal oscillation of temperatures, but also the long-term drifts in temperature through ice ages and interglacial warm periods.[346] They show average temperatures over the last 800,000 years in Antarctica were mostly around 8°C cooler than today, interspersed with warmer interglacials up to 3°C warmer than modern Antarctic temperatures.[346]

Stable water isotope temperatures are supplemented by isotopes of nitrogen and argon ($\delta^{15}N$ and $\delta^{40}Ar$), which help quantify abrupt temperature changes.[692] [384] The δD record in Greenland ice shows a remarkably abrupt shift in the year 9,703BC. At this time the δD graph parts company with the $\delta^{18}O$ trace, in as little as 1-3 years.[346] This tells scientists that the source water for the snow on Greenland changed very abruptly at the end of the last ice age. And it is this event – recorded in ice cores - that formally defines the end of the last ice age (technically the end of the "Younger Dryas") and the start of the "Holocene" period.[346] Interestingly, the Antarctic ice cores do not show the same abrupt shift.[693]

Bubbles of past atmospheres

Ice cores also contain tiny bubbles of air that was originally trapped between snowflakes. When lumps of this ice are crushed or melted they release the trapped air, which can be analyzed for the levels of gasses like CO_2 and methane.[346]

What they show is a consistent pattern of methane and CO_2 varying with temperature – warmer times have more of these greenhouse gasses, and colder snaps have less. Over the last 800,000 years, CO_2 has varied between about 180 and 280 parts per million (ppm), compared with current values of around 400ppm.[346] Methane spent most of the last 800,000 years between about 350 and 750 parts per billion (ppb) – now it is around 1800ppb.[346] These past variations in greenhouse gasses are crucial for understanding global climate change today.



27 Bubbles of past atmospheres: the tiny specks in the photo are air bubbles trapped in ice. They can be sampled to tell scientists the levels of gasses in atmospheres up to 800,000 years ago. Source: Centre for Ice and Climate, University of Copenhagen, Denmark.

DNA, desert dust and sea salt

A fascinating array of impurities gets trapped in the ice, and they reveal their own secrets of past environments.

Dust trapped in ice cores is improbably informative. Dust particles can be analyzed for their isotopes, and the results compared with dust from deserts all around the planet, so scientists can tell where ice age winds were blowing from. This isn't idle curiosity – the wind patterns help our understanding of climate drivers back then. It also shows us that there was up to 100 times more dust in the air during ice ages than today.[346] This means that not only was the climate colder, but it was also much windier, and far dryer, with less rain to wash out the dust before it got to Greenland or Antarctica.[346]

Sodium chloride (sea salt) levels vary a lot in ice cores but exactly what this means is not certain. All we know is that the salt content of the ice is about 5 times higher in glacial periods. Modern pollution in the form of sulfates, nitrates and lead show up in the ice, as does ammonia which seems to be linked to forest fires.[346]

> "they analyzed the DNA and amino acids of this frozen soup"

Several ice cores have drilled right through the ice until they met bedrock, and through the layer of dirty, silty ice that sits on that bedrock. That dirty ice contains smeared frozen remains of life that existed just before the ice formed. In one Greenland ice core, they analyzed the DNA and amino acids of this frozen soup and were able to identify the remains of flowering plants including saxifrages, dryas, daisies and peas; trees including alder, spruce, pine, birch and yew; and grasses. They were also able to identify beetles, flies, spiders, butterflies and moths. This paints a picture of a diverse open forest in the highlands of Greenland some 450,000 to 800,000 years ago, radically different from the bleak ice cap that exists today.[694]

Dating ice

Ice cores are striped with alternating clear and cloudy layers. Sometimes the layers represent an individual snow storm, but the key is the identification of a hard surface or melt layer that is at the top of each summer layer. Counting these markers of ancient summers allows dating of ice cores year by individual year. There comes a point when the ice is so compressed that it is no longer possible to do this visually, which is where other techniques are employed. Our friends $\delta^{18}O$ and δD are analyzed for summer-winter (warmer-colder) wiggles to define the annual layers, as are seasonal peaks in dust levels, other impurities and electrical conductivity. Ice cores are cross-referenced by volcanic ash layers, their methane record, and even isotopes created by cosmic rays (which are also interesting for what they tell us about space weather – covered below).[346] Volcanic ash can also be used to match-up ice cores with climate information from sediments elsewhere on the planet.

So ice cores give us an unparalleled record of the climate going back nearly a million years, but they are limited to that comparatively short time and to icy locations. To figure out what was happening to the environment for the other 99.98% of the history of the planet, scientists have had to find clues in rock.

Barometers for old atmospheres

Seeing red – oxygen

Red. It's the color of blood, rust, and tropical dirt. They're red because they contain oxidized iron, and it was that simple sign that gave geologists their first clues about the emergence of oxygen on our planet.

In rocks older than about 2.5 billion years, you don't see red. In places as far afield as South Africa [695] and Australia, [696] older sedimentary rocks are the grays, greens and blacks of an unrusted world. They contain things that just aren't possible in today's oxygen-rich planet, like pebbles of pyrite (fool's gold), uraninite, and siderite. [696] These just rust away in modern streams and beaches, but in those old times they were washed into rivers, rolled around and swept downstream before being trapped, still untarnished, in rock.

> "the color of blood, rust, and tropical dirt"

But at around 2.3 billion years ago, traces of red begin to show up here and there, and by around 1.9 billion years ago we have pebbles and sand grains with rusty coatings, and red-stained sediments. [695] These "red beds" contain iron oxide, only possible in environments with significant levels of free oxygen, and their arrival signals the fundamental change that was the Great Oxidation Event – Earth's big mid-life crisis. And in later rocks you just don't find pebbles of pyrite, uraninite or siderite incorporated into sediments.

"Banded Iron Formations" are another sign. These important reserves of iron ore are widely found in rocks younger than 3 billion years old, peaking at around 2.5 billion years ago, and then they are absent after 1.85 billion years ago, save some small occurrences linked to slushball Earth events.[24] They weren't possible without oxygen to take the dissolved iron out of the sea water and precipitate it onto the ocean floor. The Great Oxidation Event also triggered a huge diversification of mineral types in rocks formed after 2.5 billion years ago as oxygen reacted with the geosphere, [24] so it's clear that a fundamental change involving oxygen happened to the planet at this time.

That cyanobacteria were responsible, rather than something purely geological, is indicated by genetic 'molecular clock' studies, fossil stromatolites, chemical fossils (steranes), and also microfossils of cyanobacteria dating back to near this time. [697] Another clue is a major uptick of a tracer for organic carbon burial ($\delta^{13}C$) [24] at this time, which would be expected as cyanobacteria took over the world and their dead bodies rained organic carbon down onto the sea floor. But other causes have been suggested, including the loss of hydrogen from the upper atmosphere (leaving behind orphaned oxygen from water vapor - H_2O), [20] a change in the chemistry of volcanic eruptions, [440] or the evolving chemistry of rocks as continents grew. [698] They may all have played a role, but based on the levels of carbon-burial and other chemical budgets, scientists have concluded that cyanobacteria contributed the lion's share. [698]

To better understand the link between life, Earth and oxygen, we want to know quantitatively what the *levels* of oxygen were. While ice cores contain bubbles of atmospheric air that we can sample for oxygen levels, they don't take us far into the past. So we must turn, again, to proxies. [68] Unfortunately most oxygen proxies are only good for telling us that oxygen was above or below a certain level, rather than providing a continuous scale. [68] For this reason scientists work with multiple proxies to bracket the estimated levels. [68] [87] [159] [699]

For instance, in rocks from before the Great Oxidation event we see sediments that had their iron and manganese leached out of them by water. That can only happen at levels of oxygen *less than* 1/1,000th of present levels. [68] After 1.9 billion years ago, when red beds begin, we see very little solution of iron, so we can tell that oxygen was *at least* 1/10th of present levels. [68] The oxidation state of iron in ancient soils looks like it may yield more quantitative oxygen levels, especially for the early years of atmospheric oxygen, but more work is needed on that technique. [700]

Sulfur isotopes ("$\delta^{34}S$") can tell us when there was enough oxygen to dissolve sulfate – which needs more than 0.4% of present oxygen levels. [68] They are the main ingredient for calculating the oxygen levels I referred to most in Your Life as Planet Earth. But that study used the difference in $\delta^{4}S$ between sulfate and fool's gold, combined it with carbon isotope data, and applied a range of corrections for rock weathering, erosion, land area and mountain building changes over time, in million-year increments, using a sophisticated computer model. [159] So it' far from a simple proxy for oxygen, yet its levels do make sense in the context of all the other environmental changes at the time.

Molybdenum (and vanadium and uranium) are metals found combined with sulfur in black shales, which start life as muds in the bottom of lakes or oceans, and they are black because they contain a lot of organic carbon that has been preserved by the absence of oxygen. Even though the muds are devoid of oxygen, the tiny mud particles reflect the oxygen levels on land where they first weathered from rock, and the chemistry of the waters they settled through, in their molybdenum isotopic ratio. Molybdenum values also show the rise of oxygen in stages through the Great Oxidation Event, and also the increased oxygen levels in the Devonian, around 400 million years ago. [701] [90] Interestingly uranium data suggest that oxygen levels dropped between the Great Oxidation Event and the Ediacaran, about 1.8 billion years later. [702] [72]

One quasi-quantitative oxygen measure uses our fossil Swiss Army Knives – the forams. The abundance of various foram species that live in high-oxygen water is divided by the abundance of other forams that live in low-oxygen water, to derive an Oxygen Index.[703] But although this allows scientists to graph *relative* changes of marine oxygen levels over time, it still doesn't give *absolute* oxygen levels. [703]

No fire without oxygen

Land plants have been plagued by wildfires since they first appeared, and fossil charcoal can be found in rocks as old as 419 million years.[141] The charred remains of plants can retain some of their characteristic anatomy and survive in soils where moist unburned plants would just rot. And since oxygen levels need to be above 13% in air to support fire, charcoal in rocks tells us that oxygen levels must have been at least 13% at that time. [141] But the *abundance* of charcoal in sediments can also be used to deduce the levels of oxygen in the atmosphere – the more charcoal the more oxygen, broadly speaking. By extracting fossil charcoal from rocks formed in swamps, scientists have constructed a graph of the estimated oxygen levels since the earliest land plants.[165] So this would appear, finally, to be a proxy that can give us the *absolute* levels of oxygen in a scale, but it is much more "spiky" than the computer-modeled, $\delta^{34}S$ and carbon isotope-based study I referred to earlier.[159]

> "'charcoal gaps' suggest very low oxygen levels"

But it does highlight some interesting quirks of the oxygen record. It confirms the high levels of Carboniferous oxygen that led to the giant insects of that age, but there are also some swings during the age of the dinosaurs, and a couple of “charcoal gaps” that suggest very low oxygen levels. One of these is in the early days of land life, 395 million years ago (aged 91 in Your Life as Planet Earth).[141] The other is right after the Permian mass extinction (the Great Dying).[141]

Ocean death and global warming

Even when the atmosphere had plenty of oxygen, there were times when large portions of the world's oceans became stale and oxygen-less, from the shallows all the way to the ocean depths. These “Ocean Anoxic Events” are particularly important to understand, since they seem to be associated with times of high atmospheric CO_2, global warming and mass extinctions. In fact warmer oceans do hold less dissolved oxygen (Henry’s Law), but anoxic events seem also to be related to nutrient imbalances spiraling out of control.[233] One such time was at the Great Dying event at the end of the Permian. On three separate occasions the deep oceans lost their oxygen, a fact that is revealed in levels of cerium, uranium and thorium present in the fossil mouth parts of eel-like creatures called conodonts.[184] Other major anoxic events occurred 93.5, 120, 200 and 183 million years ago, all associated with global warming events and large volcanic eruptions.[233] [201] [202]

Carbon dioxide (CO_2)

The Earth breathes.

As assuredly as you and me, our planet inhales and exhales from the thin bubble of air that surrounds this planet in its travels through the vacuum of space. We see this annual cycle of inspiration and expiration in the air at the top of the Mauna Loa volcano at Hawaii[704] and other monitoring stations around the world. They show that every winter the planet exhales CO_2 from decaying leaf litter and other soil processes, and it inhales CO_2 with the re-greening of every northern hemisphere summer. This cycle is dominated by the northern hemisphere because there is less vegetated land area in the southern hemisphere.

The annual zigzag (inhale/exhale) of the Mauna Loa CO_2 record is pegged to an incessant background rise, from around 310 parts per million (ppm) in 1958, to around 400 ppm today. [704] This trend is the same in air sampling programs all over the world, from pole to pole.[704] Back in 1750 the pre-industrial levels were only about 280 ppm. And it is this, combined with the fact that CO_2 is a "greenhouse gas," that makes it the most controversial gas of our age. We need to understand how the planet will respond to rising CO_2, so it's *crucial* for us to be able to gage CO_2 levels through the climate changes of the past.

As with oxygen, we can sample ice cores to get us a CO_2 record that goes back hundreds of thousands of years, but no further. Once again we must turn to proxies for CO_2 levels in older atmospheres.

Carbon dioxide in the oceans

When *marine* proxies are used to deduce *atmospheric* CO_2, it's important to understand that CO_2 in the atmosphere doesn't automatically equal CO_2 in the oceans. There is some chemistry, which I won't go into in detail, that links atmospheric CO_2 with 6 separate chemical parameters: dissolved CO_2, acidity, salinity, temperature, how saturated the seawater is with calcium carbonate, and depth in the ocean. The point here is that to establish what ancient *atmospheric* CO_2 levels were from ocean-based proxies, scientists need to know *at least 2*[292] of those chemical factors when they use ocean-based proxies for CO_2.

For two widely-used CO_2 proxies, scientists sample the remains of plankton from sediments for alkenones (those membrane chemicals we saw used to deduce temperatures) and the calcium carbonate in their shells. With the alkenones, instead of using the amount of "saturation" as they do to measure temperatures, they instead measure the proportions of carbon isotopes ^{13}C and ^{12}C. They do the same for the shells. They apply a formula that takes account of factors like growth rate, cell size and other physiological factors, temperature, phosphate and nitrate nutrient levels, and use that to calculate the concentration of CO_2 in the water at the time the sediments were laid down. The formula has been derived from lab experiments with live plankton, and by comparing analyses from pre-industrial samples with the values of dissolved CO_2 for those times.[705] [706]

The number of factors that have to be accounted for in the formula can cause problems. For instance, different species react in different ways to short term changes[707] and long term changes [708] in CO_2 levels, and also phosphate and oxygen levels.[309] [709] This again underscores the need to have data from several different proxies agree before scientists can be confident of their conclusions.

So, to complement other proxy measurements, scientists often analyze boron isotopes ($\delta^{11}B$) found in the shells of plankton. Boron isotopes are actually a way to measure ocean acidity (pH).[292] Scientists apply a formula which calculates pH after adjusting for the biochemistry of the plankton, ocean temperature, and salinity. The ratio of boron to calcium in plankton shells is then used to calculate the levels of carbonate ions in the water when the plankton were alive, and thus armed with 2 chemical levels (pH and carbonate), they can calculate CO_2 levels.[710] [292]

Land-based CO_2 proxies

Plants breathe too.

> "The lower the CO_2 in the air, the more stomata the leaves grow to compensate"

At least, they need to get air inside their leaves to make food by photosynthesis, and they have tiny pores on leaf undersides, called "stomata," that they use to do this. It turns out that plants tune the number of these stomata in concert with CO_2 levels. The lower the CO_2 in the air, the more stomata the leaves grow to compensate. [151] Scientists count the number of stomata per square millimeter on fossil leaves using computer-aided counting systems to derive CO_2 levels. [711] But leaf stomata as a proxy suffer their own complications. For the stomata density to give accurate CO_2 levels, the temperature and humidity of the air the plant lived in, and also the microscopic shape of the stomata themselves, must be factored in, [151] and this may be one cause of the large scatter in those data. There is also evidence that some plant species respond differently to levels of CO_2. For instance, araucarian conifers are less affected by high levels of CO_2, making them useful for estimating CO_2 at times when levels were much higher than today. [712]

It may be a stretch to say that soils breathe, but they do exchange air with the atmosphere. They are an amazing mixture of broken rock, life, air, rain and ground water. Some soils become fossilized, and these fossil soils ("paleosols") are another land-based proxy used for assessing levels of CO_2 through the last 400 plus million years. This proxy involves analyzing carbon isotopes ($\delta^{13}C$) in carbonates found in fossil soils. These reflect a balance between the CO_2 of the atmosphere when the soil formed, and the CO_2 given off by the totality of life (microbes, plants, and fungi) that lived in the same soil at the time. The value used for the atmospheric $\delta^{13}C$ is measured from either marine limestone or fossilized terrestrial organic material for the same time period. Again, this proxy is complicated by uncertainties in the value of the life-produced CO_2 in the soil, and CO_2 values can vary greatly between soils or even within the same soil. [713] Nevertheless, the soil carbon record of CO_2 does broadly agree with other proxies (like leaf stomata, plankton, boron isotopes), [289] and with computer modeling of the expected CO_2 levels (based on broad-brush calculations of expected CO_2 levels based on factors like land area, weathering rates and so on). [159]

There are other proxies for CO_2 including soil goethite (an iron mineral), carbon isotopes in corals and tree rings, and even a new one that uses 3 different isotopes of oxygen in fossil teeth and bones! [714] Taken together, the data from leaves, algae alkenones, fossil soils and boron isotopes are converging, but a twofold variation between some techniques remains. [289] Recent work has focused on improving the calibration of soil CO_2 proxies in different soil types and improving the calculation for the amount of CO_2 given off by the living component of soil, [715] so hopefully the scatter in these data will diminish in the future.

Proxies link CO_2 to climate change

Combined, CO_2 and temperature proxy measurements confirm the link between CO_2 and climate for most of the geological record.

> "proxy measurements affirm the link between CO_2 and climate for most of the geological record"

For example, even as far back as the Carboniferous-Permian ice age (300-260 million years ago, aged 93-94 in Your Life as Planet Earth), CO_2 levels sank to values about as low as they did in the most recent ice ages (around 220ppm). [166] Much later, in the time of the dinosaurs when there were ice-free poles and a mostly "greenhouse" climate, the proxy record shows CO_2 levels were over 1,000ppm. There were brief cold periods even then, and those too correlate with drops in CO_2 levels. [216] Present day CO_2 levels (around 400ppm) were last seen in the Pliocene, about 3 million years ago,[336] but are higher than the *general* trend for the last 30 million years.[289]

There is one ice age that does, at first blush, seem to break the link between CO_2 and climate. The last 2 million years or so of the Ordovician period, 443 million years ago, saw an ice cap cover much of what is now Africa and South America, which were at the South Pole at the time.[132] [716] This was a period of climate upheaval and sea-level change, with a temperatures *dropping* 5°C even in the tropics, and mass extinction. The puzzle is that we had an ice cap when CO_2 levels were apparently 8 to 16 times higher than recent levels.[132] But those high CO_2 values were extrapolated from a single data point which may well pre-date the glaciation,[216] and there is good isotopic evidence for high rates of rock weathering drawing down CO_2 levels at exactly this time.[716] Moreover with the Sun being 4% less bright back then, the CO_2 threshold for glaciation was at a much higher value of CO_2 than today,[216] and the ice cap probably started above the snow line at high elevations at the South Pole, the way it did again in the later Carboniferous-Permian ice ages.[166] In other words, despite appearances, the Ordovician ice age does not actually break the CO_2-climate link.

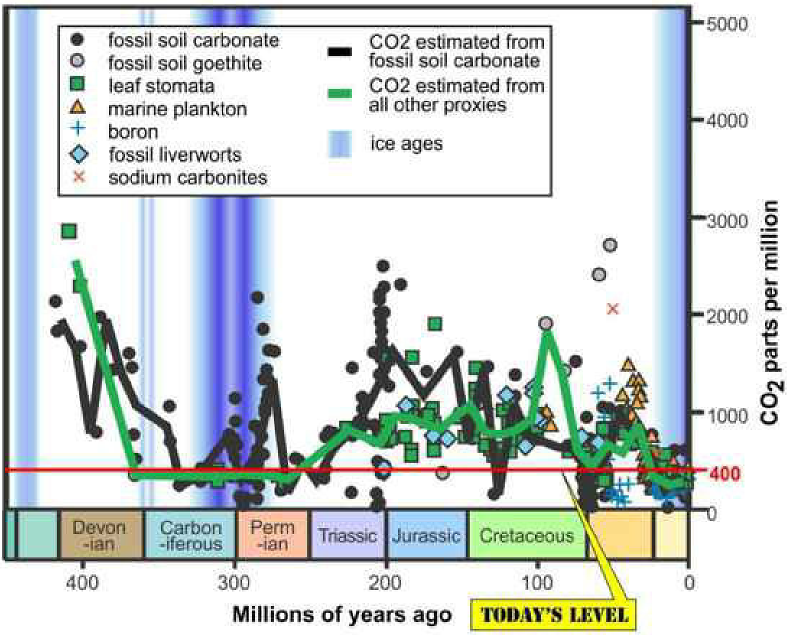
Unsurprisingly, given the complexity of our planet, there are other significant factors that affect the climate, not just CO_2. During the late Miocene (around 12-5 million years ago), oceans remained warm despite low CO_2 values, apparently due to ocean currents and the thermal structure of the Pacific Ocean at the time.[717] The Pliocene (5.3 to 2.6 Million years ago) saw summer Arctic temperatures some 8°C (14°F) warmer than today (even through cycles of orbital wobbles), but with CO_2 values around today's levels.[336] This suggests present CO_2 levels are out of balance with the modern climate, and we have already emitted enough CO_2 to drive the planet to Pliocene conditions.

Some people have claimed that CO_2 doesn't rise ahead of (or cause) global warming, but rather it follows warming. We would indeed expect CO_2 to rise in response to rising ocean temperatures because warmer water can hold less CO_2 dissolved in it than cold water (Henry's Law again). Until recently the dating and precision of the proxies wasn't fine-grained enough to delineate what lead and what followed, suggesting CO_2 may have lagged warming by maybe hundreds of years, based especially on Antarctic ice cores. Recent studies with much more precise correlation of ice cores and temperature proxies have shown that temperature and CO_2 changed synchronously in Antarctica during the end of the last ice age,[718] [719] and slightly before global temperatures.[720] Calculations show that increased warmth from the Sun due to Earth's orbit, especially in the northern hemisphere, is linked to the southern hemisphere through deep Atlantic Ocean currents,[721] which results in northern and southern hemisphere temperatures rising

> "we have already emitted enough CO_2 to drive the planet to Pliocene conditions"

out of sync with each other. [720] [719] This orbit-induced, ocean-current-enhanced warming released more CO_2 into the atmosphere which caused further warming, and so on, to end the ice age. [720] [719]

So knowing that global climate and CO_2 levels have been correlated in the past, allows us to test our understanding of current climate change, providing signposts to where our modern planet may be headed.



28 400 million years of CO_2 levels from proxies. Source: Dan Breecker, University of Texas.

Fingerprinting fossil fuels in ancient extinctions

Carbon isotope ratios ($\delta^{13}C$) do more than tell us past CO_2 levels. The $\delta^{13}C$ value is also a tracer for times when large reserves of dead vegetable matter (coal, oil, natural gas) get turned into atmospheric CO_2. Since plants prefer carbon-12 when they photosynthesize, the carbon in their cells and woody tissue is mainly carbon-12. This mainly-carbon-12 bias stays with the plant matter as it is fossilized into coal or oil. If large quantities of these fossil fuels are burned into CO_2, the proportion of carbon-12 in the atmosphere goes up, and the proportion of carbon-13 goes down as it gets diluted by all that carbon-12.

This kick in $\delta^{13}C$ values over time can be logged in rock successions associated with mass extinction events. We see a big negative swing in $\delta^{13}C$ values during the Permian Great Dying extinction event – a result of all the Siberian methane emissions and coal burning, and the release of Brazilian methane after the small asteroid impact there.[180] [177] We see similar negative $\delta^{13}C$ swings in the Triassic extinction event when oily muds were baked into methane,[195] and again in the modern era from our burning of fossil fuels.[666] Interestingly, we see a big swing in the *opposite* direction during the Great Oxidation Event, probably as a result of a boom in photosynthesizing cyanobacteria locking away lots of ^{12}C in sediments.[24]

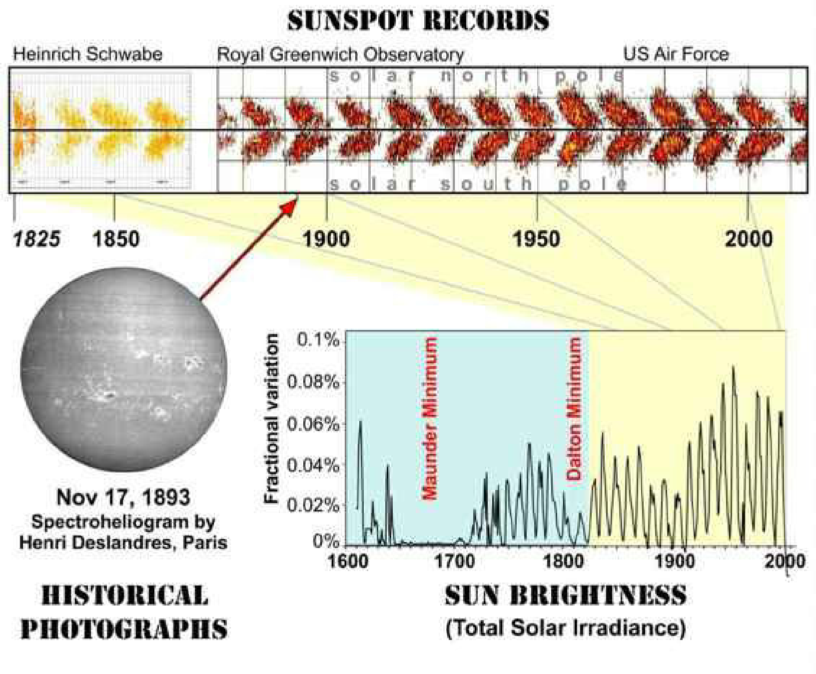
A brief history of space weather

It's easy to think of the planet as a ball spinning in inert space (apart from asteroid encounters), bathed in the constant, benign light of the Sun. But the Sun is not constant and space not inert. Earth is, in fact, subject to "space weather."

Inconstant sunlight

I mentioned the slow increase in brightness over the life of the Sun and the "faint young Sun paradox" earlier. But the Sun also goes through more rapid changes: small but measurable fluctuations in brightness, which affect the Earth's energy budget.[722]

The most obvious fluctuation of the Sun is its sunspot cycle - the 11-year cycle in the number of sunspots. This has been observed ever since telescopes have been pointed at it, and archived photographs of the Sun taken through sunspot-revealing "calcium K" filters extend back to the 1890s.[722] But accurate measurements of the *quantity* of solar energy arriving at the planet ("Total Solar Irradiance") have been around only since 1978. These show a small increase and decrease in irradiance with the sunspot cycle, but this variation amounts to only 0.1% of the total energy (more in the ultraviolet part of the spectrum) and changes Earth's climate directly by perhaps a few hundredths of a degree.[722]



29 **Sunspot cycles observed back to the 1600s and can be used to calculate variations in the Sun's brightness (Total Solar Irradiance).** Based on (clockwise) Arlt & Abdolvand, IAU 2010; NASA 2013; Foukal, Solar Phys 2012; Meuden Spectroheliogram from L'Observatoire de Paris.

> "effects are on a *cycle*, so they *cancel-out* over 11 years, so they can't explain climate change by themselves"

The Sun may have a larger *indirect* effect on Earth's energy budget. When the Sun is most active, ozone in the lower stratosphere warms as it absorbs the extra ultraviolet light. This seems to expand large scale atmospheric circulations ("Hadley Cells") shifting the jet stream northwards a little. When the Sun is least active there's a corresponding reduction in stratospheric warming.[722]

But it's important to note that both the direct Total Solar Irradiance and the indirect effects are on a *cycle*, so they *cancel-out* over 11 years, so they can't explain longer lasting climate change by themselves. [722]

The Sun also goes through longer fluctuations which can vary the Sun's light we receive by up to 0.3% over centuries. There have been prolonged periods with few if any sunspots, like the "Maunder Minimum" in the 17th century, when the Sun was virtually without sunspots for 70 years. Observations from other Sun-like stars suggest that they all undergo quiescent periods like this for less than 3% of the time. [722] The Maunder Minimum and similar solar variations do show up in temperatures recorded by tree rings in Eastern Europe, from the oldest record in 1040 AD until 1850. After that, the tree rings show the climate warmed markedly in line with greenhouse gasses, and not in line with solar changes. [723]

Cosmic rays, clouds and shifted weather

Our planet is incessantly zapped by high-energy particles from space. Some come from the Sun, like "Coronal Mass Ejections" (massive solar eruptions), which are more frequent when the Sun is most active (when it has most sunspots). Others are "cosmic rays," which mostly comprise extremely energetic protons from supernova explosions very far from Earth. [724] Paradoxically, when sunspot activity is high and the Earth is battered by increased solar wind, this shields the planet somewhat from cosmic rays. But when there are few sunspots and less solar wind, more of those cosmic rays make it into our atmosphere, with subtle but interesting effects.[722] Cosmic rays are more energetic than solar particles, so they penetrate deeper into the atmosphere where they trigger the formation of water droplets, and therefore may increase cloud formation a little. They may also affect the electric charge of the atmosphere around thunderstorms, which in turn may affect precipitation a little. [722]

Cosmic rays and energetic solar particles ionize atmospheric molecules which then eat away the ozone layer,[722] [725] triggering a cascade of knock-on effects. Reduction of the ozone layer cools the stratosphere, which moves the jet stream and expands the "polar vortex" (the persistent low-pressure areas at the poles), which in turn changes cloud distribution and storm paths. This cosmic ray effect lasts through solar quiet periods, whereas the effect from solar particle events is short-lived.[722]

The equatorial Pacific climate has a bigger correlation with solar activity than elsewhere, which may be due to cloudiness.[722] It's possible that this is a climate "amplifier," taking a relatively minor solar effect and enlarging its effects on climate, but observations show that any amplification is no more than about 20% on top of the very small Total Solar Irradiance change.[722] [726]

Measuring space weather before modern man

Cosmic rays are energetic enough to mess with the atomic nuclei of gasses in our atmosphere. They convert nitrogen into carbon-14 (^{14}C) and they shatter oxygen, nitrogen and argon nuclei to create beryllium-10 (^{10}Be) and chlorine-36 (^{36}Cl).[437] The energy level needed to make these "cosmogenic isotopes" is so high that they can only be formed by galactic cosmic rays (and rarely by "solar proton events") so they record the level of cosmic rays (and therefore periods of low solar activity) in times before we had instruments to measure solar variations directly.

^{14}C is the same isotope we use for carbon-dating, and while for dating we have to *correct* for its variable production by cosmic rays, for a space weather proxy we are interested in the opposite – the variation itself. ^{10}Be in ice cores from the poles gives a stronger signal than in lower latitudes because the Earth is less shielded from cosmic rays at the poles. The ^{10}Be proxy record shows that even in periods of no sunspots (the Maunder

Minimum) there is still a detectable 11-year cycle in cosmic rays showing that the Sun's magnetic field still fluctuated regularly in that time.[722] In addition to the 11-year cycle, proxy data reveal a 22-year cycle caused by the Sun's magnetic field reversals, and there are also 88-year and 207-year cycles. These all show up in the ^{10}Be and ^{14}C proxy records, but there is no evidence in those records for solar cycles of the order of 1,500 years that would explain (as contended by some) the climate fluctuations known as "Bond Events" (since the last ice age) or "Dansgaard–Oeschger Events" (during the last ice age).[722]

As with other proxies, space weather proxies have their challenges. In particular they are affected by variations in the Earth's own magnetic field over timescales longer than 500 years, so it's hard to separate the Earth's magnetic signal from the space signal.[722] An atom of carbon can remain in the atmosphere as CO_2 for 7 or 8 years, which smears out the ^{14}C signal from a single cosmic event, whereas ^{10}Be only hangs around in the atmosphere for a few weeks to 2 years. This makes ^{14}C a better indicator of space weather fluctuations on 11-year or longer cycles averaged across the globe, where ^{10}Be is better at pinpointing the date of a single cosmic event.[437]

> "solar cycles have been stable at least over the last 1.2 billion years"

Some ice cores show a correlation between local temperature and Sun cycles (using ^{10}Be for the Sun cycles and ^{18}O for temperature), but other locations fail to show this correlation, so it seems not to be a global phenomenon. [722] Other data do show a correlation between ^{14}C and rainfall (recorded in cave stalagmites) going back around 9,000 years. In general, proxy records show that during times of high cosmic ray flux (times of lower solar irradiance) monsoon rains are slightly weaker in Oman, India and Southern China, high latitudes are a little colder with more sea ice in the Atlantic, and Europe is wetter and cooler. Rainfall patterns also shift in Africa, Central- and South America [722]

There is solid evidence that solar cycles have been stable at least over the last 1.2 billion years. Geologists studied lake deposits from Devonian and Proterozoic periods in Scotland. They are, in fact, well-preserved "varves" with a layer per year for thousands of years. Geologists measured the thickness of every tiny layer and analyzed them for repeated cycles. They found cycles of approximately 11-years, 22 years, and, curiously, 60 years,[727] showing the same rhythm we see today.

Violent galactic events

Supernovae and gamma ray bursts near us are very rare, and potentially extremely destructive. A large and very sharp increase in both ^{14}C and ^{10}Be shows up in Japanese, American and European tree-rings, and Antarctic ice cores, corresponding to the year 774-775AD.[728] The magnitude of the increase is some 20 times the normal solar cycle, and 10 times larger than the normal galactic cosmic ray signal. It may have been caused by an exceptional solar flare,[729] the debris from a supernova washing past us, or a gamma-ray burst from two black holes or neutron stars colliding. The fact that roughly 300 times more ^{14}C was produced than ^{10}Be, tells scientists that that event was most likely a short gamma ray burst.[728] A direct hit from a nearby gamma ray burst could fry the planet causing mass extinction, but scientists estimate the 774AD event occurred roughly 3,000 to 12,000 light years away, so was mercifully weak enough to not extinguish life on Earth! Intriguingly this celestial calamity may have been seen by Anglo-Saxons as a "red crucifix" in the heavens![730]

Fossil raindrops and packrat urine

I don't have space to go into them all here, but there are proxies for many other environmental parameters used to understand the history of the Earth. These cover such diverse factors as rock-weathering rates,[731] monsoon rainfall,[732] ocean acidification,[181] ocean mixing and connections,[437] ocean salinity, hurricane activity,[733] drought, stream flow and many others.[734] They are mined from diverse sources like lake sediments, tree rings, corals, cave deposits, deep-seabed drill cores, maize harvest records, ice cores and even peat bogs.

It sounds far-fetched, but scientists even used fossil rain drops to calculate the density of the early atmosphere! 2.7 billion-year-old slabs of South African rock were found covered with small circular pits that bore all the hallmarks of rain pits from a passing shower over freshly-fallen volcanic ash. Scientists performed experiments with water droplets on various ash deposits, and used the results to calculate the density of the air through which those ancient raindrops had fallen to make the observed pits. Their results showed that the atmosphere could not have been more than twice the density of our modern air, and most likely was just slightly denser. [672] These results poured fuel on the "faint young Sun paradox" debate that I mentioned earlier.

> "plant and animal remains encased in crystallized packrat urine"

Perhaps the most bizarre proxies are from "packrat middens," ancient nests of packrats containing "plant and animal remains encased in crystallized packrat urine!" [735] The vegetation entombed there is a treasure trove of information about shifting vegetation with climate change, and the leaves have been used for stomata-counting for CO_2 levels. The crystallized urine itself is a record of chlorine-36 (^{36}Cl), which as I mentioned in the previous section, is a tracer for cosmic ray levels, forming a valuable supplement to the cosmic ray record from polar ice cores. Evidently scientists will go to extraordinary lengths to get their data!

Yet there are some things we have no proxies for, such as methane. This is a shame because methane is implicated in several climate shifts in Earth's history.

Rock-solid evidence of ancient climates

The most fundamental, rock-solid evidence for different environments in the Earth's past is the science of geology itself. The very makeup and structure of sediments betray the environment they formed in. The same rippled sands found on sea beds today can be seen preserved in ancient rocks; ancient river floodplains have the same silty layers that we find beside today's rivers; and the same can be said for desert dunes, reefs, estuaries, glaciers and all the other modern environments.

For instance, at the low CO_2 time of the Carboniferous and Permian glaciations, we find "diamictites" (also called "till" - a sediment diagnostic of glacier deposits) in Argentina, Antarctica, South Africa and Tasmania. These are associated with sediments containing isolated stones that are identical to modern "dropstones" that fall into soft sediments from melting icebergs. [166] Glacial sediments like those tell us about the "Slushball Earth" events of the early Earth, [24] but "hummocky cross-stratification," which betrays stormy influence on seabed sediments, shows the world's oceans were exposed to wind at those times. [85] We also see dust deposits called "loess" in Australia at that time, indicative of glacial times when ice-ground rock flour is uncovered by summer melting and blown away, to be deposited elsewhere. Both the loess and the hummocky cross-stratification tell us that the planet was not completely frozen over (so more a slushball than a snowball). Large, thick loess deposits are also found across Europe, the US Midwest and China resulting from the most recent ice ages.[342]

Desert sands are another example. Sands from modern deserts have grains which, if you look at them under the microscope, are nicely rounded, frosted (sand-blasted) and all a consistent size. The same is true for ancient desert sands like the Coconino sandstone in the Grand Canyon area, even down to the slanting outlines of 270 million-year-old sand dunes.[736]

30 **Jurassic desert dunes in Zion Canyon, Utah. Their drifting outlines captured like frames in a stop-motion film, sliced through by recent erosion.** Photo by the author.

Other rocks have tell-tale signs of an estuarine environment (like "flaser bedding"), others have desiccation cracks that show muds have dried in the air, and still others have salts indicative of arid soils. There are many, many more but I won't subject you to them here! The point is that the same physics that results in sediments today can be inferred for identical sediments through Earth's history.

The present is indeed the key to the past, as Sir Charles Lyell observed back in 1832.[737]

Bottom line:

Even though we can't directly stick a thermometer in ancient oceans, or directly measure the concentration of CO_2 in Jurassic air, there are a range of indirect measures – proxies - for ancient environments. Proxies are complicated and are not infallible, but their precision has been improving, the menu of them keeps expanding, and the differences between them has been narrowing in recent years.[705] [289] Fundamentally, when we compare the proxy record with the physical rock record we find they make sense together. And by revealing what has happened to our environment in the past, we can put this knowledge to work to assess what is in store for our modern planet.

6. The Future According to the Past

“The farther backward you can look, the farther forward you are likely to see”

Churchill

So what can we learn from our planet’s past?

First, this is real.

This is not fiction – there is solid scientific evidence behind this terrestrial chronicle. Yes, there are uncertainties, which I highlighted in the previous chapters, but the great majority of our understanding of the planet’s past stands on firm scientific ground. Science now has a good handle on many of the changes of Earth’s past, their causes and their effects.

Second, the Earth has always been dynamic, so there’s no reason to expect it to be static now.

Change has always been a part of Earth’s story. Orbital changes have imprinted their rhythm on ice ages and climate oscillations throughout geological time. [295] [149] [169] [269] But there have also been much bigger changes, whether caused by massive volcanic eruptions, life innovations, ocean circulation changes, or asteroid collisions. Every significant change triggered a proportional reaction, like the appearance of cyanobacteria, which filled the atmosphere with oxygen and caused the planet to freeze, or the evolution of worms that churned the sea bed and caused ocean chemistry to change, or the greenhouse gas emissions from Large Igneous Province eruptions, which triggered global warming, ocean anoxic events, and mass extinctions.

We should therefore expect similar causes now to enact similar results. It just doesn't make sense for the Earth to work any other way.

Third, humans today are changing the planet the way Large Igneous Provinces did in the past.

Abrupt climate changes were highly destructive in Earth's past. The creatures of those times didn't get off lightly – many went extinct. Several mass extinctions were caused by huge greenhouse gas emissions from Large Igneous Provinces, and some (like the Permian) came perilously close to extinguishing all complex life on Earth. The parallels between past greenhouse gas-driven extinctions and our activities today should give us cause for concern.

And as we saw in Your Life as Planet Earth, modern-looking humans evolved some 200,000 years ago, but it wasn't until the climate stabilized after the helter-skelter of the ice ages, that agriculture,[738] then civilization began.[414]

The power of humans

The 2004 tsunami-generating quake in the Indian Ocean released 23,000 times more energy than the Hiroshima atomic bomb.[739] Even the largest hydrogen bomb ever tested (The "Tsar Bomba," a 50 megaton device) was just a tenth of the energy in that single quake.[740] By those measures human power may seem puny.

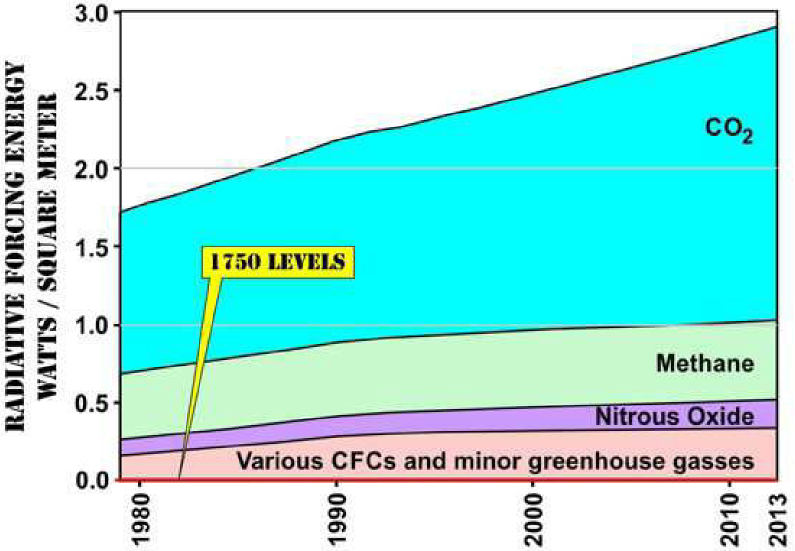
But our ability to change the Earth lies less in moments of explosive power than in the relentless accumulation of small unwitting acts on a personal scale.

"our ability to change the Earth lies less in moments of explosive power than in the relentless accumulation of small unwitting acts on a personal scale."

In just the same way that the oxygen released by a single cyanobacterium is inconsequential, but oxygen from trillions of them transformed the planet in the Great Oxidation Event, there are so many of us now on this planet that the sum of all our individual contributions can fundamentally change our Earth.

The smoke stacks from individual power stations and factories, the exhausts of individual cars, airplanes and so many other discrete sources have combined to nearly double the heat energy trapped in our atmosphere compared to pre-industrial values. [741] This extra energy in our atmosphere has built to the point where in 2013 it was the equivalent of 561 *million* Hiroshima atomic bombs, or 224 thousand "Tsar Bombas," being detonated in our atmosphere each year![B]

But less than half of Americans believe modern global warming is caused by humans. [742] For sure, the science of climate change is *immensely* complex, and uncertainties remain, but let's touch on what we do know.



31 Building energy: radiative forcing by greenhouse gasses in the atmosphere, relative to 1750 levels.
Simplified from: NOAA AGGI, 2014

The global climate is warming – beyond reasonable doubt

The planet is warming. Study after study has established this beyond doubt. Instrument drift, heat-island effects, poor quality data, selection bias and other spurious causes have been ruled out. [463] [743] [744] [258] The effect is stronger in the northern hemisphere than the southern hemisphere, and it is pronounced at high northern latitudes. [463] [743] [744] [258] Some 90% of this excess heat has been absorbed by the oceans. [745] Land temperatures have risen faster than ocean temperatures, on average by 1.5° C (2.7°F) in the past 250 years, with about 60% of that occurring in just the past 50 years. [463] If you include the oceans, global average temperatures have risen by about 0.8 °C in the last century[258] and are rising about 0.17°C per decade (faster in the northern hemisphere), despite a recent flattening of *surface* temperatures since the millennium.[744] [743] [744] [746]

Side effects

Arctic sea ice is melting at 13% a decade,[747] and ice-loss in Greenland and west Antarctica is accelerating, [748] although curiously, Antarctic *sea ice* has actually been *increasing* by 1.4% per decade. [258] Sea levels are rising[749] [748] and ocean salinity is changing.[750] Ocean acidity has increased by 30% (pH dropped 8.2 to 8.1) in response to CO_2 levels, more acidic than any time in the last 2 million years and they are getting even more so. [292] [751] [260] Ocean acidification is already affecting shell-forming creatures, reducing marine organism egg production, delaying larval development, causing abnormal fish behavior and problems in oyster hatcheries. [752] Some shelled plankton species are actually dissolving alive.[753]

These effects are déjà-vu of the Large Igneous Province eruption-driven climate changes in the past.

In Alaska the thawing ground has rendered tundra roads unusable for twice the number of days per year compared to 30 years ago, while trees rooted in no-longer-solid ground have become “drunken forests.” [754] Warmer winters have led to an epidemic of pine bark beetles causing destruction of forests in Canada and the western United States[755] while the Arctic has experienced vegetation changes equivalent to a 6 degree change in latitude (400 miles or 700 km) in just the last 30 years.[756]

Across the world extreme heat waves are more frequent, high temperature records are being broken, and weather agencies have added new colors to their charts to depict temperatures previously considered “off the scale.” [757] Many areas have experienced a greater frequency of heavy downpours, [755] with more frequent flooding an inevitable consequence. The Thames Barrier – a gateway to protect London from storm surge - has been deployed with increasing frequency in the last 2 decades.[758]

Weather is not the same as climate

> "weather is not the same as climate, any more than the stock price for an individual company is the economy"

One of the most frequent dismissals of climate change goes like: "they can't predict the weather in a few days, how can they possibly predict climate change?" But weather is not the same as climate, any more than the stock price for an individual company is the economy. Like that stock price, weather has all kinds of short-term variability whereas the climate is more like the economy – the underlying long-term trend. Weather has always been variable, so it's impossible to pin one hot day, or one massive downpour on climate change. But over time, climate change makes heat waves and downpours *more likely*, in just the same way that an improving economy tends to see rising stock prices, but not all stocks rise and short-term variability continues.

A pause in warming?

It's true that average global *surface* temperatures, which had risen rapidly from the 1970s to the millennium, have not risen much since then, despite ever-rising CO_2 levels. So the question is: is this a short-term wobble within the natural variability of the climate, or is it an actual pause in climate change? In fact, looking at the land temperature record (which is not as affected as global temperatures are by variation caused by ocean currents) the 'pause' is statistically insignificant over the natural ups and downs of the climate during the last 50 years. [759] Also, ocean probes show that extra heat is being absorbed by the oceans, and there was also a small reduction in the solar energy received during the 'pause' timeframe. [760] [761] So the 'pause' seems to be just a short-term wobble in the continuing global warming trend. [761] It reduces projected warming for the middle of the century by only about 10%, and does not materially affect projections for the end of the century. [761]

Despite the so-called 'pause,' the years from 2001 to 2013 still rank among the 14 warmest in 133 years of instrument records, [762] 2013 was tied for the fourth hottest year on record globally, [763] and hot extremes of temperature are still becoming more frequent. [755] [764] And despite recent headlines gleefully declaring "global cooling" based on a return of some Arctic ice, [765] the reality is that even in 2013, the extent of Arctic ice was still much less than the average for each of the last 3 decades. [766] The 2013 sea ice 'recovery' is an example of "weather," whereas the decades-long decline in Arctic ice is a reflection of climate.

So why the obsession with CO_2?

A planet at our distance from the Sun should be a ball of ice. Deep frozen. Lifeless.

A simple calculation of the energy received from the Sun by the Earth tells us its average temperature should be -19°C (-2°F).[295] [767] Clearly reality is different – why?

It's due to the blanket effect of "greenhouse gasses" in our atmosphere, trapping the Earth's heat. Sunlight shines mainly in the visible part of the spectrum. You can see your neighbor's house, a view on a clear day, and the road ahead when you drive, because the atmosphere is *transparent* to visible light. The warmth of sunlight on your face is the sensation of the Sun's rays generating heat in your skin, which glows in *invisible* thermal infrared light. Roads, trees, rocks – everything does the same thing, they all warm up in sunlight and that warmth glows with thermal infrared light. But the atmosphere is *opaque* to thermal infrared, so that warmth can't escape. It gets absorbed and re-radiated within the atmosphere, keeping the planet warmer than it would be without greenhouse gasses.

> "It's like a 2-way mirror in a police interrogation room"

It's like a 2-way mirror in a police interrogation room. The detectives can see into the room (like sunlight penetrating the atmosphere), but the suspect looking back just sees his own image reflected back to him (like Earth's trapped heat).

99% of the atmosphere is nitrogen and oxygen, which are not greenhouse gasses. CO_2 is in the remaining 1% along with argon, nitrous oxide, methane, CFC gases (the ozone-hole-making refrigerants), and water vapor.

CO_2, nitrous oxide, methane and water vapor are all greenhouse gasses because their atomic bonds resonate with thermal infrared radiation, and CO_2 happens to absorb infrared at the peak wavelength of Earth's heat glow. It dominates the greenhouse effect, and 80% of the increase in greenhouse effect ("radiative forcing") from 1990 to 2013 has been due to CO_2. [741] CO_2 and nitrous oxide levels continue to rise unabated, while methane levels have been variable. [741]

A simple combination of CO_2 and known volcanic eruptions is sufficient to calculate practically all the temperature variation in the last 250 years. [463] Since volcanoes produce short-lived *cooling* from their sulfur emissions, practically all the *warming* in that trend is explained by CO_2 levels. That's why we're obsessed with CO_2.

Water vapor

Water vapor is a powerful but highly variable greenhouse gas that some believe is behind climate change. But a single molecule of water vapor lasts only about 9 days in the air on average,[768] so it doesn't hang around long enough to be a primary *driver* of global warming, because the Earth takes much longer to change ("thermal inertia"), and the amount of water vapor in the atmosphere is limited by temperature.[769] This means it is a "slave" or "feedback" that only rises in *response* to warming caused directly by other greenhouse gasses,[767] but in this way it *amplifies* the warming caused by those other gasses, doubling their warming effect![770] [767] Scientists have proven that water vapor is controlled by temperature, rather than the other way around, by watching its response to the short-lived global cooling triggered by the eruption of Mount Pinatubo in 1991.[771]

The two faces of CO_2

As I mentioned in the last chapter, we know that CO_2 and temperature have moved in lock-step throughout most of Earth's history. CO_2 is both a *driver* of warming, and also rises in *response* to warming. When warming is caused by orbital changes, we see CO_2 levels rise simultaneously because warmer oceans can dissolve less CO_2 than cold ones.[719] We also know that when massive volumes of CO_2 have been added rapidly into the atmosphere in the past, this has driven global temperature rises, like in the Triassic[193] and the Permian[181] extinction events.

Basic physics (Planck's equation for blackbody radiation, absorption spectra for gasses, Stefan–Boltzmann law, Boyle's Law) tells us that extra CO_2 in the atmosphere *has* to have a greenhouse effect. If CO_2 was not operating as a greenhouse gas, the Earth would be that ball of ice,[767] so rising levels of CO_2 *must* have a global warming effect unless something else negates it. And, as I'll explain below, even though there are some climate processes that work to reduce the effect of CO_2, they do not negate it. So, aside from orbital wobbles, CO_2 is the principal "control knob" on climate change. [767]

We are the cause

How do we know humans are to blame for rising CO_2 levels now?

For a start the quantities match. The increase in CO_2 in the atmosphere matches the measured industrial CO_2 release, [772] [773] [774] [722] and global oxygen levels have been going down as you would expect from burning fossil fuels. [775] [772]

Second, the isotopic fingerprint of the CO_2 shows it came from fossil fuels, rather than volcanoes. [772] [258]

Third, the timing of the changes matches the timing of the industrial era. For instance temperature and CO_2 levels are largely explained by orbital wobbles and volcanic eruptions (with minor solar cycle influence) up to the industrial era, and then CO_2 and temperatures increase regardless of the orbital or solar parameters. [463] [723] Warming in the oceans is still mostly confined to the near-surface showing it's a relatively recent phenomenon. [776]

The magnitude of warming we have seen greatly exceeds natural climate variability, [772] so it's virtually certain that we are to blame for the CO_2 which is driving global warming. [772] [258]

It's not the Sun

Some scientists have claimed that global warming is caused by solar activity or cosmic rays. Although the amount of sunlight (total solar irradiance) has fluctuated since satellite measurements started, overall there has been no net increase while the Earth's climate warmed. Solar activity rose and then fell in the 20th century, but global temperatures kept rising, so there isn't a direct causal relationship. The cosmic ray flux decreased in the early 20th century, and from the second half of the 20th century to recently it has been high. If cosmic rays were a significant factor in climate change, then the latter half of the 20th century should have been cloudier and cooler than it was, so cosmic rays are clearly not a major factor. [722]

^{10}Be isotope data led some scientists to suggest that the Sun has much more influence on our past climate than mainstream science has it, [777] but recent research has refuted those conclusions, [722] so the most up-to-date and widely-accepted understanding is that solar variation is only a minor contributor to climate fluctuations. [722] There was also a suggestion that the cold climate in the second half of the 17th century was caused by low solar activity during the sunspot-free "Maunder Minimum," but temperature records show that the climate began warming 20-30 years before the end of the Maunder Minimum, so solar activity was also unlikely the main climate driver in those times.[722]

Most scientists studying the link between solar activity and climate agree that the solar effect on climate accounts for only 0.1% of the observed temperature changes.[722] [258]

Accepted science

You may not get this impression from some sections of the media or the blogosphere, but the reality is that scientists are not debating the evidence for man-made global warming.[778] That is accepted science - scientists with expertise in climate science are virtually certain that recent global-warming is due to human activities.[779] [258] That is also the official position of a many venerated scientific bodies, governments and corporations, including:

> The Geological Society of London[780], The American Geophysical Union[781], the Geological Society of America[782], the National Academies of Science[783], The Royal Society[772], The Australian CSIRO[784], the AAAS[785], The American Chemical Society[786], The American Physical Society[787], American Meteorological Society[788], NASA[789], EPA[790], National Center for Atmospheric Research[791], Canadian Meteorological and Oceanographic Society[792], Science Council of Japan[793], Russian Academy of Science[793], Brazilian Academy of Sciences[793], Royal Society of Canada[793], Chinese Academy of Sciences[793], French Academy of Sciences[793], Deutsche Akademie der Naturforscher Leopoldina, Germany[793], Indian National Science Academy[793], Accademia Nazionale dei Lincei, Italy[793], Academia Mexicana de Ciencias, Mexico[793], Academy of Science of South Africa[793], Australian Academy of Sciences[794], The Chinese government[795], the Indian Government[796], and even major corporations such as DuPont.[797]

These position statements include phrases like: "The evidence is incontrovertible: Global warming is occurring," [787] and "Global warming is unequivocal and primarily human-induced." [791] What scientists are debating is the extent, timing and regional distribution of changes, and the most accurate methods for predicting these. [778]

Hoax, climategate, and lobbying

Even though human-caused global warming is accepted by most scientists, it isn't by more than half of Americans, [742] because they have been misled by a small but vocal community of climate change deniers that attract disproportionate attention from the media. The deniers seize on short term weather events and misuse scientific uncertainty in a kind of smoke-and-mirrors exercise to cast doubt on the reality of climate change. [765] [778]

This phenomenon was illuminated by Naomi Oreskes and Erik Conway in their book: "Merchants of Doubt: How a handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming." [798] They detailed the exploits of a well-funded lobbying industry whose aim is to "keep the controversy alive" and *deliberately* sow doubt in the minds of the public and government. Oreskes and Conway concluded: “in creating the appearance of science, the merchants of doubt sold a plausible story about scientific debate. They erected a Potemkin village [a fake village for show] populated, in only a few cases, with actual scientists.” They found that journalists feel obliged to “balance” mainstream science with the views of the extreme minority, inflating the latter’s importance, effectively resulting in a media bias against mainstream science.

“a well-funded lobbying industry whose aim is to ‘keep the controversy alive’ and *deliberately* sow doubt in the minds of the public and government”

The Guardian newspaper of the UK has also uncovered evidence that “Secret funding helped build a vast network of climate denial think tanks,” and: “anonymous billionaires donated $120m to more than 100 anti-climate groups working to discredit climate change science.”[799]

This *manufactured* appearance of doubt (as distinct from genuine scientific debate) taints the opinions of politicians, the decisions of government[798] and even the courts. In 2011, the US Supreme Court ruled on a case of American Electric Power v. Connecticut, concerning CO_2 regulations. The Supreme Court Justices apparently placed equal weight on the unfounded opinions of climate change deniers as on the evidence-based conclusions of the overwhelming majority of scientists. As one commentary in Nature – one of the most prestigious scientific journals in the world - put it: “That the nation's highest court would repeat this misleading refrain, and seemingly endorse Dyson's views as equal to those of the IPCC and the EPA, simpl takes the breath away.”[800]

So it’s not surprising that some scientists may feel defensive in the face of this manifest conspiracy.[798] The so-called “Climategate” affair involved emails from the Climatic Researcl

Unit (CRU) of the UK's University of East Anglia, which wer hacked and uploaded to the web in 2009 and 2011. They were seized upon by climate change deniers who claimed that they showed CRU scientists had manipulated and falsified climate data. Some of the emails gave the impression that CRU scientists may have tried to abuse the peer-review process to prevent publication of papers that conflicted with their views, and may not have complied with data requests.

We rightly expect the highest standards of intellectual honesty and transparency from scientists, [801] so claims of misconduct and fraud were investigated by several independent inquiries. They concluded that the CRU scientists' "rigour and honesty as scientists are not in doubt," declaring: "exoneration," [802] and finding: "no evidence of any deliberate scientific malpractice." [803] Across the pond, the US Environmental Protection Agency declared that: "EPA reviewed every e-mail and found this was simply a candid discussion of scientists working through issues that arise in compiling and presenting large complex data sets." [804] Finally, UK legislators concluded: "it is time to make the changes and improvements recommended and with greater openness and transparency and move on." [805]

The criminal who hacked the emails and released them suspiciously shortly before the UN climate summit in Copenhagen was never found. [806]

The point is that the only hoax here is the unrelenting stream of manufactured doubt and denial that is neither supported by the *evidence* nor by the consensus of the vast majority of scientists. As the AGU President, Michael McPhaden put it: "That consensus is rooted in a foundation of scientific knowledge gained through careful, thoughtful, and thorough research, not political or ideological rhetoric." [807]

Or as US Senator Daniel Patrick Moynihan once said "Everyone is entitled to their own opinion, but not to their own facts." [807]

The last time we were this warm

True, the Earth has been this warm before.

We were on a cooling trend over the last 6,000 years, scheduled for the next ice age by around the year 3,500AD, [808] due to changes in our orbit around the Sun. But that all changed when we reached the industrial era, which has reversed 6,000 years of cooling in a century. [419] The planet is hotter now than the Medieval Warm Period (AD 800-1300)[258] [809] [419] [810] or the Roman

Warm Period (500BC to 400AD),[811] [812] or any time in the last 6,000 years. Even 6,000 years ago, during the "Mid Holocene Warm Period," when the warmer climate was caused by the same orbital change that ended the ice age, [295] [813] global temperatures were about the same or just slightly warmer than the 2000s.[419] [295]

Beyond then, you have to go back to interglacials – warm phases between ice ages - to see temperatures like today. During the last interglacial (known as "MIS5"or the "Eemian" – around 130,000 years ago), even though Arctic temperatures were around 5°C [295] to 8°C[384] warmer than today, globally the temperature was only about 1°C warmer. [295] The Earth was warm then because our orbit was delivering about 11% more solar energy to the Arctic.[295] Sea levels were 9 meters (30 feet) higher than today,[385] as a result of drastic reductions in Antarctic and Greenland ice sheets – all in a world barely warmer than today. To find the next time as warm as the 20th century, you have to go back 400,000 years ago to "MIS11." That anomalously warm interglacial, again caused by orbital changes, was in the same temperature ballpark as MIS5,[295] [814] with the Arctic sea ice at least partially melted, [815] just as we have seen in the last few years.

But in those orbitally-driven interglacials, with temperatures just slightly warmer than today, CO_2 levels rarely rose above 280ppm, compared with modern levels of about 400ppm. [346] So they were fundamentally different from today - driven by slow orbital variations in solar energy, rather than rapid CO_2 rise. To find sustained global temperatures to match those projected for the end of this century, with CO_2 at today's levels, we have to go back before the ice age, all the way to the "Pliocene" epoch around 2.5 to 3 million years ago. [295] [333] [258] [336]

That's a time before the emergence of *Homo*.

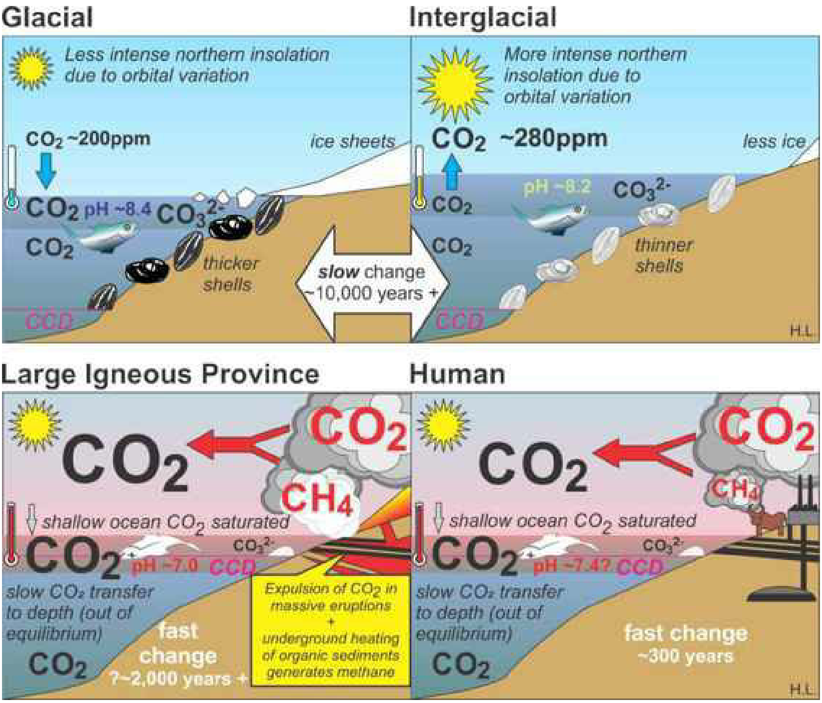
Speed of change

How do we reconcile CO_2's control on climate with the knowledge that life thrived at much higher levels of CO_2 in the deep past?

It's all about the *speed* and *volume* of those CO_2 emissions.

Our CO_2 is rising faster than in previous mass extinctions

You may recall from my description of CO_2 proxies that atmospheric CO_2 is linked to six chemical parameters in the oceans: dissolved CO_2, acidity, salinity, temperature, carbonate saturation, and depth.[292] Slow changes to CO_2 (longer than about 10,000 years) can be absorbed in the oceans without causing an environmental crisis because the excess CO_2 is buffered by those other parameters throughout the vast reservoir of the deep oceans. [292]



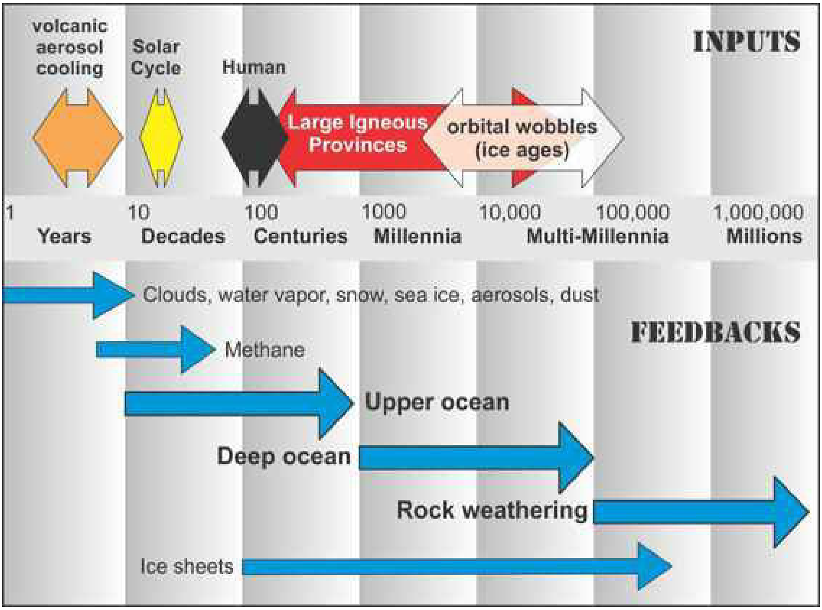
32 **How changes in seawater chemistry process CO_2 emissions. Slow changes allow ocean chemistry and atmospheric CO_2 to remain in equilibrium. Fast changes, such as those caused by LIPs and humans, are too fast for the ocean chemistry to process, turning surface water more acidic and allowing a big buildup of CO_2 in the atmosphere, causing more warming.** CH_4 = methane, CO_3^{2-} = carbonate, CO_2 in seawater is mainly bicarbonate, CCD = Calcite Compensation Depth, below which calcite (shells, limestone) dissolves faster than it accumulates. Based mainly on Zeebe, Annu. Rev. Earth Planet. Sci. 2012, with additional input from A. Ridgwell (personal communication).

> “this has knocked ocean chemistry out of kilter by making it more acidic”

Human CO_2 emissions, in contrast, have happened mostly in the last few decades. In this timeframe, the atmosphere interacts with the biosphere and the *surface* layer of the oceans. This reservoir is only about 4 trillion metric tons (4.4 trillion US tons) of carbon – about the same as our fossil fuel reserves - so we have the capacity to completely overwhelm this short-term natural compensation system. [292] The surface layer of the oceans has so far been able to absorb about a third of our CO_2 emissions, but this has knocked ocean chemistry out of kilter by making it more acidic. In fact ocean acidity is rising about a hundred times faster than any time in the last 56 million years. [108] Worryingly, there are signs that the ocean surface may already be becoming less effective at absorbing our excess CO_2. [816]

On a thousand-year timeframe, extra CO_2 gets absorbed into the vast reservoir of *deep* ocean waters. At these timescales the ocean is still more acidic than before all that extra CO_2 was introduced, and the warmer ocean is in balance with higher atmospheric CO_2 levels and temperatures, because warm water dissolves less gas than cold water. [292] In other words, climate change continues on this timescale, even if the CO_2 emissions stop.

Over *several* thousand years those extra CO_2 emissions begin to be removed by chemical reaction with deep-sea carbonate sediments and carbonates on land. Over even longer timescales (100,000 years or more) carbon burial in sediments as a result of silicate rock weathering is the major long-term remover of CO_2, balancing volcanic CO_2 production, so preventing a runaway greenhouse like on Venus. It was these long-term adjustments that kept the world habitable in the warm, high-CO_2 world of the dinosaurs, and before the ice ages. [292]



33 **Some feedbacks are slower than others: The time**

frames of inputs (forcings) compared to climate feedbacks. Partly based on Schmidt, PAGES news 2012 & Zeebe, Annu. Rev. Earth Planet. Sci. 2012.

It's when CO_2 is produced too fast for the oceans to absorb it, that excess CO_2 ramps up in the atmosphere, producing the rapid global warming, ocean acidification, seal-level rise, oxygen starvation events, and the mass extinctions we saw several times in Your Life as Planet Earth. [292]

It's true that rapid temperature changes have occurred before humans, for example "Dansgaard-Oeschger events" during the last ice ages. These large, sudden temperature fluctuations occurred in as little as 20 years (changes of about 0.5°C per year), [295] but they are not a good guide for our modern times because they were mainly in the north, and were not driven by CO_2 but instead were probably caused by ice shelf collapses due to ocean currents, [392] [258] and possibly the opening and closing of the Bering Strait. [345]

Glacial-Interglacial cycles took much longer – over thousands of years. The surface ocean was able to process the relatively small rise in CO_2 that accompanied these cycles (it rarely rose above 280ppm[346]) by adjusting its chemistry in a non-destructive way, [292] [817] with cold times having a slightly more alkali ocean with higher levels of carbonate ions, causing some marine creatures to grow thicker shells than in warm times. Throughout the cold-warm, glacial-interglacial cycles of the ice ages, calcium carbonate "saturation state" (and therefore the depth in the ocean where calcium carbonate dissolves) varied by roughly 20% to buffer the CO_2 changes. [292]

In other words, the oceans and atmosphere remained in balance (in equilibrium) through the ice ages.

It's just too much, too fast, for our oceans to catch up

The annual release of 35 *billion* tonnes of human-produced CO_2[818] is 3 to 7 times larger, and 70 times faster, than at the end of the last ice age, *overwhelming the surface ocean's ability to process it harmlessly*, and it will be many thousands of years before the oceans and atmosphere will return to equilibrium. [292]

Volume of change

Our CO_2 dwarfs recent volcanic emissions and rivals those of past mass extinctions

It's a surprise to most people that human CO_2 emissions have dwarfed volcanic emissions over the last couple of centuries. Globally every year volcanoes (including undersea volcanoes) only emit about as much CO_2 as a state like Ohio or Michigan does.[428] The combined volcanic output of CO_2 averages at around 260 *million* tonnes per year compared to about 35 *billion* tonnes of human-produced CO_2 annually. [818] Even the major volcanic eruption of Mount Pinatubo in 1991 only produced about 50 million tonnes of CO_2.[819] Human CO_2 emissions are equivalent to an extra 11,200 Kīlauea volcanoes or about 360 more mid-ocean ridges![820]

Of course a Large Igneous Province eruption would rival or exceed the CO_2 we emit, but we haven't had a LIP eruption in the last 16 million years.[272]

Uncertainty in climate change

“Uncertainty” is a much-misunderstood scientific word

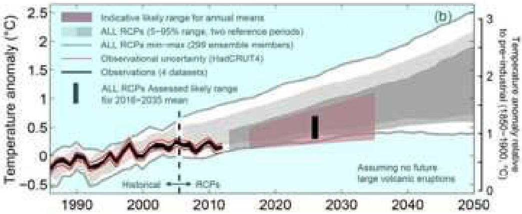
“Uncertainty” is a much-misunderstood scientific word. In everyday language “uncertainty” means tentative and unreliable, with negative connotations. That is not the way the word is used in science, and this difference confuses the media and the public, something the manufactured doubt industry exploits to the fullest extent.

Uncertainty in science is just another way or expressing how *confident* we can be in a conclusion.[778] A scientist expressing “uncertainty” is not saying they know nothing, rather they are stating in a precise way *how confident they are* in what they *do* know. We wrongly assume scientists are either 100% certain, or know nothing at all. But “certain” is like “perfect” – an ethereal ideal rarely attainable.[778] If you think about it, there are many things we treat as certain in everyday life but which aren’t so. You can’t be 100% certain you won’t be struck by lightning in the next minute, but you can be very confident (unless you are reading this on top of a mountain in a thunderstorm, in which case all bets are off). We can't be certain we won't be struck by a car as we cross the road, but we cross anyway. When doctors give an expectant mother her "due date," it's a guide rather than a 100% certain prediction.

There are almost always uncertainties in science. No measurement has perfect precision, and when you start combining data, these errors add up too. The Earth sciences are particularly challenged by less-than-perfect and sparse data sets – scientists have to work with the real world as they find it. The data imperfection creates uncertainty, which is measured and included with the results, often expressed as a number ± (plus or minus) another. The first figure is the average value, and the ± value (confidence interval) is usually set so that 95% of the data fall between those numbers. The bigger the spread (uncertainty), the bigger the ± value will be.

The IPCC (Intergovernmental Panel on Climate Change represents the consensus view of an international panel of scientists. They call conclusions "virtually certain" if they are 99% to 100% likely (a very high bar), "very likely" if the likelihood is above 90%, and just "likely" if it is above 66%. [258]

Uncertainties compound into the future when we attempt to predict climates in the coming decades. Starting with projected greenhouse gas emissions and climate sensitivity, we already have a significant spread of possibilities. Adding-in feedbacks like water vapor, methane, additional CO_2, precipitation, clouds, and so on, each with their own uncertainties, widens the spread of possible outcomes. Then factoring-in uncertainties for population growth, development, adoption rates of clean technologies, and so on, and you can see that the cone of uncertainty will get quite large into the future.



Temperature Anomaly projection
IPCC AR5 2013

Hurricane Sandy
projection Oct 27 2012

34 **Compounding uncertainties when predicting climate change (left) is a bit like compounding uncertainty predicting a hurricane path (right).**
Sources: IPCC AR5, NOAA

It's similar to the projected path of a hurricane that we see on TV. A curved cone of uncertainty starts with its apex at the present storm center, widening as the eye is projected into the future. The curve is continually revised, but anyone in the footprint of the curve takes notice and acts accordingly.

Computer models and projections

Climate science, in common with other areas of science that deal with large amounts of data, often encapsulates its understanding of the way the climate works in a computer model to handle the many complex calculations. Models are inevitably a simplification of the real world, a likeness that can't possibly capture every aspect of it. But if the computer model can reproduce actual, measured climate changes, then the model is at least a good approximation for how the climate really works. The more times that model is tested with new data and successfully reproduces reality, the more consensus builds that the calculations in the model are a true reflection of the way the real climate works.

Climate models have in fact been found to do a pretty good job matching instrumental observations so far, [821] even if they have generally predicted more surface warming over the last decade than actually occurred. [761] Their results also match values calculated independently from past climate changes, [822] so they do seem to represent the inner workings of the real climate fairly well.

Uncertainties remain

The intricacies of all the feedback loops, like the loss of organic carbon from soils, the effects on the ozone layer [772] [823] and the stratosphere, [824] and the future uptake rates of CO_2 by oceans (because of uncertainties in how marine organisms will adapt), are not all well-quantified. In combination they are generally agreed to generate a net warming, but the uncertainty lies in by how much. [772] Rainfall changes and regional specifics are also hard to pin-down [823] as are the expected changes in ocean currents in response to all the other changes. [772]

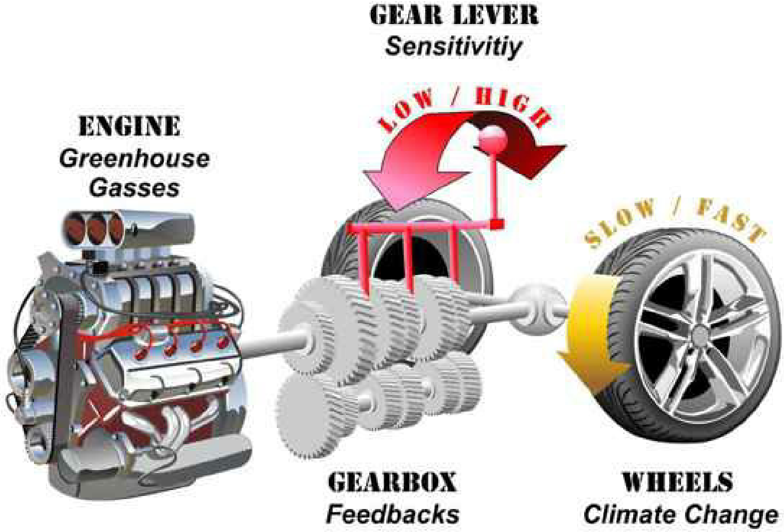
> "a big blind spot since some have suggested clouds may be nature's way of combating global warming"

The role of clouds in climate change is still poorly understood, [772] [258] and this is a big blind spot since some have suggested clouds may be nature's way of combating global warming ("Thermostat Hypothesis"). [825] But recent studies have instead found the opposite - a small net *warming* (amplifying) effect as clouds change with temperature. [826] Hopefully our understanding of clouds will improve as new satellite data come on-stream in the next few years. [772]

Of course, it's possible that some new discovery will change our understanding, but overall the uncertainty surrounding climate change has diminished. In 1990 scientists concluded global warming was about as likely natural-caused as human-caused. By 1995 they agreed there was "discernible human influence," by 2007 it was "very likely" due to human-produced greenhouse gas emissions, and by 2013 it was "virtually certain," a greater than 99% probability. [772] [258] That's odds better than 100-to-1, not wise to bet against!

A sensitive question

In order to predict how much the Earth will warm in response to greenhouse gasses, we must account for all those intricate feedback loops in the climate that stand between the *input* – greenhouse gas emissions – and the *output* – future temperatures. The number that predicts the output from the input is called "Climate Sensitivity." Sensitivity is like a car gear lever – for a given engine speed, higher gears turn the wheels faster. If the climate is more sensitive (like a higher gear), the temperature rise will be larger, if it is less sensitive (like a low gear) then it will be smaller. Real sensitivity is much more complex than that, of course, because the effect is not instant, different feedbacks work on different timescales, and can either amplify or diminish the effect, and a warming world generates further feedbacks - as if the wheel motion is fed back into the gearbox.



35 **A gear lever as a simplified analogy for climate sensitivity.** The engine represents the energy input from greenhouse gasses, the gearbox represents all the different feedbacks, and the speed of the wheels represents the amount of climate change. Climate sensitivity is like the gear lever changing the speed of the wheels.

The timescale of that output matters. We need to know how the planet will respond in the lifetime of our grandkids (which I'll call the short-term sensitivity, but climate scientists call it "Transient Climate Sensitivity"). And we would also like to know the legacy we are leaving for our grandkids' grandkids to deal with in the coming centuries (which I'll call the long-term sensitivity but is more correctly called "Equilibrium Climate Sensitivity" and sometimes "Earth System Sensitivity").

Calculations of climate sensitivity that are based on the modern instrument record have the advantage of well-constrained numbers, but they tend to deal only in the fastest feedbacks, so they may be unduly influenced by short term fluctuations – like the flattish surface temperature trend since the millennium.[746] [827] They also need their computer models to accurately represent all the feedbacks – so are hostages to the uncertainties surrounding those.

An alternative approach is to calculate sensitivity from how the Earth actually responded in the past. This has the advantage that it automatically includes all the Earth's feedbacks, but it is hostage to proxy uncertainties for the exact volumes, timing and durations of past climate changes.[822] There's probably no single magic number for the long-term sensitivity of the Earth, because each past climate change was a little different, begun from a different temperature, CO_2 level and ice cap status.[828] [822] So sensitivity values from Earth's past may be an imperfect analogue for our future because of the peculiarities of human-generated climate change,[265] [822] but they probably provide the best guide for what's in store for our children, their children and succeeding generations.

Sensitivity based on recent observations

The IPCC calculated long-term sensitivity to a doubling o CO_2 since pre-industrial times as 1.5-4.5°C (2.7-8.1°F).[258] This was based mainly on modeling from instrument data, but did include some observations from Earth's past. They also calculated the short-term, transient sensitivity as 1-2.5°C (1.8-4.5°F).[258] This short-term number predicts a global warming between 2.6 and 4.8°C (4.7-8.6°F) by the year 2100, assuming business-as-usual CO_2 emission rates.[258]

Sensitivity based on Earth's past

In contrast, studies grounded in how much the Earth actually responded in the past suggest our planet's longer-term (equilibrium) sensitivity may well be much higher.

> "This short-term number predicts a global warming between 2.6 and 4.8°C (4.7-8.6°F) by the year 2100"

One recent study of the last 65 million years of natural climate changes arrived at a *long-term* sensitivity of 2.2–4.8°C (4.0-8.6°F), marginally higher than the IPCC's range.[822] But that study drew heavily from the glacial cycles of the last 800,000 years, when the causes of change (orbital wobbles) were operating slowly enough for all the compensating feedbacks to keep up. As I explained earlier, current climate change is quite different, operating much faster than natural compensating processes can cope.

Other studies have found that the climate of the past may have been much more sensitive than the IPCC's value.[333][829] These calculate long-term sensitivity to be around 6-8°C[830][831] for a doubling of CO_2, values more in line with past LIP eruptions and mass extinctions. Even the IPCC acknowledges (with "medium confidence") that actual long term sensitivity may in fact be double its quoted Equilibrium Climate Sensitivity. [258]

In other words, calculations of Earth's responses in the past suggest the effects of modern global warming may end up being far larger than we can calculate just from recent measurements. [260]

Not just CO_2

Even though most of the recent warming has been due to CO_2, [741] humans are responsible for a zoo of other emissions that affect the climate in other ways as well.

Soot (sometimes called "black carbon") has recently been found to have a warming effect second only to CO_2. [832] It comes from transport tail pipes, coal and wood burning, burning trash, wildfires, grass fires, and slash-and-burn forest clearing. [832] In contrast, fine particles (aerosols) like smog and dust offer temporary cooling.

Our transformation of the landscape also has an effect. Developing green land into cities and roads, overgrazing, irrigation and desertification, erosion and clearing forests all have an effect. They change how the land absorbs sunlight (albedo) and they change the total amount of CO_2 that gets absorbed into plants and sediments, and they generate other climate-changing pollutants. Agricultural activity generates methane and nitrous oxide (both greenhouse gasses), and this is likely to increase strongly as global population increases and more 3rd world citizens are able to afford more meat. [258] Fertilizers in run-off and eroded soil affect ocean productivity, dead zones and coral reefs, each with knock-on effects of their own. [258]

Methane is generated from sources as diverse as cow digestion, natural gas production, coal mining, landfill sites, wetlands, permafrost, mud volcanoes, submarine earthquakes [833] and even termites.[834] About half of current atmospheric methane comes from human activities, [258] and even though it only persists in the atmosphere for about 12 years, in relatively small concentrations compared to CO_2, it is roughly 25-32 times more powerful as a greenhouse gas.[258] [259]

The point here is that while the main focus is correctly on the main climate driver - CO_2 - even if we manage to return greenhouse gasses to pre-industrial levels, we would not have removed *all* the human influences on the climate system. [801] We have many fingers in the machinery of Earth's climate.

Signposts from the past

As we saw in Your Life as Planet Earth, there have been *many* episodes of rapid greenhouse-gas-driven global warming in Earth's history. These were generally caused by enormous Large Igneous Province eruptions like those in the Permian and Triassic periods, and even the Deccan Traps eruptions at the end of the Cretaceous. Large Igneous Provinces (LIPs) emit far more CO_2 than modern eruptions because they are absolutely huge, and they release prodigious quantities of greenhouse gasses as they inject their way through the crust.[178] [88]

In order to be conclusive about the comparison of LIP-caused mass extinctions and our own time, we need to be able to *date* the carbon emissions and the eruptions to a decade- or century-level of precision. Unfortunately the most precise dates using the latest techniques are still at the multi-thousand year level at best.[179] But as each new date comes out, the trend has been to shorten the timeframe for those ancient emissions, and therefore to push them closer as analogs for modern climate change. And their symptoms are eerily similar to what's happening on our planet today.

The Permian mass extinction saw at least 100 trillion tonnes of CO_2 and methane [88] [181] [178] emitted into the atmosphere, and the initial phase of emissions may have lasted as little as 2,100 to 18,000 years.[179] That's at least 5 times the volume of our entire fossil fuel reserves, [835] emitted over a much longer timeframe than human emissions, so the *rate* of emissions might have been comparable. As we saw in Your Life as Planet Earth the result was catastrophic climate change and the extinction of 90% of species. [184] The Permian extinction was probably made worse because key calcifying plankton groups (coccolithophores and forams) had not yet proliferated – they improved the ocean's ability to buffer CO_2 changes from around the Cretaceous onwards.[178] [181] [191] Even if the volume of Permian carbon emissions and its ocean chemistry are very different from today, if our *rates* of emission are comparable, then the Permian Great Dying serves as a warning for what's possible at the *extreme* end of global warming.[260]

The end-Triassic extinction saw around 40 trillion tonnes of CO_2 and methane [195] released in perhaps a few thousand years or less. That's around double our fossil fuel inventory [835] emitted over maybe 10 times longer. [194] Subsequent eruptions spread over 600,000 years [194] exacerbated the situation and it's hard to pin down the exact timing and volumes of gasses involved, but this mass extinction event, one of the 5 biggest in Earth's history, is considered by some scientists to be a closer analogy to the next few centuries. [195]

The 183 million-year-ago Toarcian extinction event seems to have been caused by the release of about 15 billion tonnes of CO_2 *per year* over about a 650 year period. [202] That's less than half modern emission rates, but spread over a longer timeframe. [258] This was a time when sea surface temperatures increased by around 10°C (around 18°F) for around 300,000 years, and the environmental effects included extinction, dissolving reefs, ocean acidification, ocean dead zones devoid of the usual sea-bottom fauna, and increased chemical weathering on land due to the heat and acid rain. [201] [202] The similar Aptian and Cenomanian/Turonian extinction events also seem to have involved slower releases of CO_2 than today. [233] [292]

The 56-million-years-ago PETM event may be a bette analog for modern times, but it's still an area of active research. It released the equivalent of all our fossil fuel reserves over millennia (perhaps as little as 13 years [836] – but that's not generally accepted). [837] [292] [260] The volcanic cause of the PETM is no universally accepted, and some scientists believe large quantities of methane "clathrates" (a kind of methane-ice in deep sediments) were destabilized. [822] [260] But that begs the question: what destabilized them?

Still more recently, the Ethiopian-Yemeni eruptions between 31 and 29 million years ago occurred just after the Antarctic Circumpolar Current (ACC) started up. As such, this was the first large CO_2 emission event in a world with ocean currents and carbon "sinks" similar to our modern configuration.[307] These eruptions may have released a little less CO_2 than our fossil fuel inventory[307] and they are associated with a short-lived spike in CO_2 values and a corresponding blip in ocean temperatures by maybe 2°C,[309] but again the rate of CO_2 emissions was far slower than today's.

Even the warm Miocene climate 16 million years ago, triggered by the eruption of the Columbia River Basalts in the USA, had slower emissions. Hundreds of eruptions were spread over a few hundred thousand years, causing atmospheric CO_2 to increase and melting Antarctic ice to around 10 to 25% of its current size. Somewhat less CO_2 than our fossil fuel inventory was released,[307] but CO_2 peaked at levels similar to today's, with global temperatures rising by 2 to 4°C[310] and sea levels rising roughly 50m (160ft).[308]

Some scientists believe that we are less likely to create the kind of lethal hothouse climates that occurred in the Permian and the Triassic, because unlike then we are today starting from a lower CO_2 concentration, with ice caps to melt, and with the Antarctic Circumpolar Current which is efficient at drawing down CO_2. [307] Instead, those scientists see us generating a climate similar to the Miocene with hot tropics and oceans warm even into the deep sea, widespread ocean dead zones, shifted weather patterns, and melting of most northern ice and perhaps half of Antarctic ice (causing sea level rise of maybe 50m (160ft)) [308] within a few hundred years. [307]

But other scientists point out that, because we seem to be releasing carbon at rates much faster than LIPs in the past, [292] and we are already seeing large changes in ocean chemistry, we can't be complacent about the possibility of arriving at an end-Triassic-like or even an end-Permian-like environment in that same timeframe. [260]

Why care? - Prognosis

So the diagnosis is clear: we are already suffering from a major case of global warming due to human activity, of which the main driver is CO_2. But the prognosis is less clear, with a range of outcomes possible, from moderate disruption to severe impacts on society and the economy. Scientists' ability to predict the future is imperfect, but policy makers routinely respond to military threats or economic hazards with similar or even less certainty than we have for global warming. [801] The question should not be "do we know everything?" but should instead be "do we know enough?" [778]

I don't want to be "alarmist," but I do think alarm is an entirely appropriate response to scientists' projections of Miocene-like or maybe even end-Triassic-like conditions for our grandkids' world and beyond, albeit with uncertainty. I truly hope they are proven wrong, and that our climate proves to be less "sensitive" than more. I fervently wish for some unforeseen cooling feedback to swoop in like a fairytale hero, saving us from destructive climate change. But Earth's past shows no sign of that. We must remember that we're dealing with nature, red in tooth and claw, so it's important we face reality with a clear-eyed, rational assessment of the risks it holds for future generations.

Even using conservative climate sensitivities, we are talking of average temperature rises for the end of the century of 2.6 to 4.8°C (4.7-8.6°F), and for the year 2300 of roughly double that if CO_2 emissions are not curtailed until the latter half of this century. [258] [260] That may sound tiny compared to the weather variations we experience day by day, but that is about the same jump in global temperatures that resulted in the Triassic Mass Extinction, albeit from a climate already much warmer in the Triassic than we are now. Global warming is like inflation, building little by little every day. It adds up over years and decades, relentlessly accumulating a whole lot of extra energy to drive the climate to new, inhospitable extremes.

The IPCC issued a full and authoritative account of their prognosis, which is freely available on their website, and which I don't want to duplicate here. [258] Instead, I'll briefly touch on some key points, based mainly on evidence from Earth's past climate changes.

Sea level rise

> "Past climate changes have resulted in much more rapid sea level rises"

Current sea level rise will accelerate as more heat is incorporated into the oceans, which will rise due to thermal expansion and melting ice. The latest IPCC estimate is a rise o 0.53 to 0.97 meters (1ft 8in – 3ft 2in) by the end of this century, [258] based on continuing the current trend of emissions. But past climate changes have resulted in far more rapid sea level rises: rates of 1.2 meters (4ft) per century [838] to as much as 5m (16ft) per century. [308] [258] Other recent projections for this century that cluster around the 1 to 1.5 meter range (3' to 5') are more consistent with the expected Pliocene-like climate at the end of this century. [839] Those levels were at least 10m (33ft) higher than today, but it could take centuries to melt that much ice – so Pliocene levels are probably what our grandkids' grandchildren will have to deal with. [822] [258]

Because land by the sea shore is often fairly flat, [840] 1 meter (3ft) of sea level rise can easily mean 100 meters (330ft) or more of inland encroachment by the sea. The practical implications of this vary by location, but this would result in millions more people experiencing coastal flooding with associated damage to near-coastal roads, rail, electricity distribution and so on. Although current sea level rise is much slower, if it does soon accelerate to 1 meter per century, then about 400,000 homes in the states of New York, New Jersey and Connecticut alone may be vulnerable to occasional storm surge flooding by the mid-century. [841] By comparison, Hurricane Sandy's storm surge inundated about 170,000 homes in that same area. [842]

That rate of sea level rise would also displace 3.8 million people in the most fertile part of the Nile Delta in Egypt,[843] with similar effects in coastal communities around the world. Some estimate a sea level rise of 2 meters (6 ½ feet) is possible by the year 2100, which could displace 187 million people globally. [843] Even those "extreme" projections are still just half the fastest rate of sea level rise observed in Earth's past, at 5m (16ft) per century. Unfortunately the spread of these projections is so large that it makes planning for them difficult,[843] but the point is that Earth's past suggests that sea level rise is more likely to be at the faster end of projections.

Heat, drought and rain

With temperatures rising and heat waves becoming 10 times more frequent, [844] [258] crop-stress could reduce yields by as much as 15% [845] and extreme droughts will occur in some places, especially the mid-latitudes, but other areas will experience more frequent torrential downpours. [755] We could well see a doubling or quadrupling of wildfire frequency. [845] Vegetation zones will change, with a northern US state like New Hampshire resembling the growing conditions of the Carolinas by the end of the century. [754] Plants currently absorb about 25% of fossil fuel emissions, but as drought and heat waves take their toll, plants will become a less effective carbon "sink," [844] making matters worse. Some animals, birds and insects (including pests) will migrate in response, whereas less adaptable species will die out.[755]

Some major rivers may see reduction in flow,[845] and groundwater reserves in already water-stressed regions like the Middle East look likely to become severely depleted, placing additional strain on relations between upstream and downstream countries.[846]

Oceans

The trends already seen for acidification and temperature rise will worsen. Acidity is expected to increase by up to 150% (pH drop to 7.7) by the end of the century,[108] turning surface waters of the Southern Ocean, the Arctic and the Baltic corrosive for calcium carbonate (shells, corals, limestone).[108] Since acidity (pH) is a factor in many biochemical reactions, entire ecosystems may be decimated.[108] Corals will be bleached more frequently by warmer sea surface temperatures, which will eventually kill them off. This process is expected to spread to most of the world's reefs by mid-century, with a quarter of reefs hanging on 20 years longer.[847] If we're lucky that extra 20 years may enable reefs to adapt by encroaching into previously cool waters as we saw them do in the Jurassic.[847][215]

Fish in warmer oceans have a higher metabolic rate so they will need more oxygen, but warm water holds less oxygen. Warmer oceans are also more stratified, with a warm surface layer stubbornly refusing to mix with deeper layers. This restricts circulation of nutrients which, added to the oxygen limitations, could stunt fish growth to about 75% of current sizes by 2050[848] and severely reduce fish stocks relied upon by a billion people in many parts of the planet.[849]

Storms

Studies of the Atlantic Ocean have found a significant increase in the frequency of tropical-storm-strength storms since 1923, and the frequency of the most intense hurricanes has been twice as frequent in warm years. [850] These observations support projections of an increase in hurricane intensity and an increase in the annual number of intense hurricanes by 50% for each 1°C increase in surface temperatures. [851] Some suggest that Europe can expect formerly rare destructive hurricanes (like Hurricane Lothar in 1999) to be 25 times more frequent by the end of the century. [844] In contrast, the IPCC has low confidence in any increase in the frequency or intensity of tropical cyclones or hurricanes outside the Atlantic. [258]

Methane – a "carbon bomb"?

As global temperatures warm, methane release from landfills, soil and wetlands is expected to increase as a feedback. It's uncertain exactly how this methane will react with other chemicals in the atmosphere, but it looks like methane levels could double by the end of the century, [259] amplifying global warming considerably.

But that's not the biggest worry about methane.

In the permafrost that covers about a quarter of northern land and extends beneath Arctic seas, there is a reservoir of carbon about 4 times larger than all the carbon emitted by humans so far. [852] The remains of plants and animals have been accumulating in frozen soil there for thousands of years. Thawing permafrost encourages microbes to digest those remains, and they release the carbon partly as methane. [853] The rate is uncertain, but it is already happening. Since 1900, 4.5 million square km (1.7 million square mi) of permafrost area has begun to thaw, [854] and the southern limit of permafrost has already retreated northward by 80km (50mi) since 1975. [258] Ignitable [855] concentrations of methane are now bubbling from some tundra lakes and from parts of the Arctic seabed. [852] [856] Widespread thawing of the Siberian permafrost is expected if Siberian temperatures increase another 0.7°C from now,[814] which is likely this century.[258] Calculations suggest this permafrost methane and CO_2 could add the equivalent of another 5-8% of our total inventory of fossil fuels by the end of the century, even further accelerating global warming.[852]

On top of that, scientists are concerned that vast reserves of a kind of methane-ice, called "methane clathrate" or "methane hydrate," trapped in sea beds will become unstable as oceans warm, adding their reserves of many billions of tonnes of methane to the atmosphere, on top of everything I have mentioned so far. According to the IPCC, the rate of clathrate release into the ocean is expected to be slow, and then the rate it would be released from the ocean into the atmosphere will probably also be slow.[258] But destabilized methane clathrates have been implicated in large climate perturbations in the past, like the PETM,[260] and disturbingly, there are signs in the North Atlantic that about 2.5 billion tonnes of methane hydrate are already destabilizing.[857] The prospect of these vast methane reserves being unleashed on top of human emissions, like a slow but unstoppable "carbon bomb," with catastrophic, irreversible consequences for the Earth, is a nightmare scenario for scientists.[259][258]

The "carbon-bomb" is definitely a *worst-case scenario*, but if it comes to pass it suggests parallels with the more extreme climatic events like the end-Triassic or even the end-Permian catastrophes.[182][260]

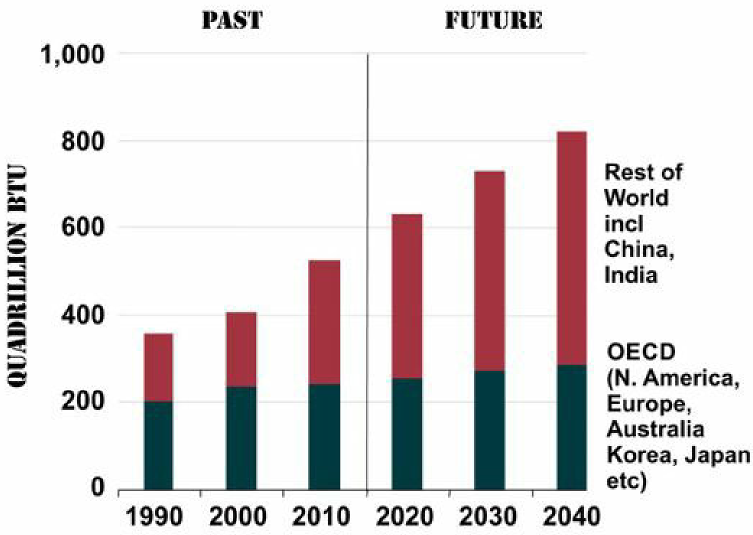
So yes, alarm is an entirely appropriate reaction to this climate "sword of Damocles" hanging over us, especially considering that if you have kids in elementary school now, your grandkids will experience strong effects of this by the end of the century, and their grandchildren may have to contend with extreme environmental catastrophe a century later, unless something is done about it now.

What to do about it

Faced with all that "doom and gloom," you would be forgiven for throwing up your hands and abandoning the situation as hopeless. But it is not yet hopeless, and failure to act will only make it worse. We can all take steps to reduce the chance of inflicting those worst-case scenarios on our grandkids.

Some steps don't have to be painful or very costly. Since heating and cooling consume the lion's share of energy (and so emit most CO_2) at home, it makes sense for individuals to invest most effort and money there [858] by improving attic insulation, sealing drafts, and installing energy-efficient appliances, light bulbs, thermostats and windows. Sourcing food and other products locally helps too, as does reducing the consumption of meat. [859] We all could, and should do more, like installing solar panels, switching off lights and 'vampire' electronics when they're not in use, carpooling, switching to electric or hybrid vehicles, and so on.

But these measures, as important as they are, are still "small change" in reducing global CO_2 emissions. [801] The millions of people across the globe who are coming onto "the grid" in the coming decades will have a *far* larger quantitative effect.[801] China, for example, now emits around twice the CO_2 of the USA and that trend is rising sharply. [860] The populations of developing nations have as much right to a comfortable lifestyle as you or I, but even if they all come on stream with exemplary energy efficiency at home and their commute, just their coming onto the grid will explode global energy consumption and CO_2 emissions in the coming decades.[801]



36 **Rising fast: world energy consumption.** Source: U.S. Energy Information Administration Jul 2013.

Decarbonization and its limits

It's very clear we must decarbonize the world economy, quickly. To decarbonize, we must either reduce economic growth, reduce population, increase efficiency, or switch to low-carbon energy, or some combination of those - a formula known as the "Kaya Identity." [801]

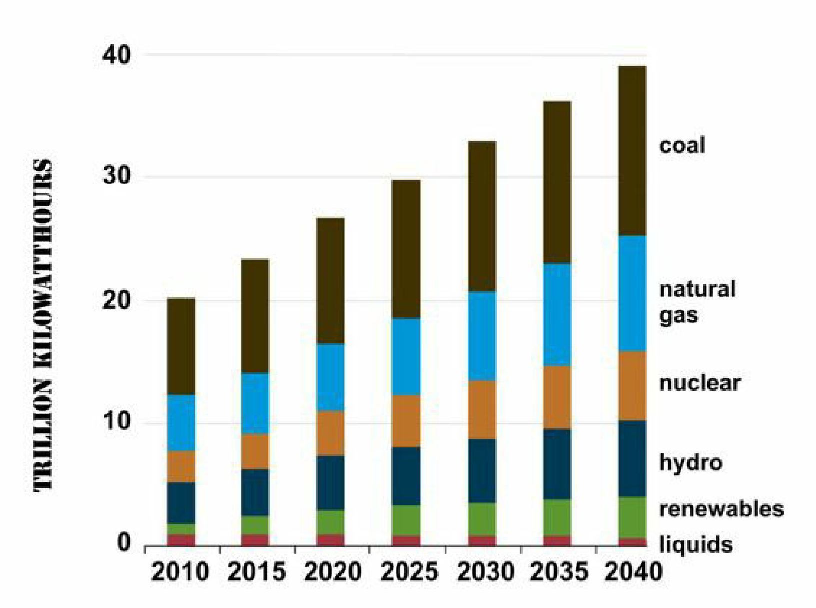
Bill McKibben in his book: "Eaarth" shows how we can live "lightly, carefully, gracefully" in our food and energy use, to significantly reduce our CO_2 emissions. [859] This requires our whole economy to "back off" a focus on *growth* and instead focus on *resilience*. But the problem with this is that each time we are faced with a choice between economic growth and decarbonizing, we pick growth every single time. This is what Roger Pielke has described as an "Iron Law" of economics, and any attempt to break it has so far proved futile.[801]

If we can't break the Iron Law (reduce economic growth) and population keeps rising, that just leaves efficiency and switching to low carbon energy for us to concentrate on.

According to the IPCC,[861] renewable energy in the form of bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy and wind energy, can meet up to 77% of the world's total energy demand by 2050, a big ramp up from 13% in 2008, requiring a huge investment of between 3 and 12 *trillion* dollars between now and 2030.[861] But although renewable energy costs have been getting more competitive, they are still generally more expensive than traditional sources,[861] so we're going to be slow to adopt them unless they get much cheaper, or the market is skewed in their favor by regulation. Currently the market is skewed in the other direction, through generous subsidies and by allowing CO_2 emissions with impunity.

Pielke calculates that in order to reduce CO_2 emissions to half of 1990 levels (required to stabilize the climate) using nuclear power alone, we would need to build more than 12,000 new nuclear power plants across the globe. That's about 1 per day coming on stream from now to 2050, which is clearly unrealistic. And that's without allowing for the 1.5 billion people who currently don't have access to electricity coming onto the grid (thousands more nuclear plants). In broad terms it takes 7 solar thermal plants, or 200 wind turbines to generate the electricity of 1 nuclear power plant,[C] so the numbers get even crazier if you substitute those renewable sources for the nuclear power plants.

In the interim, converting power stations across the globe from coal to natural gas would halve CO_2 and cut nitrous oxide emissions to one third from that sector, which is the biggest emitter. [862] [863] But moving from coal, a cheap and plentiful source of energy employing many, is political poison, and much of the gas would come from controversial fracking.



37 **No let-up in fossil fuel use for electricity generation.** Source: U.S. Energy Information Administration Jul 2013

Energy efficiency also needs to improve sharply because it allows growth and decarbonization simultaneously. Edison's incandescent light bulb technology lasted 130 years, but now we have LEDs that use a fraction of the electricity. We need more of those kinds of innovation across every energy-consuming sector, from fridges to cars, from computers to ovens to green buildings.

Even so, the world will still need "vastly more energy" (Pielke's words) than we are able to generate *even with pedal-to-the-metal burning of fossil fuels, ignoring climate change.* [801] So, as Pielke observes, this is an energy crisis as well as a climate crisis, which demands radical, out-of-the-box thinking in energy generation and conservation. [801] The problem with his undeniably true deduction is that it is "pie in the sky" – we're still emitting too much CO_2 while we wait for salvation by those elusive revolutionary energy sources.

So we won't be able to mitigate climate change by decarbonizing *alone* because we can't afford to wait for new energy sources to come on stream, the scale of the challenge is too big, global demand for energy is rising too fast, [801] and because excess CO_2 already in the atmosphere today will remain there, warming the planet for many centuries, unless it is removed through geoengineering.

Geoengineering and its limits

Geoengineering seeks to reduce climate change by tinkering directly with the climate. There are two very different kinds: one seeks to manage the climate by direct *intervention*, and the other seeks to remove CO_2 (*remediation*). Intervention is fraught with issues, but remediation looks essential. [801]

Climate intervention – the Thalidomide of climate change

Climate intervention includes things like building reflectors in space, spreading aerosols in the stratosphere, enhancing rock weathering, changing the reflectivity of land or clouds, and even fertilizing the ocean. [864] These are best left in the realms of speculation, and here's why.

The pharmaceutical industry spends between 4 and 11 billion dollars per drug to bring it to market. [865] It costs so much because drugs go through rigorous safety testing (on animals, on healthy volunteers, dosing studies, double-blind randomized trials, etc.) before they can be prescribed to patients. This costly system of presuming a drug harmful until proven safe was introduced after a relatively untested drug called "Thalidomide" was widely prescribed to pregnant women in the early 1960s to combat nausea. [866] Unfortunately it caused birth defects in many babies, and it was withdrawn in 1962. But that was too late for the affected families - the cost of not testing thoroughly was infinitely greater.

Climate intervention is like prescribing an untested experimental drug, because there is generally a limited understanding of the causal link between the intervention and its assumed effect. [801] The effects are so intertwined with natural processes that they are not separately measurable (scientifically, the experiment has too many dependent variables and no control). This means there is no way to assess their true effectiveness. [801]

For example, one experiment to whiten clouds showed that it had both desired and undesired consequences, sometimes generating a net warming, not cooling. [867] Another experiment which injected iron into the ocean successfully fertilized a diatom bloom, which then died and half the creatures sank to the deep ocean, taking captured CO_2 with them, but there are "important uncertainties" in that study, even without considering knock-on effects on the marine ecosystem. [868]

We don’t have a lab-rat-planet to try these things out on, [801] and like

Thalidomide, the unforeseen consequences may far outweigh their good. Even new software is rigorously tested before it is released to users and it can often be “rolled back” should something unforeseen occur. Climate intervention has no “undo,” no “roll back,” and no test planet.

Remediation

But remediation, which involves removing greenhouse gasses from the environment, is a more promising enterprise.

A main contender is “Carbon Capture and Storage,’ capturing CO_2 in power plant smokestacks and injecting it underground. This sounds attractive until you consider the scales involved. The International Energy Agency proposed an ambitious plan in 2009 to mitigate a large but unclear quantity of CO_2 emissions from smokestacks by 2050. [869] The numbers they envisioned have been criticized for being wildly impractical –

spending \$5.8 trillion, completing 85 projects per year (1 every 4 days), and developing 3400 carbon capture reservoirs using enough steel pipe to make 9 trips around the planet![801] Since CO_2 scrubbing projects reduce power plant efficiency, add cost, and lower energy output, [869] there needs to be an economic and regulatory incentive to implement them, but so far the incentives have not been sufficient to outweigh the costs.[869] Because of this, the technology has been limited to demonstration projects.[869]

Capturing CO_2 from the ambient air is more promising, [801] and several startups are working on it.[870] But again, these are in prototype mode and seem a long way from large-scale deployment.

Capturing CO_2 from ambient air is what plants have done through geological time, with demonstrated effects on the climate as we saw in Your Life as Planet Earth. The good news is tha forests can be a substantial sink for CO_2 [871] but the bad news is the required area of planting is huge, and the effect is slow. [872] With rising population the challenge will be to find land for forests that isn't needed for agriculture. Some progress has been made planting trees in arid regions in Africa with economic gain for the local population, [873] but this would need to be replicated on a huge scale. In short, we can't just plant our way out of this climate crisis.[872]

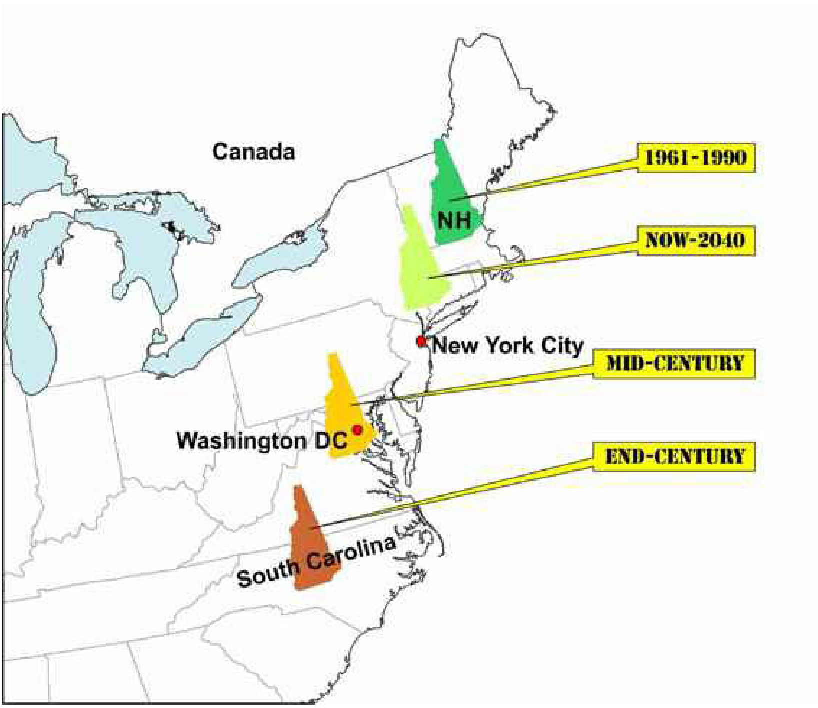
Adaptation and its limits

Adapting to the effects of global warming can take many forms, like protecting cities from rising sea levels, relocation away from vulnerable shores, and shifting agriculture locations and practices.

It could cost \$32 billion to build coastal defenses to protect just the New York Metro Area from rising sea levels.[874] Applying that figure to just 30 of the world's largest coastal metropolises comes to $1 trillion, without protecting hundreds of smaller coastal cities and towns. A simple sea wall costs about $35 million per mile, with perhaps $3 million per year in maintenance.[874] The Dutch government alone spends about $1.3 billion per year on flood control,[875] a figure likely to be replicated by more and more cities as they seek to adapt to rising sea levels and more frequent storm surges. In Alaska today, 6 coastal villages need relocation at a cost of $30 to $50 million each, and a further 160 villages are threatened by coastal erosion.[876] To make matters worse, with rising population and prosperity we keep building in coastal areas, which increases the financial and safety risk, even without factoring-in climate change. By 2050 many of the world's coastal metropolises will experience around a 20% increase in annual financial losses due to flooding over 2005 figures. That's around $1 billion to $3 billion depending on the city, every year.[877]

But we have to adapt to more than just rising sea levels.

According to "The Economist," plausible scenarios for the end of the century could see agriculture and manufacturing shift northwards by about 10 degrees of latitude, equivalent to moving Dallas to Chicago, or Frankfurt to Oslo.[878] Some parts of the world may become unpleasant or uninhabitable, whereas other areas may remain oases of moderate change or even benign improvement.[878]



38 **Shifting climate: the state of New Hampshire could experience a summer climate formerly associated with South Carolina by end-century, if business-as-usual emissions continue.** Source: EPA/Global Climate Change Impacts in the United States, Karl, et al, Cambridge University Press, 2009.

If the *rate* of change is slow (if climate sensitivity is at the low end), it is possible that a smooth geographic adjustment - mainly through human migration – may be able to preserve economic stability. But moves still cost money. A firm leaving say, lower Manhattan for an upstate city, will incur relocation costs, and a general pull-out would leave investors in the abandoned area with large losses. As more people migrate to new areas, a significant investment in new infrastructure will be required, even as old infrastructure in vulnerable areas is abandoned. Given sufficient investment, innovation, and determination we can protect coastal cities for a while, but eventually these defenses will be outflanked, overtopped or breached. This means that such cities need to incentivize people to leave vulnerable areas in the medium term, even as they invest in coastal defenses. [878]

The cost of global warming adaptation will depend largely on how easily people, and even whole cities, can relocate. Economists project that northern countries' agriculture and manufacturing will grow, trading with needy southern nations whose economies will do worse. Pressures of migration from southern nations northwards are likely to provoke geopolitical instability. [878]

> "In the most extreme global warming scenarios, adaptation will be impotent"

In the most extreme global warming scenarios, adaptation will be impotent. Economists project that those worst-case temperatures would reduce agricultural productivity in many areas to zero – a catastrophe for humankind and a cost too high to contemplate.[878]

So even in this cursory glance at adaptation to global warming, even for moderate warming scenarios, the projected costs are into trillions of dollars, without counting migration costs or losses from extreme events. Clearly adaptation alone, without addressing remediation and decarbonization, is not going to be practical.

The need to do them all

As the saying goes: how do you eat an elephant? One bite at a time!

We can't just carbon-capture our way out of global warming because of the cost and scale of the projects involved. We can't rely on climate intervention because of its risks. We can't only rely on adaptation because there are limits to our ability to adapt, and its costs are high. And while we wait for revolutionary new forms of energy to appear, we still lack the political will to decarbonize if it slows growth.[801]

We also know we don't have the capacity, either in fossil fuels or clean energy, to meet the demand of the world's growing population, and the improved living standards of formerly off-grid populations.[801] As Pielke observes: for those millions and millions of people, this isn't about climate change but rather it's about accessing the energy they need, but that the current energy sector is incapable of delivering, irrespective of climate change.

So we have to do them all – smart decarbonization, remediation and adaptation.[801]

They each have costs, but the cost of inaction is far greater. The economic burden of inundated coastal cities, diminished agriculture, restricted fresh water, and large sections of the global population becoming nonproductive environmental refugees, would be unsupportable. And denying energy to the people of developing countries is untenable.

We need regulatory and financial incentives to innovate clean energy, and efficiency. [801] We need more nuclear power (with newer, safer designs and safe nuclear waste disposal) *and* we need *much* more renewable energy. [801] We need to grasp the political nettle by replacing coal-fired power stations with natural gas stations, with an eye to replacing those too with renewables in the medium term. We urgently need to reverse deforestation, and we need to plant forests in every available area of land, especially in the tropics. We need smart power grids to allow a decentralized multitude of small energy sources, including home and workplace energy generation and storage (through solar, windmills, flow batteries, etc.).

Population growth urgently needs to slow, since it is people that drive demand for land, resources, energy, goods, food and the general carbon-emitting economy. Voluntary family planning, and also improved economic standing for traditional societies [879] is vital for bringing the population down, and therefore slowing energy demand in the long run. On current trends population growth is expected to slow by mid-century, but not before reaching 10 billion, [879] compared to 7 billion now and just 2 billion as recently as 1930.

We need to deploy carbon capture in every feasible location where it can be powered by clean energy. We should be as concerned with reducing our nitrous oxide footprint, our methane footprint, our soot footprint and our fluorocarbon footprint as our CO_2 footprint. Just reducing those four pollutants would help reduce the rate of warming. [880] The Montreal Protocol succeeded in controlling ozone-eating gasses – a similar treaty could tackle those. [801]

Each step represents a "bite" out of our climate change "elephant."

But even if we do, miraculously, stabilize CO_2 emissions, the warming effect of greenhouse gasses already in the air will continue for many years. As McKibben observes, we are already living on a strange new planet. [859] So we must also adapt, with strategies to enable migration away from adversely affected regions to more benign areas. We do indeed need to *invest* in a more resilient, less centralized economy. Delaying action only multiplies the costs, and the cost of inaction may well exceed our ability to adapt.

We cannot afford to wait for every uncertainty to be resolved. Mobilizing now is an insurance policy against an uncertain future. [876]

Bottom line:

"The greatest danger to our future is apathy." — *Jane Goodall*

Surviving climate change requires more than our own individual incremental energy efficiencies. It requires strategic thinking and actual *action* by governments. It requires whole sectors of the economy to approach energy use differently. It requires the kind of transformation in the energy generating sector that the assembly line or computers delivered to businesses in the 20th century. But none of that will happen unless you as a voter, consumer and shareholder insist on it.

And climate change is just one of the Earth hazards that humanity faces. Earthquakes, volcanic eruptions, landslides, sinkholes and asteroid impacts can only be understood, predicted and ultimately mitigated through science. We rely on science to find and recover the mineral resources that are the raw materials for manufacturing everything from buildings to electronics, many of which are projected to be exhausted by the end of this century.[881]

It takes political leadership to act on scientific information, and science needs our support to assess these hazards for the sake of our own prosperity and our grandchildren's future.

But too many of our current crop of political leaders have a complete disregard for science. In the last few years alone, we have seen elected officials in America go on record with bizarre pronouncements that have no basis in fact,[882] even claiming proven science is "lies straight from the pit of Hell"![883] It's not just in America – judges in Italy recently jailed scientists because government officials failed to grasp the meaning of their advice.[884]

For the sake of our grandchildren – and theirs - we need to release the brakes on our progress caused by pseudoscience and political propaganda created by the manufactured doubt industry and fundamentalists for ignorant politicians to regurgitate. Making allowance for religious tolerance or political opinion should not extend to denying or distorting scientific fact. Carrying the burden of ignorance in the upper echelons of power constitutes an enormous drag on society's ability to respond to the most profound economic and security challenges of our time.

After all, as the saying goes: "We do not inherit the land from our ancestors, we borrow it from our children," [885] or in the case of climate change, our grandchildren.

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[A] Incidentally, my father was at the first excavation of *Kenyapithecus wickeri* by Louis Leakey at Fort Ternan in Kenya.

[B] I wouldn't blame you for being skeptical of these figures, so here's where they came from. The energy build up in the atmosphere comes from NOAA's Annual Greenhouse Gas Index (AGGI).[741] For 2013 the additional heat energy since 1750 was calculated by NOAA to be 2.916 watts for every square meter on the planet, which is the same as 2.916 joules per square meter per second. All that remains is to multiply that by the number of square meters covering the Earth and the number of seconds in a year to get 4.69×10^{22} extra joules globally over a year. The Hiroshima bomb was equivalent to about 0.02 megatons of TNT, which in joules is 8.37×10^{13}. Dividing NOAA's extra energy figure by this number arrives at about 561 million Hiroshima bombs. This does not allow for the cooling by various feedbacks – doing so reduces the energy imbalance to something like 180 million Hiroshima bombs per year. Still a lot.

[C] Using rough representative values of 1,000MW for nuclear, 150MW for solar thermal, 5MW for wind turbine

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First Edition. Visit ylape.com for citation list and most up-to-date links.

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Howard is a freelance Earth science writer and blogger on past climates. He earned his B.Sc in Geology and his M.Sc in Remote Sensing at the University of London, and he is a Fellow of the Geological Society of London (FGS). Howard draws upon years of experience in diverse Earth Science industries (seismic hazard, geothermal exploration, mining and radioactive waste disposal, oil and gas exploration) for his writing.

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