CHAPTER 3

Hell on Earth

"Long is the way, and hard, that out of hell leads up to light."

John Milton, *Paradise Lost*

If you want to construct a picture of the earth on which life first emerged, think about how we've named it. There are four geological eons spanning the earth's 4,540-million-year existence. The most recent three names reflect our planet's propensity for living things, all referring to stages of life. The second eon is called the Archean, which rather confusingly translates as "origins." The third eon is the Proterozoic, roughly translating from Greek as "earlier life"; the current eon, the Phanerozoic, started around 542 million years ago and means "visible life."

But the first eon, the period from the formation of the earth up to 3.8 billion years ago, is called the Hadean, derived from Hades, the ancient Greek version of hell.

Life does not merely inhabit this planet; it has shaped it and is part of it. Not just in the current era of man-made climate change, but all through life's history on Earth, life has affected the rocks below our feet and the sky above us. And necessarily, the origin of life is inseparable from the fury of the formation of the earth in the first place. A picture of the Hadean earth is crucial to understanding the wild natural laboratory in which life contrived to be born. Just as the formation of our home world is an event in space, we'll come to see how the emergence of life here is essentially a cosmic event.

The study of the early geology is all rock-hard science, but the evidence is often both literally and metaphorically thin on the ground. It requires geological detective work with clues dotted around the planet, and off the world, too. Geology gives us clues to how the earth formed from the bits and pieces of matter floating in space around the sun. Yet it also begins to describe the world that will evolve into the host of the only living things that we know of. While our lives are built on the stability of the earth, we also are keenly aware that our planet is sporadically violently active. The solid surface (including the seafloor) is made up of seven or eight leviathan continental plates and a collection of smaller ones. These all float on the slowly flowing but solid rock of the earth's mantle, itself encapsulating the molten core. The plates that form the crust are in constant flux, grinding and unhurriedly jiggling together. Some, such as the Pacific and North American plates, grind against each other, forcing up new land inch by inch. The subcontinent that is now India was once an island, and crunched into mainland Asia in a process that began around seventy million years ago, inching forward and crumpling up the land into the mountains of the Himalayas. These mountains will continue to grow at a rate of a few millimeters every year as the Indo-Australian plate continues to muscle its way into mainland Asia. Others plates are pulling the earth apart at the seams. The United States' colonial expansion continues westward every day, as the coast of Hawaii grows new land at a rate of many feet per year. with molten rock gurgling up above sea level and solidifying. Earthquakes shake the land and the seabed, dislodging mountainous blocks of water that become tsunamis, such as the one that wrecked the east coast of Japan in 2011. Still, these events are currently anomalies, though they remind us that our planet is alive not just with cellular life but also with slowly flowing rock. Yet for the most part our earth is reassuringly stable.

Not so in the past. The birth of planets is a process of summoning order from the chaos of the early solar system. Violence ensues. The sun, the star at the center of our planetary system, formed around 4.6 billion years ago as a colossal cloud of free-floating molecules collapsed under its own gravity and condensed into the huge nuclear fusion reactor that continues to heat the earth today. In the immediate aftermath, the sun sat in the center of a solar nebula, a flat disk of detritus left over by its formation but held there by its own gravity. Over the course of the next few million years, this matter, mostly dust and gas, began to stick together in clumps. At first these were the size of medium-size concert halls, but over hundreds of centuries, lumps collided and stuck together in a process called accretion. Closer to the hot sun, the temperature is higher, which makes it harder for gasses to condense and accrete. It's for this reason that the inner four planets of the solar system—Mercury, Venus, Earth. and Mars—are terrestrial, made of rock, whereas the outer four—Jupiter, Saturn, Uranus, and Neptune—are gaseous.[1]

It's impossible to describe a whole planet in simple terms, as we know very well how our home is not a unified land mass. Much of the surface of modern Earth is solid; more is ocean. Of the grounded parts, there are extremes of temperature and geography, snow, deserts, marsh, forests, plains, mountains, and so on. The rock beneath your feet is likely to be very different from the rock underneath a reader's feet on the other side of the planet. Similarly, it's virtually

1 Pluto, once the ninth, is no longer considered a fully fledged planet, as it one of several similar-size bodies in that area of our solar system.

impossible to describe simply what Earth looked like in the Hadean. The evidence is vanishingly sparse, and as a result this period unhelpfully gets called the Cryptic era. Yet we can extract meaningful models in broad terms. We know that immediately after accretion, the planet was probably largely molten. Contrary to previous thinking, however, we now think this period of molten Earth was short-lived. There are no surviving rocks from that era, so in the past we had assumed that there were no rocks. Yet the absence of evidence is not the same as evidence of absence.

Just as we look in rocks for the traces of recent life—the fossilized forms of dinosaurs, or even cells, for example—our planet's history before life is embedded in geology. The oldest dated matter on Earth comes not from rocks, but in the form of zircon crystals, an abundant mineral found all over the world but probably best known as a cheap substitute for diamonds in jewelry.

Zircons have two convenient characteristics. The first is that they can withstand metamorphosis—the brutal churning of rock over very long periods of time. The second is that the atoms of zircons are naturally arranged in a neat cubic structure. This molecular box can trap atoms of uranium inside them, as few as ten parts per million. A small proportion of uranium, like many elements, is radioactive, and over time will decompose into lead. Due to the precise nature of their crystal structure, when zircons form they can include uranium, but exclude lead atoms. Once imprisoned in this cage, radioactive uranium slowly mutates into lead over the course of millions of years, and because this decomposition happens at a fixed rate (what we call a half-life), the moment a zircon crystal forms, it sets a clock at zero. Lead found inside zircons must have begun its life as imprisoned uranium, so by quantifying it we can date the origin of that crystal with 99 percent accuracy. Out in Jack Hills in Western Australia, zircon crystals have been found that trapped their uranium 4.404 billion years ago.

Dating is not all we can tell from the constituents of cheap jewelry. We can also infer from those same crystals that their formation was part of a solidifying process, the development of a crust. This means that, although there are no rocks from that period, we can know that there was land in the Hadean. We can also determine what other ingredients were present. The Jack Hills zircons also harbor a particular type of radioactive oxygen whose presence looks like that found in modern crystals, which are formed as the earth's crust gets sucked down beneath the ocean floor. The presence of this oxygen suggests that from as little as a hundred million years after the initial molding of the earth, water was present. On Earth, there is no life without it, though this water was likely to have been extremely acidic.[2]

Therefore, the early Cryptic days on Earth might not have been quite the hellish inferno of endless seas of molten lava. Within a mere hundred million years, the earth had a solid surface and oceans. Sounds pleasant enough, but let's not paint such a picturesque portrait. The earlier theories of a molten Hadean Earth were based on a solid observation: we can't find any rocks from that era. If there was a rocky surface, what in hell's name happened to it?

It turned out that we were looking in the wrong place. In fact, we were looking on the wrong heavenly body altogether. To address the question of what happened to the early earth, we sent twelve men to the moon. The moon itself was born out of the most destructive impact that Earth has yet suffered. Somewhere between fifty and one hundred million years after the formation of our solar system, the earth had its worst day. It was struck by Theia—a terrifically and

2 The source of the earth's water remains controversial. The absence of an atmosphere and its position in space so close to the sun may have caused much water on Earth to evaporate. Yet perhaps the shape of the rocks that first accreted to form this planet held water in their crannies. Another idea that some scientists promote is that most of the water on Earth was delivered in one or several icy comets whose frozen payload melted on delivery.

inappropriately pretty name for such a harbinger of doom. Current theories suggest that Theia was a rock the size of Mars. It blasted enough matter from the embryonic earth into space that it reformed as our closest celestial neighbor: the Moon. The impact was devastating, enough to rip the first atmosphere from the planet. Theia's glancing blow may be what shifted the earth's axis from vertical to its off-kilter stance of 23.5°. This lean is what causes the seasons, as the distance from the sun varies with the axial tilt of the earth.

But it was what came after the formation of the moon that concerns us. It's the characteristic pock-marked lunar visage that gave us clues to the state of the Hadean earth. Between 1969 and 1972 the Apollo program of the U.S. National Aeronautics and Space Administration (NASA) landed six missions and twelve explorers on the moon, beginning with Neil Armstrong's famous first small step. Over those missions, astronauts collected around half a ton of rock and brought it back home for analysis. The last man to walk on the moon, Commander Gene Cernan in Apollo 17, is quoted as saying that "we went to explore the Moon, and in fact discovered the Earth." There is a great truth in that quotation, as it was in the subsequent analysis of lunar rocks that we were to discover the nature of the earth's formative years. Unlike the earth, the moon has no atmosphere or winds, and no shifting geology, so the craters formed by meteorite impacts are left undisturbed alongside the footprints of the Apollo pioneers. What that means is that we have a record of meteorite activity in the local solar system, footprints unscathed by the winds, seas and tectonic grind of the earth. Geologists dated lunar rocks bearing the hallmarks of meteor strikes. These are called impact melt rocks; they all occurred in a precise window of time, between 4.1 and 3.8 billion years ago. We can deduce that this was a period of intense local meteoric activity, and by inference, that the earth also suffered this hellish pummeling from above. The young solar system was crowded with debris and leftovers from its birth, and for a period of three hundred million years, until the end of the Hadean, we got the full brunt of it. This period is called the Late Heavy Bombardment—so named because it was mercifully the last time Earth would suffer such a battering.

How heavy is heavy? Meteors fall from the skies all the time. Almost all, thank goodness, are tiny, burn out, then fade away in the atmosphere as shooting stars. Occasionally, a big one hits, whereupon they become meteorites, such as one that fell on the small Australian town of Murchison in September 1969, just a few weeks after Apollo 11 returned Armstrong, Buzz Aldrin, and command module pilot Michael Collins to Earth. That one weighed more than two hundred pounds, and carried a payload of interest to this story, as we will find out later.

If you're prone to making a wish when you see a shooting star, why not hope that we don't get to witness anything near the size of the best-known meteorite. Sixty-five million years ago a five- or six-mile-wide rock smashed into an area of what we now call Chicxulub in Mexico. The crater is now hidden, mostly beneath the sea, but its 110-mile-wide shadow remains and was spotted by oil prospectors in the 1970s. In the ground and seabed, there is a broken but detectable ectopic circle of tiny glass beads that were forged from molten rock during the heat of impact. And from space we can see the same circle in minuscule gravity distortions only measurable from precision equipment in satellite orbit. There has not been an impact anywhere near that magnitude since then, and be thankful for that. The Chicxulub meteorite was the trigger that extinguished the reign of the dinosaurs and paved the way for small mammals to evolve, eventually into us. An impact of that order means that it's very likely that the meteorite instantaneously wiped out many millions of creatures, with an expanding circumference of mile-high megatsunamis racing away from the impact site, leveling the land like a wave crashing on a beach. With that there also would have been a fireball hot enough to melt sand and rock into those telltale glass beads. But the full impact of the meteorite would have taken thousands of years, a dust cloud thrown up that blotted out the sun. The Chicxulub impact irreversibly changed the earth's system, wiping out once dominant life-forms. And yet compared to what was happening on the infant planet, the place on which life began, Chicxulub was a drop in the ocean.

Scientists have estimated that during the Late Heavy Bombardment something like fifteen astronomical rocks over one hundred miles wide, twenty times the size of Chicxulub, bruised our world. Of these maybe four of them were two hundred miles wide. For three hundred million years, giant rocks rained down from the sky, some as big as decent-size islands. The power of any one of the tens of thousands of impacts during this time would make the most destructive nuclear bomb seem like firecracker. Global environmental destruction would have occurred at least every few centuries. Any potential surface habitat for living organisms would have been destroyed over and over and over again. The relentless pounding the planet suffered during the Late Heavy Bombardment was enough to boil the oceans and vaporize the land.

And then it significantly calmed down. The meteoric blitz of the Hadean ended around 3.8 billion years ago, leaving a frazzled earth, still tempestuous and rough, but at least not barraged from the skies. The sun was dimmer than today, probably less than three-quarters of its current strength. Because of that, the earth cooled quickly, and water from volcanoes and comets condensed into oceans that covered the planet.

The precise point at which life began is unknown, and almost certainly unknowable. It may be that it began multiple times, maybe during the Hadean, but was wiped out all but once by the sterilizing spray of Late Heavy Bombardment. One 2009 computer model by scientists in Colorado suggests that even had the Hadean eon sterilized the surface of the Earth, life could have survived at the bottom of the ocean.

The consensus (though not unchallenged) is that the first evidence for living matter dates to around 3.8 billion years ago, coinciding with the end of the Late Heavy Bombardment. These clues come in the form of that vitally important atom, carbon. Cells, defining life as we know it, are not visible in the fossil record at this age, as rocks older than 3.5 billion years tend to have undergone the harsh geological metamorphosis that irretrievably churns up any shadow of living structures. Therefore, we have to look for the chemical signatures of life trapped in rocks. In a formation on the west coast of Greenland, rocks have been found that contain the merest trace of a form of radioactive carbon that has no earthly reason to be there, unless it had been processed by a living organism.

We don't know what that life-form was: only by the presence of that carbon can we infer that an organism that had similar fundamental mechanisms to modern life existed all that time ago. Skip forward four hundred million years and the remnants of life are abundant and much less controversial.[3] The best of these comes in the form of stromatolites: foot-wide stone mushrooms that sprout from the shallow seas in Australia and other locations around the world. They are formed when floating mats of solar-powered bacteria trap tiny particles of grit in their slimy mucus, and over millennia this floating scum slowly settles into layered lumps of stone.

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3 I say "less controversial," as some scientists contest that stromatolites could form from a nonbiological process—abiogenesis. Nevertheless, the consensus leans heavily toward these rocks being strong evidence for an Archean world thronging with microbial life.

Ingredients

Yet that is hundreds of millions of years of evolution after the end of the Late Heavy Bombardment. What we see from then are scant pieces bearing evidence of living things in a colossal jigsaw. We have a picture of Earth, more settled than it had been for hundreds of millions of years, but still violent, with electrical storms, churning land masses, volcanoes chugging out gasses into the atmosphere, and tumultuous seas. This is a contemporary understanding of the early earth, and has helped us formulate experiments and hypotheses for the conditions in which life emerged. However, the first speculations about life's emergence predate our current ones by a century.

In 1871, Darwin wrote a letter to his friend Joseph Hooker contemplating the switch from inanimate chemistry to life. On the second page of this almost unreadable document[4] he considers not the origin of species, but the origin of life:

> It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts,—light, heat, electricity &c. present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter wd be instantly devoured, or absorbed, which would not have been the case before living creatures were formed.

4 Darwin's handwriting was extraordinarily sloppy, to say the least, and the original letter is barely legible.

With this famous "warm little pond" Darwin is prefiguring the concept of primordial soup (*primeval,* meaning "original" or the "earliest time," and *prebiotic,* meaning "before life," are also used, largely interchangeably). He lists the ingredients of the soup there, just like a recipe. Though ignorant of our modern picture of the Archaean earth, Darwin had casually meandered into what would become the dominant idea of the origin of life. He was not the only one to take these speculative baby steps. One of his biggest champions was the German zoologist and polymath Ernst Haeckel, an early proponent of the idea that biology and chemistry were continuations on the same spectrum. In 1892, he proposed a process in which "the origin of a most simple organic individual in an inorganic formative fluid, that is, in a fluid which contains the fundamental substances for the composition of the organism dissolved in simple and loose combinations." Chemists were already dabbling in biological alchemy, not gold from base, but conjuring the molecules of biology from chemistry. In 1828, a German scientist, Friedrich Wöhler, synthesized urea, a key biological molecule and a component of urine, noting in his methods that he had done it "without the use of kidneys, either man or dog." This contradicted the then-popular concept of vitalism, that life was somehow fundamentally different from nonlife. Wöhler had shown that the molecules of life could be made synthetically.

The idea that the birthplace of the first life was a rich pond of ingredients was formalized in the 1920s when a Russian, Aleksander Oparin, and an Englishman, J. B. S. Haldane, both independently wrote about the emergence of complex biological molecules and life in conditions fueled by an oxygen-depleted atmosphere on the early earth. Haldane—a truly great scientist who went on to become a central figure in the emergence of evolutionary biology in the twentieth century and a gifted science communicator—is an important character in this scientific journey, as he first used the phrase "prebiotic soup," and the idea of soup as the stock of life has bubbled away ever since.

Soup had its greatest moment in 1953, a vintage year for science. Crick and Watson revealed the structure of DNA in April, certainly the scientific achievement of the twentieth century. But at exactly the same time, a young student was building on Haldane's and Oparin's ideas to put together another, similarly iconic experiment. Stanley Miller was a twenty-two-year-old chemist at the University of Chicago, and as part of his PhD he begged his supervisor, Nobel Prize laureate Harold Urey, to let him put together a rather fanciful experiment. He built a set of interconnected glass pipes on an electrified metal grid six and a half feet square. This kit now sits in a dimly lit room in the labs of one of Miller's students, Jeffrey Bada, now an emeritus professor at the Scripps Institution of Oceanography in San Diego. It looks, not inappropriately, like a 1950s sci-fi experiment, with sparks and bubbling gasses and colored liquids. Miller filled the glass beakers with water, methane, hydrogen, and ammonia, in an attempt to emulate what was believed at the time to be the essential ingredients of the early earth. Moving on to the next stage set by Oparin and Haldane, Miller reasoned that the absence of oxygen in the atmosphere was key to the chemical maelstrom necessary to prompt the emergence of essential biological molecules. Miller put thousands of volts' worth of spark into that pipework, mocking the electrical storms and lightning that thundered from the turbulent Archaean sky.

Harold Urey had the good grace to let him pursue this experiment with the caveat that it would be shut down and he would have to move on to less implausible research if it bore no fruit within a few months. No such time was needed. Within days the mix turned pink, then coffee brown. Miller extracted the rich brew; his analysis of it found the presence of the amino acid glycine and a handful of the other biological amino acids essential for building proteins. He published his results in the journal *Science*, noting in the methods that the conditions were designed to emulate the primitive earth, not to optimize the production of amino acids. Just to consolidate that extraordinary result, there's a sweet coda to this experiment. In 2008, a year after Miller died, Jeffrey Bada rediscovered some of the original samples from this experiment tucked away in the back of a dusty draw. He then subjected them to twenty-first-century analyses. Even in these fifty-year-old samples, precision inspection revealed not just the few that Miller had seen, but all twenty of the biological amino acids, and five others, too. It seems that under those conditions, the spontaneous production of essential biological ingredients was a trivially straightforward happenstance. Those simple units, it might be thought, would string together into proteins that all life depends on, and with their function the processes of life could begin. Miller had shown that in the tumult of the Archaean earth, the molecules that form the universal workers of living systems—proteins—were simply summoned into existence by the equivalent of a bolt of lightning.

The experiment was so appealing that Miller became an international celebrity. The press was amazed and excited;, their reporting exaggerated the results to the point where some claimed that Miller had created life. Naturally, amino acids are not life, though they are essential for it, and their creation was big news. This experiment was seen as a stamp of approval for the idea of primordial soup, cementing its place as part of our culture, and the most tenacious idea in the origin of life. In a location somewhere on the earth, a wet surface or pool or floating pumice was exposed to the gasses of the Archaean atmosphere and a bolt of lightning. It carries a sense of drama: the spark of life injected into a corpse, invigorated from the skies – the moment of creation.

But could it have been like this? As we have seen in earlier chapters, the mechanics of life are mesmerizingly complicated. A cell is a hive of densely packed activity receiving input from its environment (whether this environment is as part of an organism or as a single free-living cell). Inside the cell, there is code that encrypts proteins, and those proteins enact the functions of living: feeding, communications with other cells, and the reproduction of the organism to perpetuate the genes it bears. To see the spontaneous emergence in a test tube of the molecules (or components of those molecules) that perform these vital acts certainly provides credence to the idea that the origin of life is neither mystical nor supernatural. At the beginning of the Archaean, simple chemical ingredients did make the transition from chemistry to biology, and Miller's iconic experiment follows in the direct scientific lineage of Darwin's warm little pond. In that charming speculation the recipe includes "ammonia and phosphoric salts,—light, heat, electricity &c.," all of which are plausible components as they relate to some of a typical cell's processes. Miller's experiment tested this idea, basing the ingredients on a better understanding of the conditions of the infant earth—ammonia, methane, hydrogen, water, and lightning. In the sixty years since, many experiments have further refined the recipe, or shown similar and more sophisticated spontaneous construction of biological molecules out of a soup of ingredients. It's an attractive idea, and one that has stuck. But there are fundamental outstanding questions that underlie these experiments. Can life emerge by cooking up a chemical soup? Is a spark what it takes to drive a chemical reaction into a biological one? To answer these questions, and to get to the bottom of the origin of life, we must ask a very simple question, one with a deeply elusive answer.