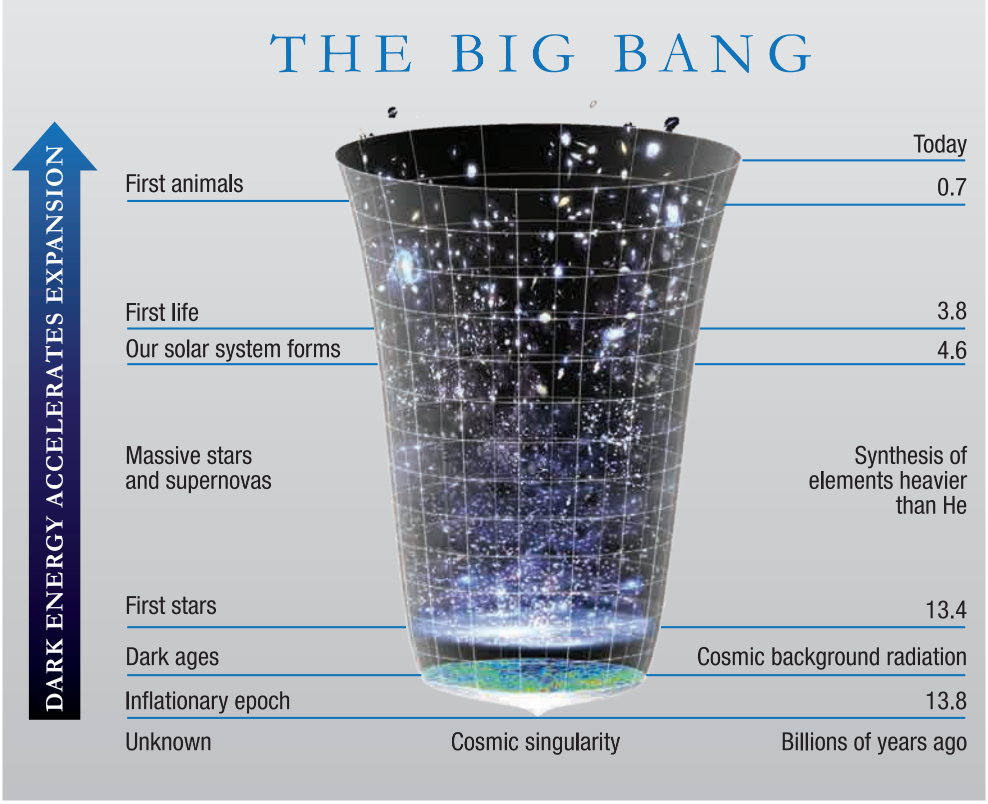
1 Abiotic to animal world

Therefore I should infer from analogy that probably all the organic beings which have ever lived on this earth have descended from some one primordial form, into which life was first breathed.

Charles Darwin *Origin of Species*

It took a long time and a lot had to happen before anything even remotely resembling us lived on Earth. Earth started out as a hot, uninhabitable planet without life (abiotic) but over the deep aeons of geological time an amazingly rich diversity of life evolved. The story of our origins starts here with a brief, sweeping account of the events leading up to the emergence of the first animals on Earth. Placing human evolution within the context of the remote and distant past underscores just how recent our arrival is and, more importantly, that our arrival depended on all those who came before us. Our origin can ultimately be traced back to the first forms of life through the fact that we are related to and share many features with all other life. As expressed early on by Charles Darwin and later succinctly captured by Bill Bryson as 'all life is one,' this profoundly unifying and big-picture feature of evolution is often unappreciated. Not only do we embody a rich history of past evolutionary events, our arrival depended upon them. Thus, to understand how we came to be requires going right back to the very beginning.



Deep time: the big bang expansion as a cone of time, space and matter

In the beginning...

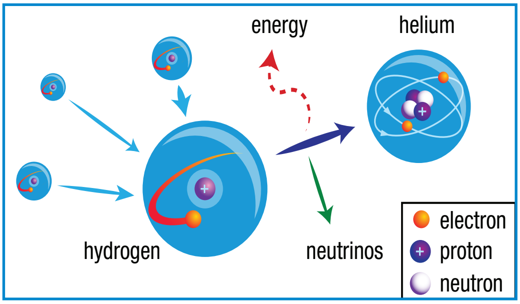
Every story has a beginning, a starting point from which all past events cascade to the present. Our story begins at the event furthest back in time that we are able to go, to the limit of what science can inform us about the origin of anything at all. A more grandiose beginning is hard to imagine, let alone comprehend. It all started at literally a point, called a cosmic singularity, into which everything we observe in our universe — space, energy and matter — was somehow squeezed. Out of this point our universe began expanding outward as the big bang approximately 13.8 billion years ago. What everything was doing at this single point, how it all ended up there, where it was before then and why it started expanding when it did are all unknowns. What we do know is that time, and hence our story, starts with the big bang.

The night sky

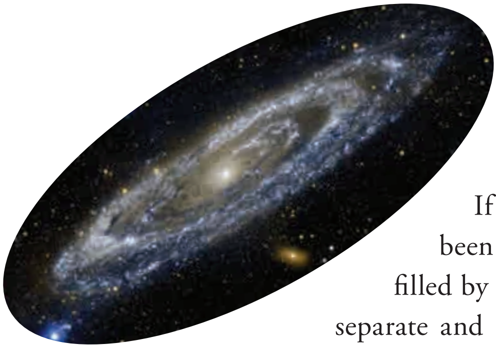
It is not at all apparent to us while star gazing into the tranquil night sky that we too are riding on the throes of this ongoing cosmic explosion of energy and matter. But the multitude of seemingly stationary twinkling points of light, which include the 100 billion galaxies of our observable universe, are hurtling through space at incredible speed. And they show no sign of slowing down. In fact, they are accelerating faster and faster away from one another at speeds approaching that of light, occupying an ever more enormous universe. It is owing to the vast distances that we are unable to perceive the incredible speeds at which all those light sources are receding away from us. But astronomers are able to measure the speeds and the distances and find that those furthest away are moving fastest. If the paths of expansion of all the stars and galaxies we can see are run in reverse, they all end up together at a single point, a cosmic singularity, approximately 13.8 billion years ago. This is not to imply that it all started here — the observable universe would appear to converge on any observer no matter where they were.

What would an observer looking from outside our universe have seen as the big bang unfurled? In the initial fraction of a second, known as the inflationary epoch, a flash of exponential expansion at speeds exceeding that of light took our universe from the subatomic to cosmic scale. After this initial flash of pure energy, the universe continued to expand, but at more pedestrian speeds not exceeding that of light. As it expanded, it cooled. Within 20 minutes it had cooled enough to allow the conversion of some energy into atomic matter. The atom to form first and foremost was hydrogen, the lightest and simplest element, consisting of a nucleus with a single proton enveloped by a single orbiting electron.

In these first minutes while space was not too big, some of the hydrogen atoms collided into each other with enough force to stick together and form helium. Initially the hydrogen and helium existed as charged atoms, but after around 400 thousand years temperatures had cooled enough for them to capture electrons. The universe went from an opaque cloud of charged gas to a transparent but dark universe full of individual neutral hydrogen and helium atoms. The faint afterglow of the transition to transparency remains to this day as the cosmic microwave background radiation. Although now transparent, the universe was dark.



Collision of hydrogen formed helium

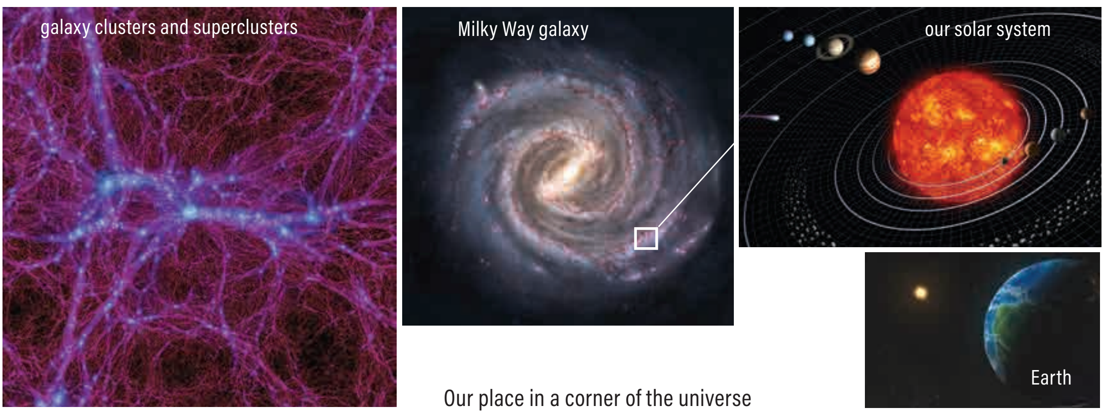


Andromeda, our closest galaxy

Fortunately the universe's Dark Ages didn't persist. If they had, the history of our universe would have been boring and bleak: an ever-bigger cold and dark space filled by individual hydrogen and helium atoms increasingly separate and alone in a lifeless universe. But the hydrogen and helium atoms shooting out into space didn't go solo for long. They came together in clumps thanks to variations in the density of energy and matter brought about by gravitational waves that had rippled through the big bang since the inflationary epoch. These clumps of hydrogen and helium atoms, along with mysterious dark matter and energy, are believed to have seeded galaxies. In those seed regions of relatively dense, focused pockets of matter, gravity started to pull the hydrogen and helium atoms closer together. The inward collapse of these atoms into many massive balls released enough heat to ignite the first stars. The first lights were switched on, ending the Dark Ages and shedding light on the mostly empty intervening space of our expanding universe.

These first-generation stars formed within 400 million years after the big bang and were hundreds of times larger than our Sun. The gravity of these large stars attracted other stars and held them together as clusters of stars in what was the initial assembly of individual galaxies. Over the billions of years since, these galaxies have been pulled together, sometimes in spectacular intergalactic collisions, forming the intricate web-like structure of galaxy clusters and superclusters containing the 100 billion galaxies observed in our universe today. One of these galaxies would become our Milky Way and include our Sun — just one of 200 billion stars that swirl about the Milky Way's enormous central black hole.

Stars, like our Sun, are great massive balls of burning gas. They burn so hot that hydrogen atoms collide with enough energy to stick together to make helium. In this

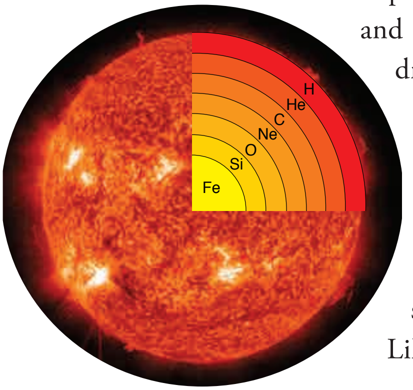


Our place in a corner of the universe

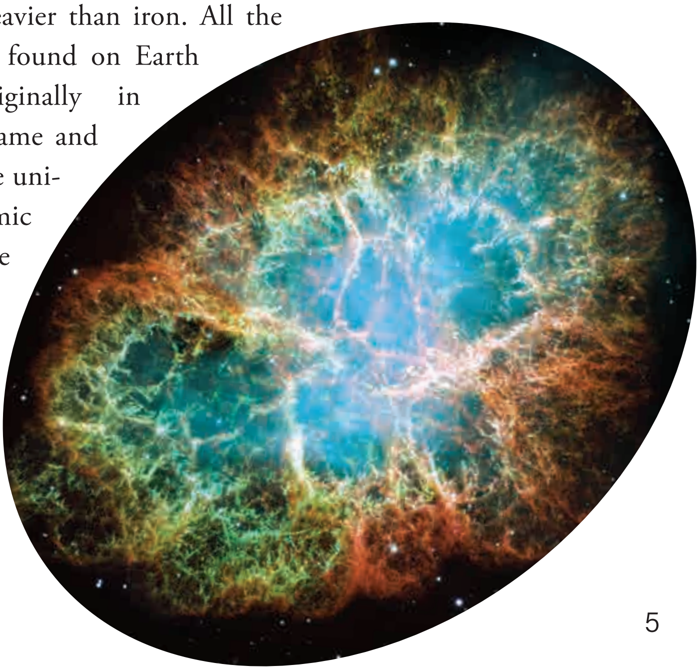
fusing of hydrogen into helium, a small amount of mass is converted into a huge amount of energy ($E = mc^2$) which sustains the burning star. The early stars were huge, and the bigger the star the faster it burns. Once all the hydrogen is burned into helium, the star collapses in on itself. If big enough, its collapse generates sufficient heat to ignite the burning of helium. Helium burns to form yet heavier elements, such as carbon and oxygen that are essential for life. Our Sun is too small to burn appreciable amounts of helium, and when it runs out of hydrogen fuel 4 billion years from now it will collapse into a dense, faintly glowing white dwarf. Any carbon it manages to make before then is likely to end up in the form of diamond at its core. But stars far more massive than our Sun carry on burning, layer upon onion-like layer, forging increasingly heavier elements from increasingly hotter nuclear fires right the way up to the element iron.

white dwarf

Upon reaching iron, nuclear fires within stars become unstable, and rather than continuing to burn they are ripped asunder into dramatic explosions called supernovas. The Crab Nebula was a supernova observed by Chinese astronomers in 1054 AD and Orion Nebula is easily seen today as the middle light source in the sword of Orion — captured, along with the Carina supernova, in great detail by the Hubble space telescope. Supernovas not only disperse elements up to iron into space, they also simultaneously shoot out abundant neutrons. Like buckshot fired from a gun, some of these neutrons stick to the nuclei of the atoms they hit and rapidly build elements heavier than iron. All the elements found on Earth formed originally in large stars and supernovas that came and went throughout our region of the universe as it was expanding. But atomic elements make up relatively little of our universe today (5%), with the balance made up of mysterious dark energy (72%) and dark matter (23%).



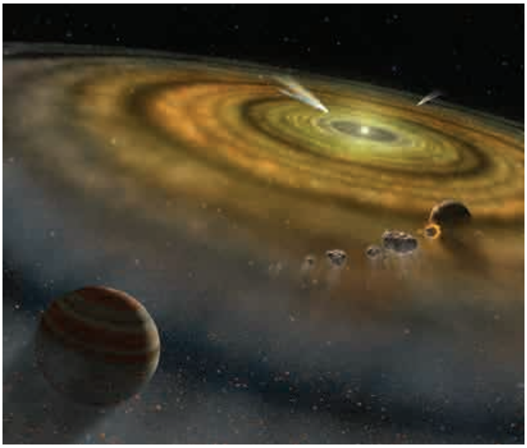
Elements up to iron (Fe) form in large stars



Crab nebula

Orion nebula

And among the elements, hydrogen (73%) and helium (25%) atoms still dominate. At an average rate of one supernova per galaxy per century over the billions of years since the big bang, only 2% of hydrogen and helium have managed to be fused into heavier elements and, in general, the heavier the element the less abundant it is.



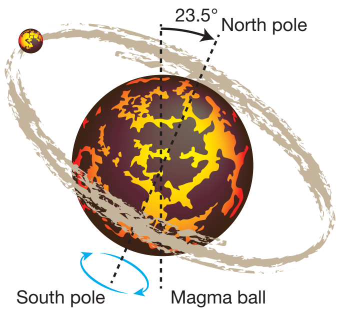
Our solar system formed from a minor swirling offshoot (above) during a supernova explosion, such as the Carina Nebula (left)

Planet Earth

Our own little solar neighbourhood, situated two-thirds the way out on a spiral arm of the Milky Way, came to be 9.2 billion years after the big bang, or 4.6 billion years ago. Our Sun and all the planets that make up our solar system most likely originated as a relatively minor swirling offshoot of dust and gas from a supernova that exploded at that time. Most of the dust and gas of this spiralling offshoot was pulled by gravity toward the centre of the spiral. The amount of heat released from the gravitational collapse was enough to ignite our Sun, composed mostly of hydrogen and helium in proportions similar to the universe as a whole. Gases and dust on the outer, colder regions of the swirling disc rapidly coalesced into the 'dirty snowball' outer planets Jupiter, Saturn, Uranus and Neptune.

In between the Sun and outer snowball planets were left the relatively dense residual bits of metal and rock. This metal and rock, which started out as supernova dust, condensed into small rocks that collided into yet larger bodies that in turn attracted other bits until they had amassed into planetesimals (small planets). Planetesimals eventually coalesced into a few dozen planetary bodies ranging from a hundredth to a tenth as massive as Earth. More gradually these planetary bodies combined through a series of multiple giant impacts and formed the small rocky inner planets Mercury, Venus, Earth and Mars. The condensation of the swirling rings of dust into the rocky planets is estimated to have taken somewhere between 63 and 127 million years after the birth of our solar system 4,567 million years ago, such that Earth was fully assembled sometime between 4,504 and 4,440 million years ago.

Mercury, Venus, Earth, Mars and asteroid belt form the inner rocky planets; Jupiter, Saturn, Uranus and Neptune form the 'dirty snowball' outer planets (distances not to scale)



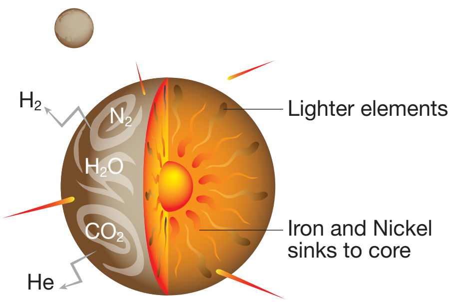
Earth's last major impactor (above) rendered Earth into a magma ball, tilted its spin axis and sent out debris that coalesced into our Moon (below)

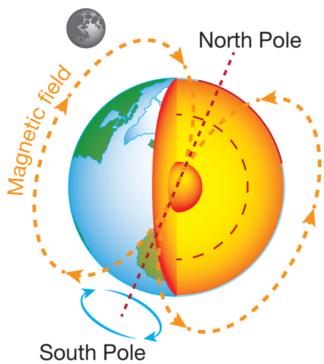
The final, planet-defining impact in Earth's assembly was with a planetary body the size of Mars. This colossal collision had several long-lasting consequences: it tilted Earth's spin axis by 23.5 degrees from the vertical to give us seasons; it sent rock debris into orbit where it aggregated to give us our Moon; and it captured most of the impactor's iron core to give Earth an unusually large amount of iron and an enduring magnetic field.

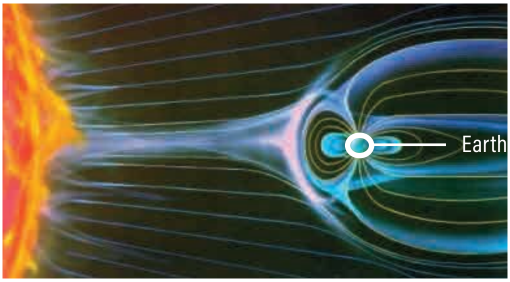
Hence, Earth represents a small, highly distilled concentrate of all the elements heavier than hydrogen and helium, a rarefied collective condensate of elements that otherwise make up only 2% on average of our entire solar system. Elements like iron, silicon, oxygen and magnesium are the most abundant, but all the stable elements that can exist are to be found here on Earth. Most importantly for life, these elements hastily thrown together by collisions were soon further distilled. The lightest elements percolated to the surface. Hydrogen and helium gas were too light to be held by Earth's gravity and escaped into space. But water, nitrogen and carbon dioxide accumulated in the atmosphere and ocean, which along with rocks exposed at the surface held an abundance of all the ingredients necessary for life.

While the lightest elements rose to the surface, the heaviest among them, mostly dense molten blobs of iron and nickel metal, sank by gravity relatively quickly to the centre. Earth has since cooled down and has crystallised out a solid iron-nickel inner core. However, much of the iron-rich liquid remains as the outer core and envelops the solid inner core. The continuous roiling about of the outer core's liquid

Metals sank to the core while lighter elements rose and were retained by gravity except for H and He (left); roiling of the liquid iron core initiated Earth's magnetic field (right)







Our magnetic field deflects the harmful solar wind (not to scale)

iron acts like a dynamo that generates a magnetic field. This magnetic field is critical in making Earth habitable by shielding it from high-energy solar winds harmful to life. Therefore, the early rapid distillation of the bulk Earth that included a dense iron-rich core capable of generating a magnetic field and an outermost envelope of light gas and water at the surface made it a place conducive to life.

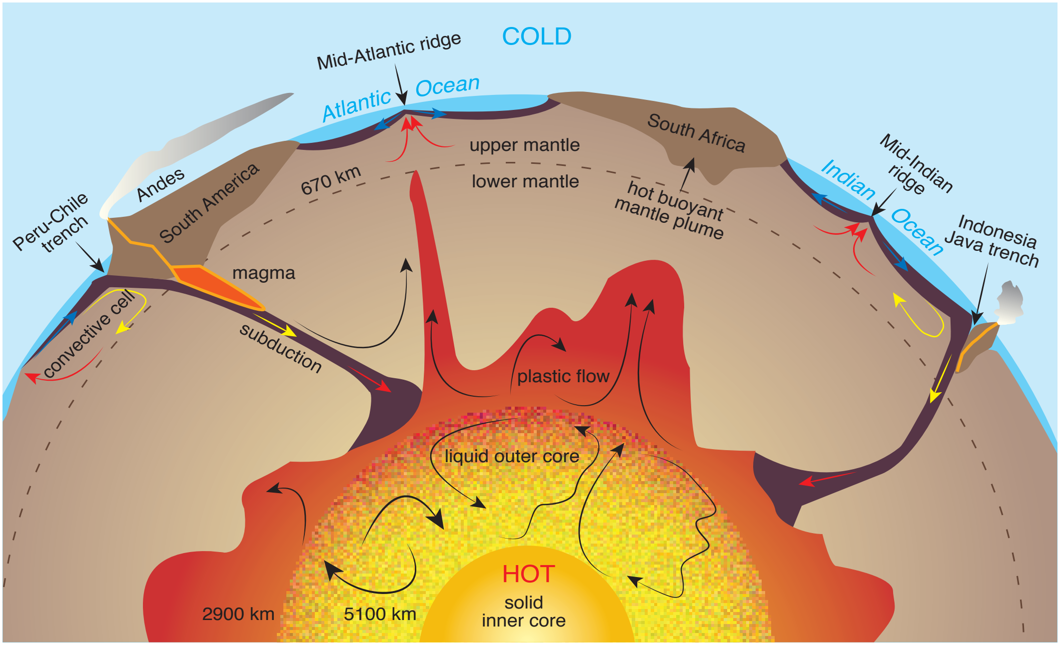
Initially Earth was too hot for life, forming a semi-liquid magma ball from the huge amount of energy released as heat from the impacts that formed it, as well as from heat released by the decay of unstable, short-lived radioactive elements left over from the supernova. But within several tens to 100 million years after final construction, Earth's surface had cooled down enough for it to crust over and for much of the water vapour to rain out as ocean. It would appear, then, that Earth was habitable as early as 4.4 billion years ago. However, if life did exist, it would have had to survive major cataclysmic events during the Hadean (the first geologic aeon, named after Hades, the ancient Greek god of the underworld).

It was throughout the Hadean between 4.5 and 4 billion years ago that conditions on Earth were particularly hellish, owing in large part to the final sweeping up of the substantial rock bodies lingering in our orbit. Episodic collisions continued to pummel Earth with sufficient energy to melt and recycle much of the thin solid crust as well as repeatedly boil off much of the oceans. Even now, Earth continues to receive as much as 100 metric tons of debris from space daily, most arriving as innocuous shooting stars. On occasion though a bigger, more threatening impactor arrives — like the one 10 kilometres in diameter that wiped out the dinosaurs. But by 4 billion years ago, the late heavy bombardment period was pretty much over and Earth presented a far more conducive place for life to take hold. And yet even after the Hadean bombardments had ceased, Earth was not a completely placid place for life.


Hellish Hadean

Earth had back then as it does today, its own internal rumblings expressed at the surface in the form of earthquakes and volcanic eruptions. As we shall see in the next chapter, some volcanic eruptions, like meteorite impacts, would have major repercussions for life on Earth. Earthquakes and volcanoes result from movement deep within Earth. Just as your cup of hot coffee cools, the most efficient way for a hot Earth to cool is by the hottest, deepest and least dense material rising toward the surface while the coolest, most dense material that is closest to the surface sinks into the hot interior. This slow churning (convective overturning) of Earth occurs in its liquid iron outer core as well as in the thick overlying mantle rocks, where solid rocks slowly flow like hot wax. The mantle is capped by a skin-of-an-apple-thin crust that is divided up into around twenty large individual rigid plates. Plate tectonics is the continuous movement of these crustal plates relative to one another, movement that is ultimately driven by the convective overturning of deep Earth.

In plate tectonics, plumes of hot, buoyant mantle rock rise up to generate magmas that form new oceanic crust at the surface. New oceanic crust forms along the mid-oceanic ridge, a winding submarine volcanic mountain chain that runs like the seam of a baseball for 65 thousand kilometres along the sea floor throughout the world's oceans. As new magma comes up, it forces the existing oceanic crust to move



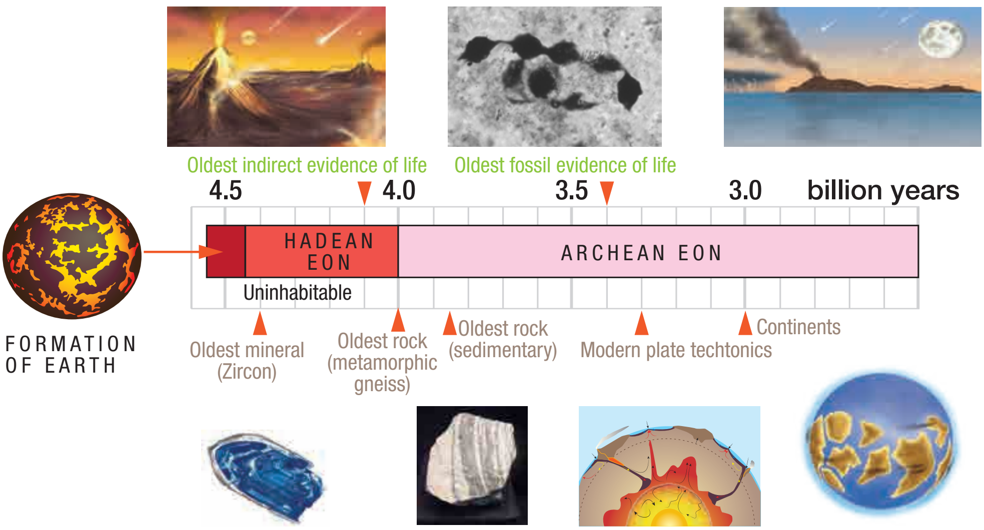
Internal cutaway showing convection in the liquid outer core that generates our magnetic field and convective plastic flow of hot, solid mantle rock that drives plate tectonics

Lava lamp

aside and the ocean basins widen. Eventually the oceanic crust cools and becomes dense enough to sink back down into the mantle and ocean basins shrink. This overturning of mantle rock may have initially been, as in your cup of coffee or a lava lamp, dominated by vertical up and down movement. It was only once Earth had cooled enough by around 3.3 to 3 billion years ago that the formation of rigid crustal plates having large continents resulted in less vertical and more sideways crustal movement that we observe today.

The continents that ride high above the ocean basins represent the accumulation of the lightest rocks, those too buoyant to be recycled back into the mantle. They are forever relegated to float like scum on the surface, episodically colliding together or breaking apart. Continents started out small, but over time they grew from the accumulation of lighter elements that had percolated to the surface. Most continental crust was in place by 3 billion years ago. But the barren, high-and-dry rocky surfaces of continents would only much later be home to a highly diverse assemblage of life forms.

Continual recycling of the crust by plate tectonics makes the oldest rocks the least likely to survive and as a result most of early Earth history has been erased. The oldest bit of Earth's crust dated thus far is a 4.4-billion-year-old zircon, a mineral commonly found in continental rocks and known for its ability to survive rock recycling. The oldest rock, a metamorphic rock called gneiss, is just over 4 billion years old, and the oldest oceanic sedimentary rocks known were deposited 3.85 billion years ago. These ages suggest that Earth had become a place suitable for life at least several hundred million years before the first indirect evidence of life is found in rocks 4.1 to 3.8 billion years old, and the first direct fossil evidence of life is found in rocks 3.4 billion years old.



Time line of Earth's early history

First life

Around 4 billion years ago, Earth would have looked familiar to us in many respects, but eerie and odd in others. In addition to there being no life, the days were shorter, spun out by a faster-rotating axis; the days were more dimly lit as the Sun shone a third less brightly than it does today; and our newly minted, not-so-distant Moon loomed large in the sky. The atmosphere was relatively enriched in the greenhouse gases water and carbon dioxide. Greenhouse gases are so called because they absorb Earth's outgoing infrared radiation and retain heat that would otherwise be lost to space. The greenhouse warming effect of these gases helped to compensate for our faint young Sun by keeping temperatures within the bounds conducive for life. Ocean covered most of the surface breached by small incipient continents and volcanic islands each with familiar rivers, lakes, valleys and mountains. Continental and submarine volcanoes violently spewed forth gases that weathered rock, while rivers carried sand and mud along with dissolved salts to the sea. The atmosphere lacked oxygen gas, but the wind stirred the ocean and the sky was blue and full of a mix of sunshine and clouds, many bearing rain, sometimes as violent thunderstorms. It was a mix of the familiar and the unfamiliar, and a world without life.

Early Archean Earth