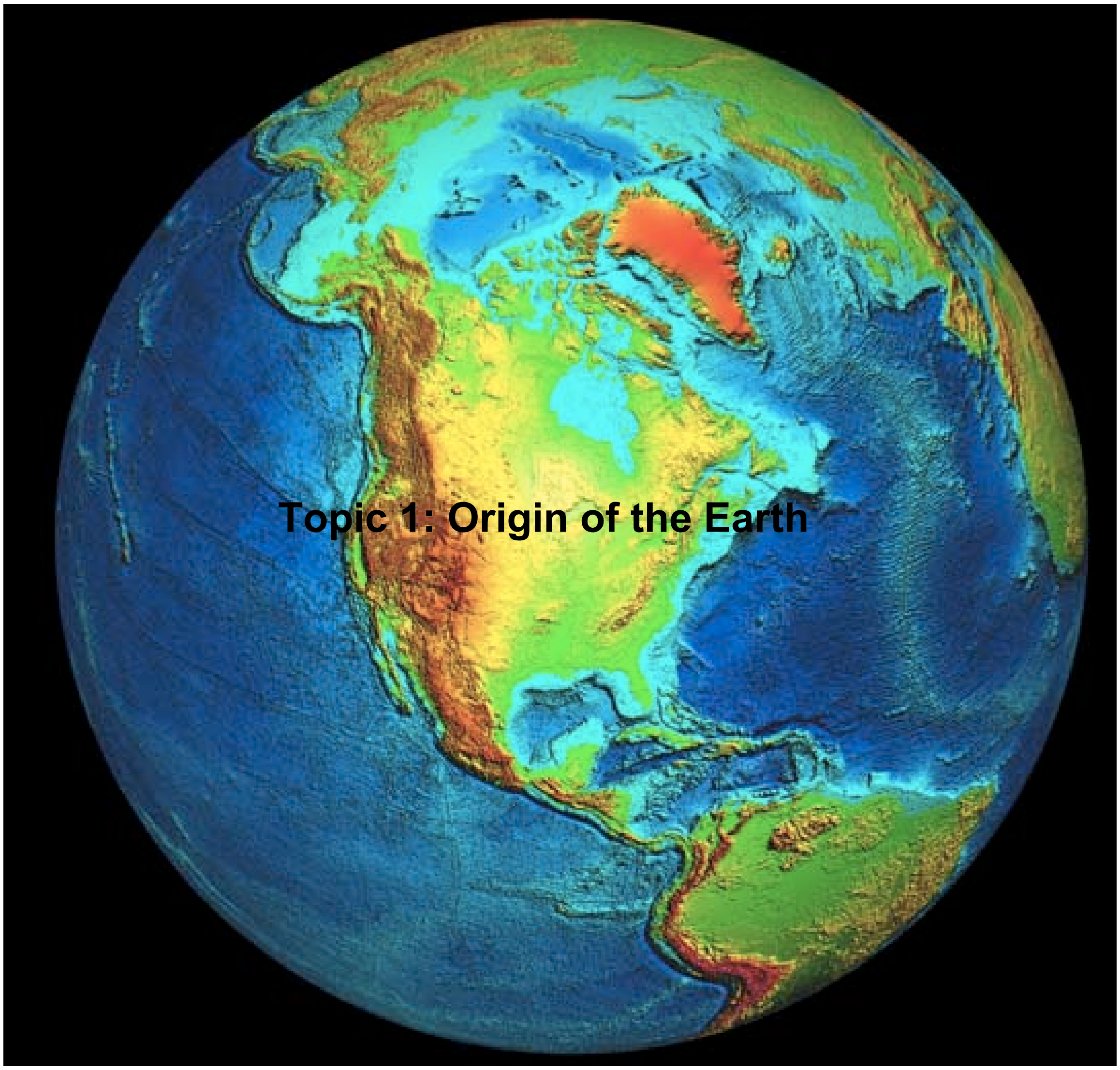
Planet Earth: An Introduction to Earth Sciences



Roger N. Anderson
Columbia University

Planet Earth Topic 1: Origin of the Earth

Roger N. Anderson

Any of us fortunate enough to have sailed so far from shore that we could no longer see land must have wondered where all that ocean came from. There is enough water to cover 70 percent of the planet's surface with a coat averaging two miles thick from sea level to seafloor. Why don't other planets in our Solar System, like Mars, Venus, Saturn, or our Moon for that matter, have water at the surface? But maybe some of them did. How would we know? Jupiter's moon Europa may be covered in ice with a vast ocean underneath (Figure 1-1). How could we measure that? Or maybe they DID, but the water is long gone. How would we tell? This exploration of Planet Earth is concerned with how science sees, measures, and senses the unknown. We can't go to the stars, but we know their chemical composition. We can't drill to the center of the Earth, but we know its density.

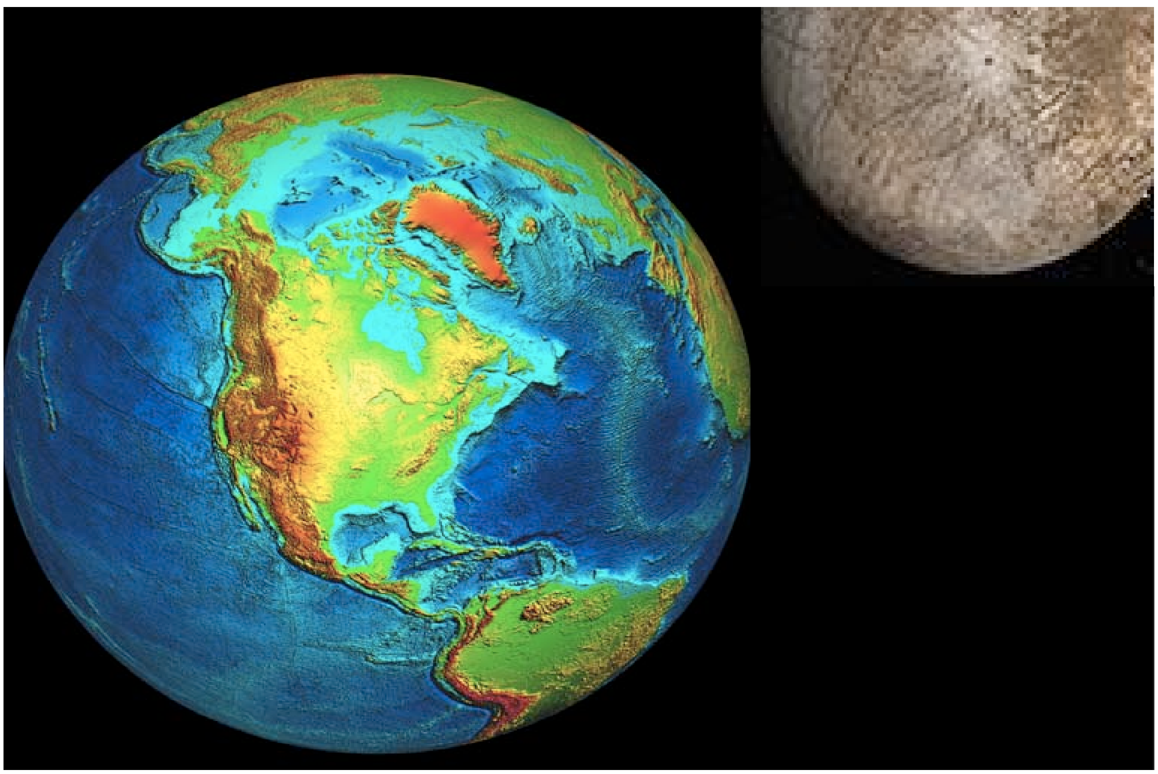


Figure 1-1. Contrast the surface of Earth to that of Europa, a moon of Jupiter, that is the only other object in our Solar System with extensive oceans. Europa is covered with a thick sheet of ICE that is thought to be covering a deep ocean like that on Earth. The brown coloration is from dust and the cracks are crevasses like in glaciers. Photo credits: NASA and NOAA).

In order to begin to understand how our Earth works, we must discover how we go about exploring its hidden mysteries, and what better way to begin than to ask the hardest of all questions – where did the planet come from in the first place. And we will find that the secret locked within the origin of the Earth, along with how it came to have its magical oceans holds the key to the way the Solar System itself began.

Back in Time: From the Solar System to the Big Bang

Although we still have not solved the entire puzzle of how the Universe, our Galaxy, the Milky Way, and our Solar System formed, several rigid constraints do exist. For example, we have never found a single rock that is older than 3.7 billion years old on the Earth. Yet we know the solar system and the Earth are 4.5 billion years old. And we know the Universe is about 14 billion years old. How can we be so sure of the age of the solar system or of the Universe if we can 't find rocks on the Earth of those ages? The truth is that there are indeed rocks on the Earth that have radiometric ages of 4.5 billion years, but these are all meteorites that have fallen to the Earth from space. Also, the greatest geological expeditions of all time, the Apollo missions to the Moon, recovered rocks that were ALL older than 4 billion years. And missions to Mars and Venus by robots leave little doubt that all the planets formed about 4.5 billion years ago.

The paradox is that the Earth has no old rocks, but the Moon has none younger than our oldest rocks! And science likes paradoxes, because they often lead to solutions. So where did all that old rock from the Earth's earliest days go? And could the missing rock have anything to do with the oceans we have? Did the Moon come out of that ocean? A hint at the answer to these questions comes from the KIND of rock that oldest Earth record is – it was deposited on soft mud at the bottom of an OCEAN.

But where is the record of all that missing rock? Since we cannot have oceans without rock underneath, the oldest covering on the planet must have been destroyed and replaced with younger rock. What kind of catastrophe could have wiped out the entire surface record of the planet for its first billion years of existence? And did it have anything to do with the fact that the astronauts returned no rocks younger than the oldest Earth rock from the Moon?

Such a cataclysm makes theories that the dinosaurs were wiped out by a large meteor impact seem of trivial dimension in comparison. When we look at the early histories of the Moon, Mercury, or Venus, we see that their crater-marked surfaces show that meteor impacts were the dominant geological event in the early solar system. But the massive meteor-impact craters that surely hit the early Earth are gone, along with every other trace of that time period.

Let's begin with the chemical composition of the Earth, Planets, Moons, and Stars. How do we know the chemistry of a star, for example? By its color. The optical spectrum of the light given off by any body carries the unique fingerprint of its chemistry.

And when we accumulate the composition of all the stars, planets and moons, we get an interesting view of how those elements came about in the first place. We have all studied the periodic table at one time or another in our lives. What you might not know about the elements that make up our existence is that the abundance of each heavier element is about twice that of its lighter neighbor 9with a few interesting exceptions). This "exponential" decrease in abundance with added complexity means that there is twice as much hydrogen – element 1 – as helium – element 2. And twice as much helium as lithium element 3 – and so on. This tells us not only the composition of the dust cloud that made our solar system, but how the universe formed all its dust, rock and gases in the first place – in supernovas of exploding stars (Figure 1-2).

Figure 1-2. Glowing gaseous streamers of red, white, and blue — as well as green and pink — illuminate the heavens like Fourth of July fireworks and tell scientists their chemical composition. The colorful streamers that float across the sky in this photo taken by NASA's Hubble Space Telescope were created by the universe's biggest firecrackers, the titanic supernova explosions of massive stars. Such supernovas make heavier elements from fusion of lighter ones. The color spectrum of each reveals its chemical composition.. Photo Credit: NASA.

The key clue to what did occur in the early days of Planet Earth comes from physical and chemical constraints on what the Earth must have been like in order for it to have evolved into a planet covered by so much water (the oceans). Obviously, we must have been different from Mars or the other planets, but what made us so different?

Although we don't know the exact mechanism, the planets accreted from swirling dust clouds of what are called planetesimals (Figure 1-3). All the planets revolve not only in one direction (counterclockwise) but also in one plane about the sun (except for Pluto, which probably isn’t a planet anyway). Also, there is a consistent spacing of the planets; they are not randomly distanced from one another. They seem to have acted as "vacuum cleaners," sweeping the debris from each of their orbits into first small proto-planets, then into planetesimals, and finally into one major celestial body for each orbit. We do not yet know the physics of how this vacuuming occurred, and we also do not know why it failed in one particular orbit next to Mars where an asteroid belt exists instead of another planet.

Figure 1-3. The deepest views of the cosmos from the Hubble Space Telescope yield clues that the very first stars may have burst into the universe as brilliantly and spectacularly as a fireworks finale. Except in this case, the finale came first, long before Earth, the Sun and the Milky Way Galaxy formed. Studies of Hubble's deepest views of the heavens lead to the conclusion that the universe made a significant portion of its stars in a torrential firestorm of star birth, which abruptly lit up the pitch-dark heavens just a few hundred million years after the "big bang," the tremendous nuclear explosion that created the cosmos. Though stars continue to be born today in galaxies, the star birth rate is a trickle compared to the predicted gusher of stars in those opulent early years. Photo Credit NASA.

There is another peculiarity of the solar system which tells us something of how the Earth began. The sun has 99 percent of the mass of the solar system, whereas most of the angular momentum of the system is in the planets. Angular momentum is mass times velocity, so either the sun is rotating too slowly or the planets are rotating too fast for their mass. For this anomalous momentum to have resulted, the solar system must have begun COLD! How could we possibly know that about temperatures from mass and velocity? And how could the mass and velocity have gotten out of balance? The only way the physics makes any sense is for the solar system to have begun as a ring of cold gas and dust swirling around a central nucleus. As gravity pulled more and more dust (mass) to the center, the nucleus heated up, much as a tire pump will get hot as air is compressed in its chamber. Bang! The center became so hot that a nuclear explosion ignited the sun, AND the blast blew enough heavy dust out to the planets to disrupt the mass-velocity balance of the solar system. The awesome logic of the laws of physics give us the ability to see into the very origins of our solar system.

The dust driven away from the sun first accreted into planetesimals, then into planets, and the solar system was formed. What kept any of these new planets from getting too hot and exploding into suns themselves? That is how binary-sun systems happen. The outcome depends only upon how much dust there was in our particular galactic neighborhood when our solar system began to form. Jupiter very nearly became a companion star to our Sun, but there was not quite enough dust to compress Jupiter to nuclear ignition temperature. This was just one of a string of fortuitous events that resulted not only in our planet being the only one with oceans, but also the only planet with elaborate forms of life - in our solar system, that is!

Not only are there billions of stars, but scientists have recently been able to confirm that there are also billions of planets outside our solar system that are rotating around those stars, as well. Less than a decade ago, scientists had no knowledge of any planets outside our solar system because we had no way to detect them. Improved space telescope technologies have now enabled scientists to identify nearly 100 exo-planets in our Milky Way Galaxy. These exo-planets offer the tantalizing possibility of life flourishing elsewhere.

The processes that created our Sun and Solar System—and ultimately allowed life to develop and flourish on Earth—are the same processes that have created every other star and planet in the Universe and continue to do so today. Galaxies, including our own Milky Way, are "factories," recycling matter to manufacture stars and planets within a swirling cosmic soup of gas and dust.

Closer to home, *Europa,* one of Jupiter's four giant moons, is encased in an icy crust that shows signs of covering a deep ocean of liquid water. Hot springs on the floor of that ocean may well support life –if you believe Arthur C. Clarke in the novel 2010.

And it all started with the biggest explosion of all time. The Big Bang can be dated from how fast the galaxies, and there are billions of stars, are receeding from each other and the pin prick that was the big bang's point of origin. The light from these stars has a "red shift", and the farther away they are, the bigger the red shift. This not only tells us they are screaming away from us and each other, but it allows the date of origin to be computed. 14 billion years ago is the beginning of everything we know. The date-of-origin has been corroborated as well by the Hubble Space Telescope (Figure 1-4). This rapid expansion of the universe is why the sky is dark at night. Your head is guaranteed to start hurting if you think too long about what existed before the Big Bang. We have no evidence of any kind of anything that existed before then.

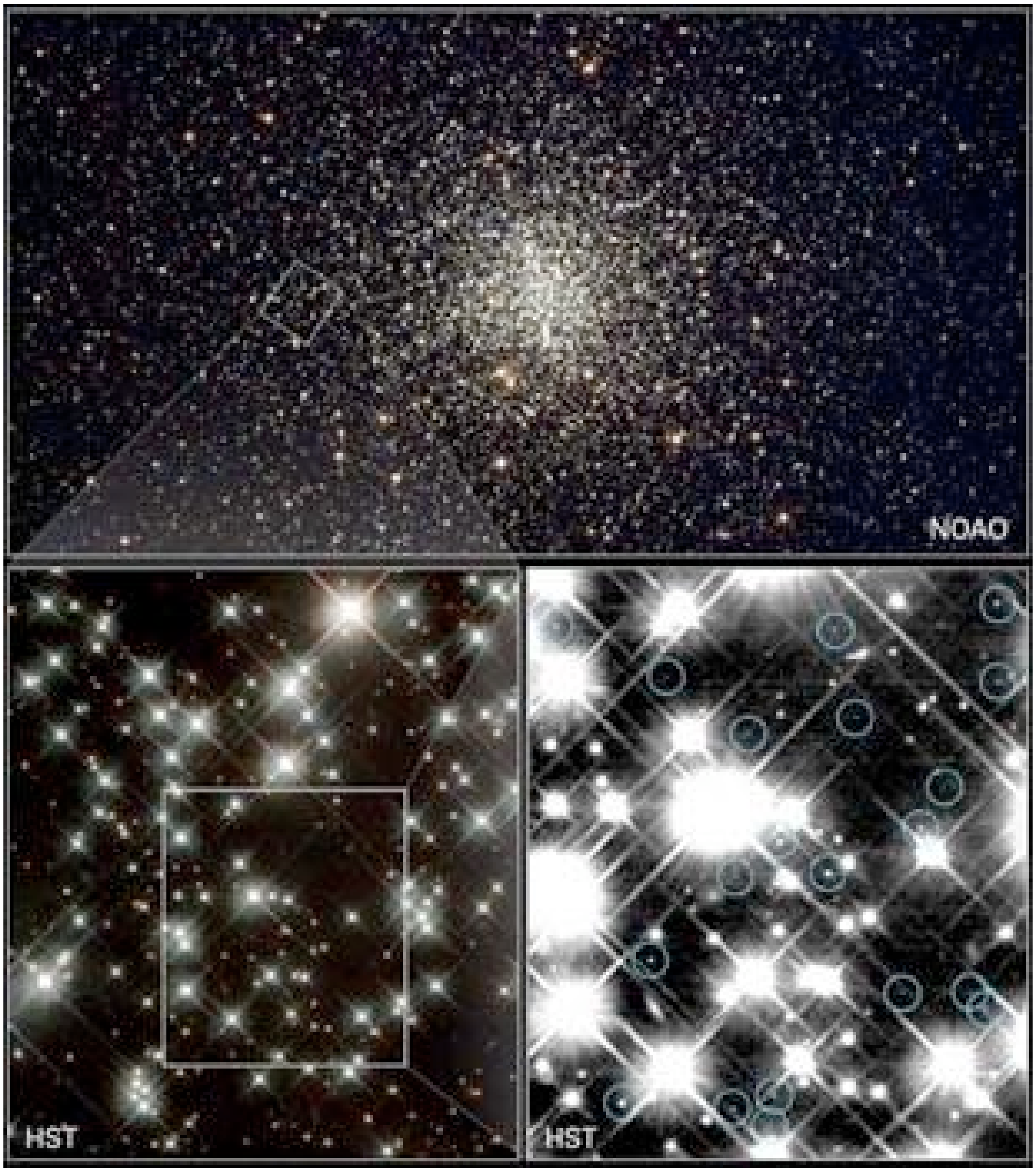


Figure 1-4. Pushing the limits of its powerful vision, NASA's Hubble Space Telescope has uncovered the oldest burned-out stars in our Milky Way Galaxy. These extremely old, dim stars provide a completely independent reading of the universe's age without relying on measurements of the universe's expansion. The ancient white dwarf stars, as seen by Hubble, turn out to be 12 to 13 billion years old. Because earlier Hubble observations show that the first stars formed less than 1 billion years after the universe's birth in the big bang, finding the oldest stars puts astronomers well within arm's reach of calculating the absolute age of the universe. Photo credit: NASA.

Back to the Early Planet Earth

The early Earth must have been much like Mars or Venus are now. The surface was surely pockmarked with craters. But the planet must have ALSO accreted cold. Again we jump from seemingly unrelated observations to temperatures. How do we know that the planet did not accrete as a volcanically molten body? The answer comes from the truly unique constraints placed upon the formation of the Earth by the presence of our vast oceans.

Where did all the water come from? Water's combination of two hydrogens and one oxygen, the 1st and 16th most abundant elements in the universe, is not all that unexpected. The odds are high that water must have been trapped in the earth and lost in all the other planets. But how? The only way to trap water inside the Earth for an extended time is as minerals. Water forms an important constituent of a whole set of minerals known as hydrates, like clays. The one common characteristic of all hydrated minerals, however, is that if they get too hot, they dehydrate, and release their water.

Did you every wonder how a pottery kiln works? A soft and wet clay blob is molded into a pot, then put into a kiln to make it hard. What happens physically is that as the kiln is heated to above 350 degrees Centigrade, heat dehydrates the clays, driving out the chemically bound water, which then becomes steam and evaporates. The resulting pot is hard and dry.

The Earth must have saved its kiln days until relatively late in its history. Why? Because an atmosphere is required in order to capture water that is out-gassing as steam. It must be prevented from going all the way to space so that it can condense and form an ocean. The reason for this is that the water must be insulated enough to cool and form a liquid. An atmosphere of gases is a natural insulator from radical temperature fluctuations and therefore would have been required to form oceans. Why is there no water on Mars then? The famous canals may indeed have resulted from early water on Mars, but all the water is gone now. There may be a little left in the polar ice caps. Coincidentally, Mars has very little atmosphere. Also, Mars is half the size of the Earth, and as we shall soon see, size controls how hot the planet's kiln becomes. Perhaps Mars still has most of its water locked inside because its kiln was never fully fired.

Evidence of the evolution of Earth's atmosphere is given by a 2.7-billion-year-old sequence of rocks from Ontario, Canada. The first single-celled organisms died and precipitated out of the oceans, only to be fossilized and preserved as iron sulfide bands in the rock formation. The iron sulfide bands stopped forming once the atmosphere and ocean were saturated with oxygen, roughly 1.7 billion years ago. Other examples of this nascent period include stromatolites, fossil rocks from West Australia which were formed as deep sea bacterial mats some 900 million years ago.

One additional piece of the early history puzzle comes from the composition of the Earth's present atmosphere compared to that of the Sun. But how do we know the composition of the Sun's atmosphere? As we discussed earlier, the spectrum of the light given off by the Sun is a function of the gases burning to produce that light. And the Sun has one million times more neon, krypton, argon, and all the other inert gases as the Earth. These gases are called inert because they do not bind chemically with any other element.

So if the Earth has much less of these gases than the Sun, it must have lost great quantities in its ancient past. It lost one entire atmosphere! Our atmosphere, like the rock surface, is the second that existed on the planet. Consequently, it is short of inert gases. The plot continues to lead to a catastrophe of unimaginable dimensions. Not only have we lost all record of any rock existing at the surface of the planet for its first billion years of existence, but one entire atmosphere has been lost as well. And we are about to learn how the surface of the planet was then covered by trillions and trillions of gallons of water .

In order for so much water to have been available for the second atmosphere, it could not have been out-gassed during the first billion years of the Earth's history. We only had so much water in the first place -- a function of how much hydrogen and oxygen there is in space dust. A planet with a cold interior was required. Otherwise, the kiln would have cooked out all the water early on in its history .Yet the very fact that an ocean ultimately formed indicates that the Earth's kiln was eventually fired. This story is slowly leading us to the other most prominent physical part of our Earth besides the oceans -- it's iron core.

What do we know of the present temperature inside the Earth? You can be assured that it was hotter then than it is now. When one goes deep into the Earth, it gets very hot very quickly. Just ask a South African gold miner. The average amount of heat coming out of the Earth's surface per second is one micro-calorie per square centimeter (1 microcal/cm2/sec). This flow of heat can be converted into temperatures inside the Earth by multiplying by the distance down to the point of interest, the center of the Earth and dividing bv the thermal conductivitv of the rock in between (a measure of the ease with which the heat is transported through a solid). To illustrate the importance of thermal conductivity, a silver teaspoon gets very hot in a cup of coffee, but the cup does not if it is made of styrofoam . The thermal conductivity of silver is much higher than that of styrofoam. So the temperature at the center of a silver earth would be much lower than that at the center of an styrofoam earth for the same surface heat flow, since we divide a constant by a larger number in the silver example.

What is happening physically is that the silver earth conducts the fixed quantity of heat faster and more readily to the surface and thus cools it off faster, resulting in cooler temperatures at any given time. But if we convert surface heat flow to temperatures at the center of the Earth using thermal conductivity values appropriate for rock, we get a temperature at the center of 100,000 degrees centigrade -hotter than the sun! How can that be?

This puzzle has been a famous paradox in geology for centuries. The great Lord Kelvin even fell prey to it 150 years ago. He was interested in the age of the Earth, so he calculated it assuming that the entire body began at 1200°C, the temperature of magma, or molten rock. He wanted a maximum possible age so he assumed the most extreme case he could imagine – that the earth started as a molten blob. He knew the present-day surface heat flow and the thermal conductivity of rock, so he calculated the time it would take to cool from molten conditions to the present-day surface heat flow of only one micro-calorie per square centimeter per second.

His answer of 45 million years pleased no one. Not only did it.directly contradict the views of paleontologists who were arguing much older ages because of the fossil record with its vast population of dinosaurs and ancient seas, but there were creationists then as now saying the Bible dates the Earth at only a few thousand years old.

Lord Kelvin made the same mistake as that of the French Count of Buffon in the 1700's. The Count was Napolean's chief cannon-ball maker and an industrial giant of his time. Having an avid curiosity, he made a series of progressively larger-diameter molten spheres in his huge foundry in Paris, and measured the length of time each took to cool to the touch. He reasoned that the Earth began as a molten ball, so he plotted the time to cool versus the diameter of each molten sphere, and then extrapolated that rate from his largest ball he could make, which was two feet across, to the diameter of the earth. His estimate of the Earth's age was tens of thousand years old - not much more incorrect than Lord Kelvin's more scientifically derived age. But again he drew the wrath of the church, unjustly ending up as the origin of the slang expression for a fool -- buffoon.

Their mutual mistake was solved only by subsequent scientific discovery. During their times, heat was known to travel only conductively (from grain to grain by transferring vibrations, like the heat moving through the walls of a building) or convectively (by moving and carrying the heat with it, like the heat carried by spilling coffee into your lap – not recommended). It took Marie Curie's discovery of radioactivity to solve the paradox. The Earth is much older than Lord Kelvin calculated because additional heat is constantly being generated within the earth by radioactivity to replace that lost to the surface. The center of the Earth does not have to be 100,000°C because heat is constantly being generated throughout the earth's interior, allowing the center to be much cooler.

Radiation provides the mechanism both to have begun the Earth cold and to have eventually fired the kiln. But the amount of heat generated in the first billion years far surpassed that of a kiln, instead reaching that of an iron smelter (Figure 1-5). Not only did the Earth heat up to the dehydration temperature, but it also became hot enough to melt iron in its interior. And liquid iron is both mobile and heavier than rock. It first melted in the mantle, sank to the center of the Earth, displacing light rock upward. This frothing of the entire planet was the cataclysm to end all cataclysms.

This catastrophe is called differentiation, in which the heavy elements of the Earth sank to the center and the light elements frothed toward the surface. Light elements rose to the surface to form our oceans and second atmospere. This overturn also destroyed all evidence of the original surface of the planet.

The heat source was from the elements collectively called KUTh, or potassium (chemical symbol is K), uranium (U), and thorium (Th). These three radioactive elements provide 99 percent of the internal heat generation within the Earth, and each has a half-life (the time required for half its total mass to have decayed radioactively) of about a billion years. So about one twentieth of the original KUTh present at the formation of the Earth is still generating heat inside the Earth today.

The rate of heat generation is tied entirely to the size of the planet because there are only so many calories per gram of KUTh present in rock. It's the number of grams that counts. The total heating within the first billion years of the Earth's history was purely a function of the amount of KUTh originally present. There is a fixed amount of KUTh in any cloud of cosmic dust – remember the exponential periodic table of elements. So the amount of heating is completely a function of size or diameter of the dust cloud only.

Here is the first fortunate coincidence affecting our present Earth's environment. If the earth had been too large, there would have been so much KUTh that the kiln would have fired too early and water would have been driven from the hydrous minerals too early in the Earth's history for water to have been captured during the differentiation event. The water would have escaped with the inert gases from the first atmosphere.

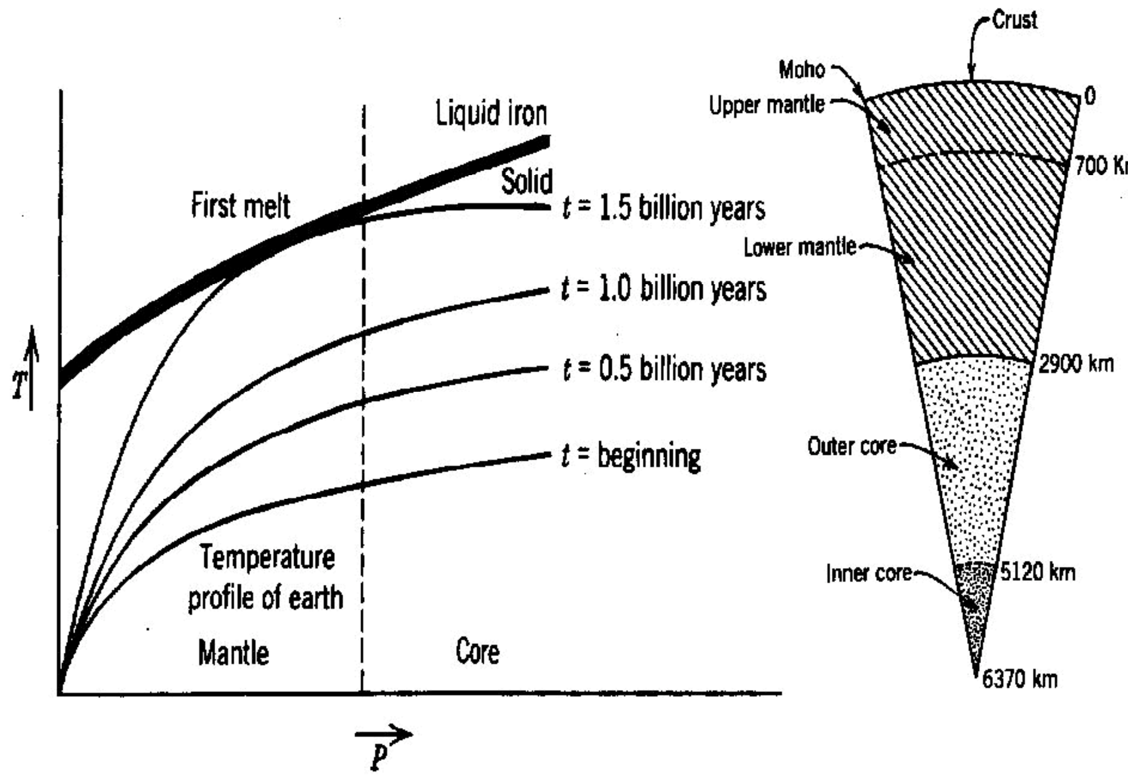


Figure 1-5. Melting of iron occurred 1.5 billion years into the Earth's existence, causing liquid iron to settle into a core and wiping out all surface record of what was present until then. The inner core is solid iron because the pressure is too great for liquid iron to exist.

If the earth had been too small, the planet still would not have heated enough to fire the kiln and the water would still be trapped in the interior. Did this happen on Mars which has no core How do we know that Mars does not have a core? We certainly can't go inside the planet to prove it. If you were to attach a tennis ball to a string and sling it rapidly about your head, the ball would flatten at the poles from its original spherical shape into an ellipsoid. If instead you attached a string to a baseball and slung it around, it would deform or flatten much less. Why? Because it has its heaviest mass at its center, whereas a tennis ball is hollow with all its mass near its surface. By simply observing Mars with a telescope we can see that it is much more elliptical than the Earth. Mars therefore has little or no core. It is likely that water existing in Mars is still present deep inside, largely because differentiation has not occurred, yet. Why not? Not enough KUTh, because the planet is too small. Mars is about half the size of the Earth.

This simple illustration of how basic physics is applied to deductions of the origin and thermal history of Planet Earth is a good example of how science works. We cannot go more than a few miles into the Earth even with a drill bit, yet we can make observations and deductions based upon the constraints imposed by the laws of physics and chemistry. You will soon be surprised by how much a geologist can learn from some seemingly scanty information.