**Nova – Origins Part 2 – How Life Began**

**NEIL deGRASSE TYSON** (Astrophysicist)**:** A hellish, fiery wasteland, a molten planet hostile to life, yet somehow, amazingly, this is where we got our start. How? How did the universe, our planet, how did we ourselves come to be? How did the first sparks of life take hold here? Are we alone in the cosmos? Where did all the stars and galaxies come from? These questions are as ancient as human curiosity itself. And on *Origins*, a four-part NOVA mini-series, we'll hunt for the answers. This search takes unexpected twists and turns. Imagine meteors delivering Earth's oceans from outer space. Descend into a toxic underworld where bizarre creatures hold clues to how life got its start. And picture the view when the newborn moon, 200,000 miles closer to Earth than today, loomed large in the night sky. This cosmic quest takes us back in time to within moments of the Big Bang itself and retraces the events that created us, this place we call home and perhaps life elsewhere in the cosmos. Coming up tonight: the origins of life.

**MICHAEL MUMMA** (NASA Goddard Space Flight Center)**:** The early Earth was not a Garden of Eden. There were no clear blue oceans, there were no plants. There was no life at all.

**NEIL deGRASSE TYSON:** So where could the building blocks of life have come from?

We think that all the carbon in your body arrived on the Earth in meteorites like this. So it makes you wonder: if the building blocks of life were delivered courtesy of comets and meteors, could any of the tiny ingredients they carry have survived the landing? And if they did, how did they generate those first traces of life? A walk on the ancient surface of the Earth offers clues.

These are the oldest fossils in the world, at about 3.5 billion years old. Life evolved on this planet very early and very fast. Journey back to an age when invisible microbes ruled the planet and caused the greatest transformation in Earth's history.

Over a billion or two billion years, the amount of oxygen that these little creatures produced was enough to actually change the entire atmosphere of the planet.

The story of how life began, on this episode of *Origins*, on NOVA, right now.

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**NEIL deGRASSE TYSON:** In the endless reaches of the universe Earth seems unique. It's a planet shaped and molded by life, a planet that six billion people call home today.

But when it was born, some 4.5 billion years ago, Earth was a violent place, so hostile it's hard to believe life could ever begin here. Covered in lava, and smothered in noxious gases, Earth was a planet under siege.

**PENNY BOSTON**(New Mexico Institute of Mining and Technology)**:** If you were a human, going back into time, and trying to stand on the early Earth, it would be just like visiting a planet that was not your own.

**LISA PRATT** (Indiana University)**:** This was a hazardous world, no doubt about that. If you were located in the wrong place at the wrong moment, you were simply vaporized.

**NEIL deGRASSE TYSON:**It was a planet plagued by catastrophe. If you condense all of Earth's history to just 24 hours, then only minutes after it formed, the entire globe melted and reformed. Then, to make matters worse, another planet about the size of Mars slammed into Earth, a cataclysm that created our moon. But soon after these disastrous beginnings, the most radical transformation of all time hit the planet: the origin of life.

So how did life begin? Well, over the years, people have come up with some pretty creative answers to this question. One of my favorites comes from a 17th century scientist who wrote down a recipe for creating life from scratch.

Let's see, it says here, "Take a dirty garment, place it in a vessel. Next add wheat." Then, according to the recipe, after fermenting for 21 days, mice will appear fully formed.

Of course, we all know that life doesn't form this way. But at some point in the Earth's early years, life did emerge out of non-living ingredients. And for clues to the real recipe of life, we have to go back some four billion years to a time when Earth was nothing like the planet we know today.

**MICHAEL MUMMA:** When we think of early Earth we must recognize it was not a Garden of Eden. There were no clear blue oceans, there was no clear water, there were no plants. There was no life at all.

**NEIL deGRASSE TYSON:** The young sun was weaker than it is today. And its light barely penetrated the atmosphere of carbon dioxide spiked with the pungent fumes of hydrogen sulfide.

**STEPHEN MOJZSIS** (University of Colorado)**:** Since the atmosphere was thicker and dominated by CO2, the Earth had a reddish tinge to it. It didn't have the familiar blue sky. The oceans would have had an olive green color rather than our familiar blue color.

**NEIL deGRASSE TYSON:** For about the first 600 million years, comets and asteroids pounded our planet, a time known as the "Heavy Bombardment."

These interplanetary missiles measured up to 300 miles across. Their impacts vaporized Earth's oceans and melted its crust. With its extreme temperatures and toxic rain, seemingly nothing could survive here. But we now think that in this hellish environment, life first took hold. And today, hidden away in remote corners of our planet, conditions that in some ways resemble the extremes of early Earth can still be found.

Penny Boston and Diana Northrup are microbiologists on an expedition to investigate how life can survive in those harsh surroundings.

Buried in the depths of this tropical rainforest is a cave called Cueva de Villa Luz. Located in southern Mexico, it's an underground world laced with hydrogen sulfide, a foul-smelling gas that was present on Earth some four billion years ago.

**PENNY BOSTON:** These relic, or antique environments like Cueva de Villa Luz offer the same kinds of environments that we would have found on early Earth, and we're hoping to get clues to work backwards from those.

As you approach the cave you begin to get these faint whiffs of the rotten egg smell. And as you get closer this becomes more intense.

**NEIL deGRASSE TYSON:** Hydrogen sulfide is can be extremely poisonous, so the scientists have to wear gas masks inside the cave and carefully test them for leaks.

**PENNY BOSTON:**Have you got everything in there? I think I got everything.

At the levels at which humans can't live very long in hydrogen sulfide you don't smell it at all. It will just simply cause you to go unconscious and die very quickly.

**NEIL deGRASSE TYSON:** But can any other forms of life survive in the deep recesses of the cave so toxic to humans? Here, hydrogen sulfide, an invisible gas, escapes from the underground springs, reacts with oxygen in the water, and coats the cave with sulfuric acid.

**PENNY BOSTON:** The longer it sits there on the walls, the more acid it becomes. And so, eventually, by the time the drop is falling on you it's a very, very acid environment.

It's very fatiguing, and even with the protective masks that we have, we pick up loads of toxic gas through our skin and perhaps through tiny leaks.

Look at those stalactites to your left.

**NEIL deGRASSE TYSON:** Amazingly, despite the extreme conditions, it appears that life is thriving inside the cave. It comes in a strange package: colonies of single-celled bacteria that form slimy drips scientists call "snottites."

**PENNY BOSTON:** The snottites are drippy, gooey, mucusy formations that look like stalactites. And that's why they were called snottites, because they resemble strings of snot. We believe that the snotty, gooey stuff is to protect them against extreme acidity because when we measure the drips on the snottites, they are as extreme as battery acid. And so, while we find that daunting, this is where they thrive.

**NEIL deGRASSE TYSON:** Bacteria are among the most primitive and most common organisms on Earth. Like all forms of life, they grow, adapt to their environment, and reproduce. Inside each single-celled bacterium is a molecule of DNA, the code of life which allows them to multiply. There are millions of bacteria in each snottite.

And down in the underground streams, Penny Boston has found different kinds of bacteria in slimy clumps she calls "phlegm balls."

In fact, the cave is home to a huge number of bacterial colonies. And astonishingly, instead of being poisoned by the hydrogen sulfide, these bacteria depend on it for their survival.

**PENNY BOSTON:** They take the hydrogen sulfide and they get chemical energy out of it. It doesn't poison them. It's home sweet home for them, and this is a pretty new finding for these organisms.

**NEIL deGRASSE TYSON:** Conditions on early Earth may have been far worse, but these bacteria suggest that primitive life could have thrived in extremely hostile environments.

But where did the very first life come from? For more than a century, scientists have known that life is the result of chemistry, the combination of just the right ingredients in just the right amounts. Today, we know these ingredients aren't things like dirty garments and wheat, which people used to think would spontaneously generate mice. The ingredients of life are actually much simpler.

All living things, from bacteria to mice to you and me, are made from a small set of chemical elements: hydrogen, oxygen, carbon, nitrogen—four of the most common elements in the universe. Combined in just the right way, these are the fundamental ingredients of life, and carbon is the star of the show.

**LISA PRATT:** Carbon's everywhere. It's all over the universe.

**ANDY KNOLL** (Harvard University)**:** What makes carbon special is the kind of bonds that it makes, both with itself and with other elements.

**LISA PRATT:** We know of no other atom that has the flexibility that carbon has to form diverse types of compounds.

**NEIL deGRASSE TYSON:** And the idea that life could have started when carbon and other ingredients combined in the harsh conditions of early Earth was first put to the test in the 1950s by a young graduate student named Stanley Miller. To simulate the newborn Earth in the lab, Miller assembled a contraption made out of flasks and tubes. He filled one flask with gases thought at the time to represent Earth's primitive atmosphere, and he connected that to another flask with water to represent the oceans.

**ANDY KNOLL:** And then he did a brilliant thing. He simply put an electric charge through that to essentially simulate lightning going through an early atmosphere. And after sitting around for a couple of days, all of a sudden there was all this brown goo all over the reaction vessel, and when he analyzed what was in the vessel now, he actually had amino acids.

**NEIL deGRASSE TYSON:** Amino acids are compounds that form when molecules of carbon and other elements link together. They are the essential building blocks of proteins and cells, vital ingredients of all living things.

Stanley Miller's experiment was headline news and jump-started the scientific search for the origins of life.

**ANDY KNOLL:** Life is really chemistry; there's no question about that. In fact, it's a chemistry that, when you get the recipe right, it goes, and it goesfairly quickly.

**NEIL deGRASSE TYSON:** That recipe is hotly debated today, and most scientists think the environmental conditions on early Earth were very different from the ones Miller simulated in his lab. And another debate rages about when this recipe first got cooked up.

On our 24-hour clock, the barrage of asteroids and comets lasted from about midnight until almost 3:30 in the morning. The assault then weakened, but continued for more than 100 million years.

It's hard to believe that life could have gained a foothold during this unstable period, but new discoveries reveal that life may have existed as early as four in the morning, or about 3.8 billion years ago.

The evidence comes from some of the oldest rocks on the planet, found in the remote regions of West Greenland.

**STEPHEN MOJZSIS:** The geology of Greenland is unique. It contains a record of some of the earliest geological processes that we know of on the Earth. The rocks themselves are thought to be between 3.7 and 3.9 billion years in age.

**NEIL deGRASSE TYSON:** These rocks are so old that any fossils they once contained have been destroyed. So to find out if life existed when they formed, Mojzsis had to look for evidence that is far more elusive.

**STEPHEN MOJZSIS:** There may have at one time been small fossils, microfossils but under the conditions of heat and pressure that these rocks experienced, such fossils would have been disaggregated and destroyed. So what we have left behind then are chemical fingerprints of ancient bacteria or microbes.

**NEIL deGRASSE TYSON:** To search for those fingerprints, Mojzsis first extracts a sample from the ancient Greenland rocks. Then he will analyze its chemical composition looking for carbon, a signature of life.

But carbon comes in several different forms. And Mojzsis wants to know if the carbon in this sample is the kind left behind by living creatures. If so, he believes that life may have existed when these rocks formed over 3.8 billion years ago, a controversial claim.

**STEPHEN MOJZSIS:** It was a surprise for us to find evidence of ancient life in these rocks. We didn't know if it would be there. You know, just because the stage is set doesn't mean that the actors are present. But these samples, here, represent the first evidence we have, direct evidence of a biosphere on our planet.

**NEIL deGRASSE TYSON:** If it emerged so early, life was lucky to miss the greatest cataclysm of all time, an impact like no other in our planet's history. It happened when another rocky sphere about the size of Mars collided with Earth. The outer layers of our planet were vaporized, and the debris from this collision coalesced to form the moon. That impact was so powerful that any building blocks of life that existed on Earth would have been destroyed.

This gives rise to speculation that the ingredients of life didn't form on Earth at all, but arrived special delivery, from outer space.

Hollywood has always been taken with the idea that life came from outer space. But it's not as far-fetched as it might sound.

**STEPHEN MOJZSIS:** Space is not very far away. Space is only about 20 kilometers that way. Now, that's very close and space is vast.

**NEIL deGRASSE TYSON:** And a scientist named Don Brownlee designed an experiment to find out if space might actually harbor the building blocks of life.

**DON BROWNLEE** (University of Washington)**:** There are 40,000 tons of bits of comets and asteroids that impact the Earth every year. This is mostly in the form of particles that are less than a millimeter in size. We breathe them, they're in the food that we eat, but they are very difficult to find. You can only find them in very special places.

**NEIL deGRASSE TYSON:** To see if this shower of space-dust contains the ingredients for life, Brownlee needed to obtain samples uncontaminated by Earth's atmosphere. So to get just a few micrograms of dust, he commissioned a former spy plane to fly close to the edge of Earth's atmosphere. Sticky pads on the plane's wings collected the space dust. Then, Brownlee's colleagues sliced the dust particles into slivers less than one-tenth the thickness of a human hair. And they discovered that these tiny particles are rich in the seeds of life.

**DON BROWNLEE:** If you look on an electron microscope, you'll see this wonderful array of minerals and carbon and organic materials that are 4.55 billion years old and we believe are the building blocks of life.

**NEIL deGRASSE TYSON:** And this extra-terrestrial dust isn't the only possible source of life's ingredients. In a region of space called the Asteroid Belt are huge amounts of debris left over from the formation of the solar system. And sometimes, chunks of debris containing metal and rock fall to Earth bearing surprising gifts.

One such meteorite landed in the town of Murchison, Australia, in 1969.

**NEWSREEL ANNOUNCER:** It's a gold mine, this little chunk of meteorite which fell on Australia last year. For the past six months they've been taking it apart and have discovered that it contains amino acids, the building blocks of life.

**NEIL deGRASSE TYSON:** It was the first time that complex organic compounds had ever been found in material from space. And if meteorites like it were common perhaps they had delivered vast quantities of the original constituents of life to early Earth.

**MIKE ZOLENSKY** (NASA Johnson Space Center)**:** Enough organics are present here that we think that meteorites like this provided the early Earth its entire budget of organics. So all the organics in your body, all the carbon in your body and in your lunch you had today, arrived on the Earth in meteorites like this.

If they come through the atmosphere in large enough objects, they're like little capsules coming in the atmosphere. They break apart on the Earth's surface and deposit their cargo of organics.

**NEIL deGRASSE TYSON:** More than 70 kinds of amino acids have been found in meteorites, and many are the fundamental ingredients of proteins that make up living cells. During the Heavy Bombardment, millions of meteorites may have seeded the Earth with the stuff of life. And there might have been an even more efficient delivery system.

Comets are like giant dirty snowballs made of ice and rock. Some comets that hit the early Earth were the size of mountains, and a large portion of their mass could have contained organic compounds.

The destructive power of comets and meteors is astronomical. The meteor that slammed into Earth some 50,000 years ago, here in Arizona, blasted a hole in the ground nearly a mile wide—from here to here—and so deep it could hold a 60-story skyscraper. And as if that weren't enough, the force of the impact was so great that it instantly vaporized nearly the entire meteor, three hundred thousand tons of it.

So it makes you wonder: if the building blocks of life were delivered courtesy of comets and meteors, could any of the tiny ingredients they carried have survived the landing? And just what happens to things like amino acids when they slam into Earth with such devastating power?

To answer those questions, one scientist came up with an ingenious experiment. Using a huge gas-powered gun, Jennifer Blank simulates the extreme pressures and temperatures that are unleashed when a comet smashes into Earth.

**JENNIFER BLANK** (Lawrence Livermore National Laboratory)**:** We set out to test whether or not materials would survive or whether they would break down. And we expected that, or we were hoping that, some fraction would survive. We figured the parts that didn't survive would break down into smaller components, but in fact what we found is much more exciting.

**NEIL deGRASSE TYSON:** The gun fires a bullet at 5,000 miles an hour towards a sample that represents the organic molecules inside a comet. The sample consists of a solution of five different amino acids, two of them present in every living cell. The mixture is inserted into a steel capsule. The gun will send a shockwave through the capsule simulating the extreme pressures of a comet's impact.

**JENNIFER BLANK:** I think it's very hard to just imagine what kinds of pressures we're generating in these experiments. If you think about going to the bottom of the ocean, the pressures you'll have there are only a hundred times atmosphere. So these are hundreds of thousands of times atmospheric pressures.

**NEIL deGRASSE TYSON:** Will Jennifer Blank's experiment show that the building blocks of life can survive a crash landing on Earth?

**JENNIFER BLANK:** Clear the room...Charging now...Okay, bringing up the X-rays...35.Three, two, one, fire. Three, two, one, fire.

**NEIL deGRASSE TYSON:** When they remove the capsule it's undamaged. But have its contents survived the impact?

The once clear solution of amino acids has turned a tarry brown color. And the analysis revealed that not only had the material withstood the colossal pressure of the impact, but it had transformed into a new compound.

Amino acids, combinations of carbon and other basic elements, had fused together to form more complex molecules called peptides.

**JENNIFER BLANK:** We went from our initial small compounds—and here's an example of one of them, a simple amino acid—and we used the energy associated with the impact to build larger molecules. Molecules like this—this is a peptide—and we show that we can use the impact energy to grow larger molecules from the simplest building blocks of life.

**NEIL deGRASSE TYSON:** Peptides link together to form larger building blocks, proteins, which make up all the cells in our bodies. But the leap from non-living ingredients to a living creature, complete with DNA which allows cells to replicate, is staggeringly complex.

No one knows how this process started or what course it took.

**ANDY KNOLL:** It is hard to really get your head around the great leap from non-living to living.

**LISA PRATT:** Well, it's hard enough that nobody's succeeded in doing it in the laboratory.

**ANDY KNOLL:** I think it's an astonishing mystery, and one that we truly don't understand in any great detail.

**NEIL deGRASSE TYSON:** While we don't yet know how the spark of life occurred, we can try to figure out where it might have gotten a foothold.

And because the planet was under such devastating assault from comets and meteors, the leap to life may not have taken place up here on Earth's surface. To take hold, life may have needed a safe haven, perhaps underground.

A team of scientists descends into one of the deepest mines on Earth to investigate whether microbial life can survive far below the Earth's surface.

**JAMES HALL** (Carnegie Institution of Washington)**:** And the mining environment gives us this fantastic window into the deep subsurface. It's a unique scenario because there is nowhere else on planet Earth that allows you to have access to that sort of sample location at two, three, three and a half kilometers deep.

**NEIL deGRASSE TYSON:** It takes 45 minutes to reach the heart of this South African mine. Conditions here are extremely uncomfortable, for humans, that is. The temperature of the rock is 120 degrees Fahrenheit, and the air pressure is twice that at Earth's surface.

Life down here survives entirely without sunlight. If they exist, microbes need to find a way to live in pitch darkness, drawing chemical energy from water and minerals trapped in the surrounding rocks.

**JAMES HALL:** Microorganisms have been shown potentially to be able to use these molecules to provide themselves with energy and support themselves completely independent of photosynthesis. And if we can prove that that is the case here, then that is very interesting because that adds credence to the idea that you could have life originating in the deep subsurface.

**NEIL deGRASSE TYSON:** As the miners drill into the rock, they break into ancient pockets of water, havens for microorganisms.

**JAMES HALL:** We're not sure how organisms can live in such extreme environments. The major thing is there's such low nutrient availability, there's nothing really for these guys to continually use and process to survive, and yet somehow they do. And the question is, "How do they do it?"

**NEIL deGRASSE TYSON:** The first step is to collect pristine samples of the water and see if they can grow the microbes it contains.

**JAMES HALL:** I'll get a very big sense of achievement if I can actually take something that's been isolated for 200 million years, put it in the laboratory and actually find out what it is this organism needs to survive.

**NEIL deGRASSE TYSON:** In a makeshift lab near the mine, the team attempts to recreate the environment deep inside the rock. And they have found that these microbes are dining on a variety of strange gases.

**JAMES HALL:** It turns out that in the deep subsurface there's an abundance of methane gas and ethane and propane. Now, for you and I that's not a very exciting diet, but what we think is that these organisms may be taking that kind of gas and actually using that as a food to survive.

**NEIL deGRASSE TYSON:** On such an exotic diet, the bacteria draw just enough energy to divide and reproduce only once every thousand years, suggesting a way that life could have survived deep beneath the surface of the early Earth.

And the Earth's crust may not have been the only place where life could have hidden from the Heavy Bombardment. Another safe haven may have been the ocean. Volcanic activity was intense on the early Earth. Chemicals from deep inside the planet spewed into the primitive seas. Even today, marine biologists have discovered volcanic vents on the ocean floor.

Despite scalding temperatures, acid eruptions and total lack of sunlight, they found creatures of all types thriving down here. And at the bottom of the food chain are microbes that live on the noxious hydrogen sulfide gas erupting from the vents.

On early Earth, primitive life may have survived in similar environments.

**STEPHEN MOJZSIS:** If all of the bombardment was occurring near the surface, survivors would be existing in just these kinds of hydrothermal vent communities where there's abundant water and nutrients and heat and food in the form of chemical energy. It has been found that organisms collected there nowadays are genetically akin to some of the earliest organisms that we think existed on the Earth.

**NEIL deGRASSE TYSON:** By about three and a half billion years ago, or five o'clock in the morning on our 24-hour clock, the bombardment of asteroids and comets had ceased. With far fewer violent impacts on Earth, microbial life could now survive outside its protective hiding places.

After it reaches Earth's surface, life would take advantage of another source of energy: the sun. Up here, microbes evolved a green pigment known as chlorophyll. This allowed them to trap sunlight and use it to drive a chemical reaction that converts carbon dioxide and water into food. Called "photosynthesis," it was a clever invention that enabled some bacteria to grow and reproduce almost without limit.

Once it started, photosynthesis was a runaway success, and today it's how all green plants make their living.

As Earth cooled, this new generation of cells spread across the oceans. Immense colonies of green slime would take over the world, kicking off the greatest transformation in our planet's history.

**ANDY KNOLL:** Photosynthesis is the great liberator of biology. With photosynthesis, the energy is coming from the sun, and life could spread, literally, over the entire planetary surface.

**NEIL deGRASSE TYSON:** And this remote corner of Western Australia holds clues to how that happened. These domed structures, called stromatolites, are built up layer by layer over thousands of years by tiny microbes. These microbes may be similar to life forms that dominated our planet billions of years earlier. And in the arid hills nearby, there may be evidence of these ancient creatures.

These rocks have remained unchanged for three and a half billion years. Here it's possible to walk on the surface of early Earth. Martin Van Kranendonk spends months at a time in this wilderness, studying the geology and producing maps. In a secret location in these hills is what could be one of the greatest geological discoveries of all time.

**MARTIN VAN KRANENDONK** (Geological Survey of Western Australia)**:** These are the oldest fossils in the world, at about three and a half billion years old, and they're composed of stromatolites. And at this outcrop we can see two different types of structures that these creatures formed. First are these black mats that have wrinkly textures all through it, and the second are these larger domes that form these broad structures. The most likely way these things formed is by the growth of microbes.

**NEIL deGRASSE TYSON:** Like modern stromatolites, these ancient structures could also have been built by colonies of bacteria. And not far away are fossilized ripple marks which suggest they might have grown in shallow water.

**MARTIN VAN KRANENDONK:** And here, you can see we've got a smaller structure that we call the "Mickey Mouse Ears," which is this beautiful doubly branching structure. And there is nothing else that we can think of which would make that except something that was growing on the bottom of the ocean.

**NEIL deGRASSE TYSON:** So perhaps the ancient stromatolites were formed by microbes like the ones that build these structures today.

**MARTIN VAN KRANENDONK:** These big stromatolites are composed mostly of rock at the bottom, and the only living part of the stromatolite is a thin layer on top. And that thin layer on top is made up of microscopic blue-green bacteria called "cyanobacteria."

**NEIL deGRASSE TYSON:** Named after the blue-green color of their cells, these cyanobacteria use photosynthesis to collect energy from the sun. They secrete a sticky coating to shield them from ultraviolet radiation. As tiny pieces of dust and sediment settle on top of the sticky cells, the bacteria migrate closer to the surface to reach the light. The layers of sediment build up by about half a millimeter a year. These structures contain living microbes, just as they have for thousands of years.

**MARTIN VAN KRANENDONK:** The amazing thing about these stromatolites is that the microorganisms which build them are so tiny. And the structures that you see around me, compared to their size, are enormous. It'd be like if humans made a skyscraper that was a hundred and five kilometers high by seventy kilometers across. These are massive structures for the size of the organisms that make them.

**NEIL deGRASSE TYSON:** Many different shapes and sizes of what appear to be fossilized stromatolites have been found in the rock. It seems likely that these structures were formed by some type of microbe living on the early Earth, perhaps even by the ancestors of today's cyanobacteria.

**MARTIN VAN KRANENDONK:** We're looking at sort of a cross-section through the top of these cones. And layers that were laid down year after year, and the fact that they're all different sizes on this one surface, shows that there was a colony of microorganisms growing on this one bedding plane. And that's really fascinating because it means that life evolved on this planet very early and very fast.

**NEIL deGRASSE TYSON:** And it's the cyanobacteria that would bring about the most astounding changes in Earth's history, a change that could have started as early as three and a half billion years ago.

Over time, stromatolites spread out across the planet. As a byproduct of photosynthesis, the ancient bacteria produced a waste gas: oxygen. The oxygen was absorbed into the oceans at first. There, it combined with iron erupting from undersea volcanoes to form iron oxide particles that fell to the ocean floor. Over the next several hundred million years the planet literally rusted.

There may have been other forces at work, but eventually, all the iron was turned into oxide, building up layer after layer, one of the most valuable mineral deposits on Earth, iron ore.

Located in Western Australia, this is one of the world's largest iron mines. The iron here was originally deposited on the floor of a primordial ocean.

**MINE CREW MEMBER:** We are at the current position as connected. We will fire in 10 seconds with a five-second count down.

**NEIL deGRASSE TYSON:** Every week they excavate half a million tons of iron ore used to make steel for everything from cars to skyscrapers. In a more pristine state, thousands of ancient layers of iron ore are preserved in the Karijini Gorge, just 30 miles from the mine.

The layers exist because different amounts of iron oxide were deposited at different times of the year. Cyanobacteria produced oxygen in varying amounts as water temperatures changed with the seasons. All over the world, vast amounts of iron ore were laid down in similar ways.

On our day-long clock, this process continued until one in the afternoon.

Eventually, oxygen produced by cyanobacteria began to build up in the atmosphere. Slowly but surely this transformed the planet. Over the next eight hours or so, tiny microbes raised the level of oxygen from less than one percent to today's 21 percent. The time was about 9 p.m.

It's amazing to contemplate, but without cyanobacteria, there would be no oxygen and Earth would still be smothered in noxious gases. Plants, animals and humans would have never evolved.

**ANDY KNOLL:** We're sitting here today breathing an oxygen-rich mixture of air. We couldn't be here without that oxygen, but that oxygen wasn't present on the early Earth, and it only became present because of the activity of photosynthetic organisms.

**PENNY BOSTON:** Life has made this environment what we know. It's allowed us to live on the surface, it allows us to breathe, it allows large organisms like we are to function at very high rates of activity.

**NEIL deGRASSE TYSON:** The oxygen also helped protect life from the sun's lethal ultraviolet radiation, by creating a layer of ozone in the upper atmosphere.

**PENNY BOSTON:** One of the fascinating properties of that is that it actually screens out—just sort of like a sunscreen does on your skin—screens out this harmful radiation.

**NEIL deGRASSE TYSON:** With the protection of the ozone layer, life was able to diversify into more complex organisms. It took only the last three hours of the day for all the other life forms on our planet to evolve.

The first multicellular life emerged at six minutes past nine in the evening. Then came fish, and insects, and reptiles. By about 10 minutes to 11 in the evening, dinosaurs roamed the Earth. The first primates appeared at 20 to midnight. And with less than 30 seconds to go, the first humans made their appearance.

**DON BROWNLEE:** It's only been the last 10 percent of the Earth's history where there was life on the surface of the Earth that you would see with your naked eye. So, for most of Earth's history, life has basically been invisible on the Earth.

**MARTIN VAN KRANENDONK:** Over a billion or two billion years, the amount of oxygen that these little creatures produced was enough to actually change the entire atmosphere of the planet.

**STEPHEN MOJZSIS:** Multi-cellular life that we're most familiar with—animals, plants, their environment—was made possible by the slow, toilsome task of bacteria to oxygenate the atmosphere.

**NEIL deGRASSE TYSON:** Microbes ruled the planet for more than three billion years, two thirds of its history. These tiny organisms had transformed an entire planet. Without them, complex life, humans included, would have never evolved.