The Formation of the Earth

Those bodies caught securely in the gravitational grasp of our star make up the solar system. They constitute earth's neighborhood, the only immediately accessible portion of the universe physically available to us at this time. We are in an age of exploration of our solar system, a time when previously inconceivable facts about our sister planets and their moons are found with each new space probe. Moreover, it is now clear that the process that led to the creation of our solar system has been at work in the formation of other stars, and that they too have planetary systems of their own.

Just as the name implies, the largest and most massive body in the solar system is the sun. The sun dominates our existence. Human beings have evolved sleep and waking patterns in accordance with the sun's appearance and disappearance. Our calendars chronicle the seasonal relationship between the earth and the sun. In fact, our very survival depends on constant nourishment by the sun. Our mythologies, our folklore, and our pseudo-sciences all have reflected our innate intuition that our lives are inextricably bound up with the solar system.

The bodies that make up our solar system are the sun, the planets, dwarf planets, comets, moons, asteroids, and meteoroids. Approximately 99.9% of the mass of the solar system resides in the sun. Most of the remainder is in the form of planets. Because of its large mass, the sun dominates the motion of all the other objects in the solar system.

The planets and most of the remaining matter are distributed in a plane. As seen from a vantage point far north of the solar system, the sun rotates counterclockwise about its axis. The planets and asteroids lie nearly in the sun's equatorial plane and revolve counterclockwise around the sun in elliptical, but nearly circular, orbits. With the exceptions of Venus and Uranus, the planets spin counterclockwise, and moons orbit their planets in the same way. Comets are distinct in the solar system with respect to their orbits around the sun. Rather than all lying in the same flat plane, they are spherically distributed. They also have highly elliptical orbits and are just as likely to have clockwise as counterclockwise orbits. Comets are to the solar system as halo stars are to the Milky Way Galaxy.

In addition to these regularities of motion, there are certain regularities of chemical distribution within the solar system. Solar system material generally falls into one of three broad categories: gases, volatiles, or rocky-metallic materials. The gases are mostly hydrogen and helium. Volatiles include water, methane, ammonia, and carbon dioxide. The solid forms of volatiles are called ices. Rocky-metallic materials are primarily compounds of iron and silicon.

These materials are not randomly distributed within the solar system. The innermost planets and moons are almost entirely rocky-metallic in composition. The asteroids are rocky-metallic, with the outermost ones containing significant fractions of icy material. In addition to rocky-metallic and icy material, the planets Jupiter, Saturn, Uranus, and Neptune contain huge quantities of gas. In fact, Jupiter and Saturn, like the sun, are mostly hydrogen and helium. The dwarf planets and moons of the outer solar system are rocky-metallic and icy in composition.

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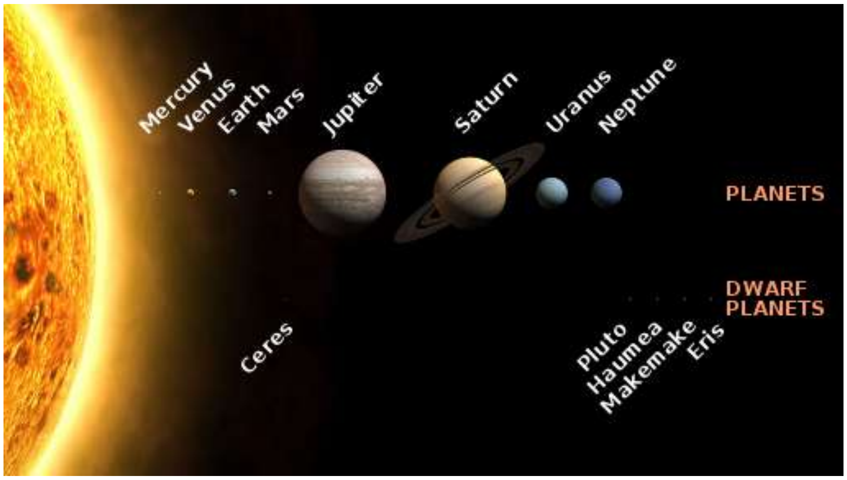
The Solar System



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The Origin of the Solar System

The first scientific theory of the origin of the solar system was that of the French philosopher René Descartes. In 1644 he proposed that space was initially filled with swirling gas in which large whirlpools evolved into stars, while the planets and their satellites formed from much smaller vortices. The German philosopher Immanuel Kant applied Newton's laws to Descartes' model in 1755 and concluded that the swirling gas would assume a disk shape. The French mathematician Pierre-Simon Laplace independently proposed a similar theory in 1796. Known as the nebular hypothesis, this theory stated that the gravitational collapse of an interstellar cloud accounted for the flattened appearance of the solar system, the nearly circular orbits of the planets, and the fact that the planets moved along their orbits and rotated about their axes in the same direction that the sun rotated.

By the end of the nineteenth century, however, it had become clear that there were two serious problems with the nebular hypothesis. First, the planets and moons contained insufficient mass to have formed from gravitational collapse. Second, the gravitational collapse of a cloud of gas and dust should result in a sun that rotated much more rapidly than our sun does. By the latter half of the twentieth century, both these problems had been resolved.

We now understand that the formation of the planets and moons began not with gravitational collapse but with the sticking together of small, solid grains in the solar nebula. This process is called accretion and is exemplified by a snowball rolling down a snow bank and gaining mass as it does. Accretion also explains why dust sometimes concentrates into dust bunnies. Only after the bodies have gained sufficient mass does gravity play a part in the final formation. The problem with the sun's rotation was resolved when it was discovered that the sun constantly emits high-speed charged particles. These are known collectively as the solar wind. As the solar wind leaves the sun, it passes through the sun's magnetic field, and the particles are deflected by the magnetic force. For every action there is an equal and opposite reaction (Newton's third law of motion), and therefore, the force the sun exerts on the solar wind is accompanied by the force the solar wind exerts on the sun. This reaction force slows down the sun's rotation. In this way, over the history of the solar system, magnetic braking has slowed the sun's rotational period from its original value of less than ten hours to its present value of about 25 days.

In the process of star formation, the gravitational contraction of the interstellar cloud increases the temperature of the cloud and causes it to spin faster and faster. Both of these results played an important role in the formation of our solar system. As the contracting solar nebula spins faster and faster it begins to flatten out. This rotation causes some of the material to go into orbit around the central object (which in our case would eventually become the sun). The temperature increase is greatest in the center of the cloud and decreases with distance from the center. The center heats to temperatures sufficient for hydrogen fusion while the outer regions are not much hotter than the original interstellar cloud.

The temperature of the central object and the region immediately surrounding it are sufficient to evaporate all of the solid grains from the original interstellar cloud. Out somewhat farther, the temperature is sufficient to evaporate the icy grains, but not the rocky-metallic grains. Still farther, past the frost line, both rocky-metallic and icy grains can exist.

Accretion will therefore produce rocky-metallic objects in the inner part of the solar system and rocky-metallic-icy objects in the outer part. Accretion in the inner part of the solar system produced Mercury, Venus, Earth, Mars, and, soon afterwards, our moon. Four of the rocky-metallic-icy objects in the solar system's outer part, Jupiter, Saturn, Uranus, and Neptune, had sufficient mass to gravitationally capture the gas in their vicinity and are therefore composed mostly of hydrogen and helium. The moons of these four gas planets and the dwarf planets lying beyond them did not have sufficient mass to capture the hydrogen and helium and thus are rocky-metallic-icy objects.

The nebular hypothesis clearly predicts that stars other than our sun should have planets in orbit about them. This prediction was made well before any planet outside our solar system had been observed. The first extra-solar planet was discovered in 1988. Since then, well over 500 have been discovered, with new ones being continuously added. Current data estimates that there are at least 50 billion planets in our galaxy. A small, but non-negligible, fraction of these have masses similar to earth and occupy the habitable zone (temperatures that allow for liquid water) of their planetary system. For this reason, many scientists believe that life is common in our galaxy.

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The Age of the Solar System

Humans have speculated on the age of the earth for thousands of years. The Brahmins of India believed that the earth was eternal, as did Aristotle. In early Judeo-Christian cultures, estimates of the age of the solar system were based on the Bible. The traditional Jewish calendar starts from 3760 BCE, which is taken to be a date for the creation of the earth. In 1650, Anglican bishop James Ussher used the Jewish Bible to calculate that the earth's creation took place on the evening of Sunday, October 23, 4004 BCE of the Julian calendar.

By the eighteenth century, naturalists had begun to seriously doubt Ussher's calculation. One of the first estimates based on natural processes was made by George-Louis Leclerc, Comte de Buffon, in 1774. He estimated that the time it would take for a molten earth to cool would be about 75,000 years. By the end of the eighteenth century, James Hutton, the founder of modern geology, introduced the concept of "deep time," pushing the estimate to millions of years. His student and fellow geologist, Charles Lyell, a friend and confidant of Charles Darwin, popularized the concept that geological layers were in perpetual change, eroding and reforming continuously at a roughly constant rate. (Darwin read Lyell's landmark text, *Principles of Geology*, while sailing on the *H.M.S. Beagle*, and was influenced much by it.) Lyell's "uniformitarian" view challenged the traditional view that the geological history of the earth was essentially static, with changes brought about by intermittent catastrophes or supernatural interventions such as Noah's flood. Lyell estimated the age of the earth to be in hundreds of millions of years.

Radioactivity was discovered in 1895 and, because of the constant rate associated with the decay of a particular radioactive substance, was soon recognized as a technique for dating rocks. For example, uranium decays through a sequence of reactions to lead. Because the chemical properties of uranium and lead are different, these two elements would not be found mixed together in a rock that has just formed, say from solidified material from a volcanic eruption. As the rock ages, uranium atoms are gradually transformed to lead atoms, with the lead homogeneously mixed with the uranium. Knowing the rate at which this occurs, the relative proportions of uranium and lead in a rock is a direct measure of the time that has passed since the rock formed. On our geologically active earth, rocks are constantly being recycled, and while the ages of rocks vary, by 1907 the age of some earth rocks had been measured to be in the billions of years.

Ancient rocks exceeding 3.5 billion years in age are found on all of earth's continents. The oldest rocks on earth that have been found so far are in northwestern Canada and are dated to be just over four billion years old. Some rocks in western Greenland are 3.7 to 3.8 billion years old. These ancient rocks have been dated by a number of radiometric dating methods, and the consistency of the results give scientists confidence that the ages are correct to within a few percentage points of error.

The moon is less active than the earth and some of its rocks are older than any of those found on earth. A small number of rocks have been brought to earth from lunar missions. The oldest of these rocks were formed between 4.4 and 4.5 billion years ago, providing a minimum age for the formation of the solar system.

Meteorites are fragments of asteroids that fall to earth. The oldest of these formed between 4.53 and 4.58 billion years ago. Because their structure indicates that they have never melted, we take their age to be the time at which the first of the solar system's solid objects formed. Thus, our solar system is about 4.6 billion years old.

Another way to determine the age of the solar system is to use stellar computer models to determine how long it would take a star with the mass and chemical composition of our sun to reach its current value of luminosity and surface temperature. Although this method is not as accurate as radiometric dating, it too gives an age of somewhat less than 5 billion years for the age of the sun, consistent with the value determined from radiometric dating.

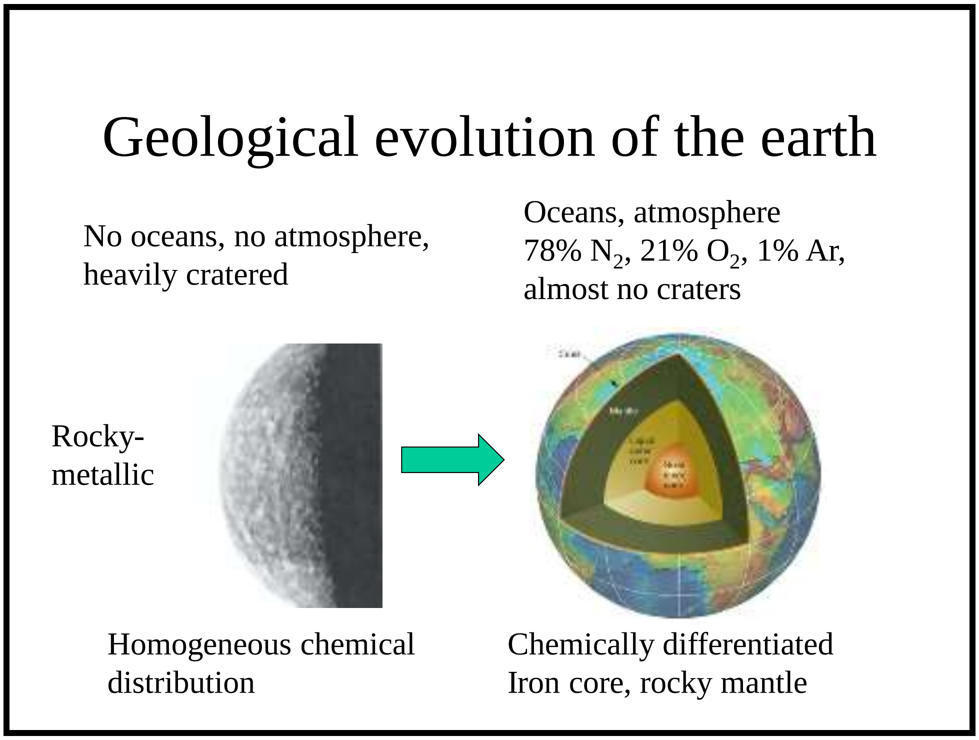
The Geological Evolution of the Earth

Earth formed by the accretion of rocky-metallic grains in the solar nebula. In its final stages of formation, aided by gravity, most of the remaining debris in its zone was swept up, depositing a tremendous amount of energy on the earth's surface. At the same time, radioactive elements were decaying throughout the planet, releasing energy that, like the energy from accretion, was converted into heat. The heat could not be radiated away fast enough and temperatures rose above the melting points of the various materials.

During this molten stage of the earth's development, the denser metallic materials settled toward the center and the lighter, rocky materials floated toward the top. This process is known as chemical differentiation. An iron-nickel core formed, surrounded by the earth's mantle, a layer of rocky material. The mantle extends almost to the earth's surface. The top layer of the earth is the crust, composed of rocks that are generally less dense than the mantle. The crust is several miles thick under the oceans and some twenty or so miles thick under the continents.

When the bombardment of debris falling toward the earth diminished, the surface of the earth solidified. Though diminished, bombardment continued leaving the surface covered with impact craters, much as parts of the moon and Mercury are today. At this time, the earth had no oceans and no significant atmosphere.

The early earth would have been unrecognizable as our future home. The processes by which this transformation occurred are known as geological evolution. Geological evolution is primarily driven by the heat produced by radioactive decay. The heat produced led not only to chemical differentiation, but it also contributed to the formation of our oceans and atmosphere and the elimination of impact craters.



Geological evolution of the earth

No oceans, no atmosphere, heavily cratered

Oceans, atmosphere
78% N_2, 21% O_2, 1% Ar,
almost no craters

Rocky-metallic

Homogeneous chemical distribution

Chemically differentiated
Iron core, rocky mantle

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Radioactivity decreases exponentially with time. As a result, the earth has begun to cool. Material that once was liquid has now re-solidified. The iron-nickel core is solid in its center with a surrounding liquid shell. It is this liquid iron and the rotation of the earth that produces the earth’s magnetic field. The radius of the iron-nickel core extends to about half the earth’s radius. The mantle, for the most part, is not molten. But it is not exactly solid either. It behaves somewhat like a plastic and can flow under pressure.

Liquid rock, or lava, occasionally breaks through the crust, releasing into the atmosphere gasses previously trapped in the rock. This process is called “outgassing.” The two most abundantly outgassed gasses are water (steam) and carbon dioxide. At our distance from the sun, the surface temperature of the earth is such that the steam condenses into a liquid and falls back to the earth as rain. This is in part how the oceans formed.

Carbon dioxide is soluble in water (soda water is an example) and dissolves into the oceans, later to precipitate out as carbonate rock such as limestone. With the two principle outgassed substances removed, nitrogen constituted almost all of the early earth’s atmosphere. Life evolved on earth and some forms were able to photosynthesize water and carbon dioxide into food (carbohydrates) with oxygen as a byproduct. Gradually the oxygen began to accumulate and today makes up about 21% of our atmosphere.

The third most abundant component of the present atmosphere is argon. The source of the argon is the radioactive decay of potassium mentioned back in a previous reading. The argon is also released through outgassing.

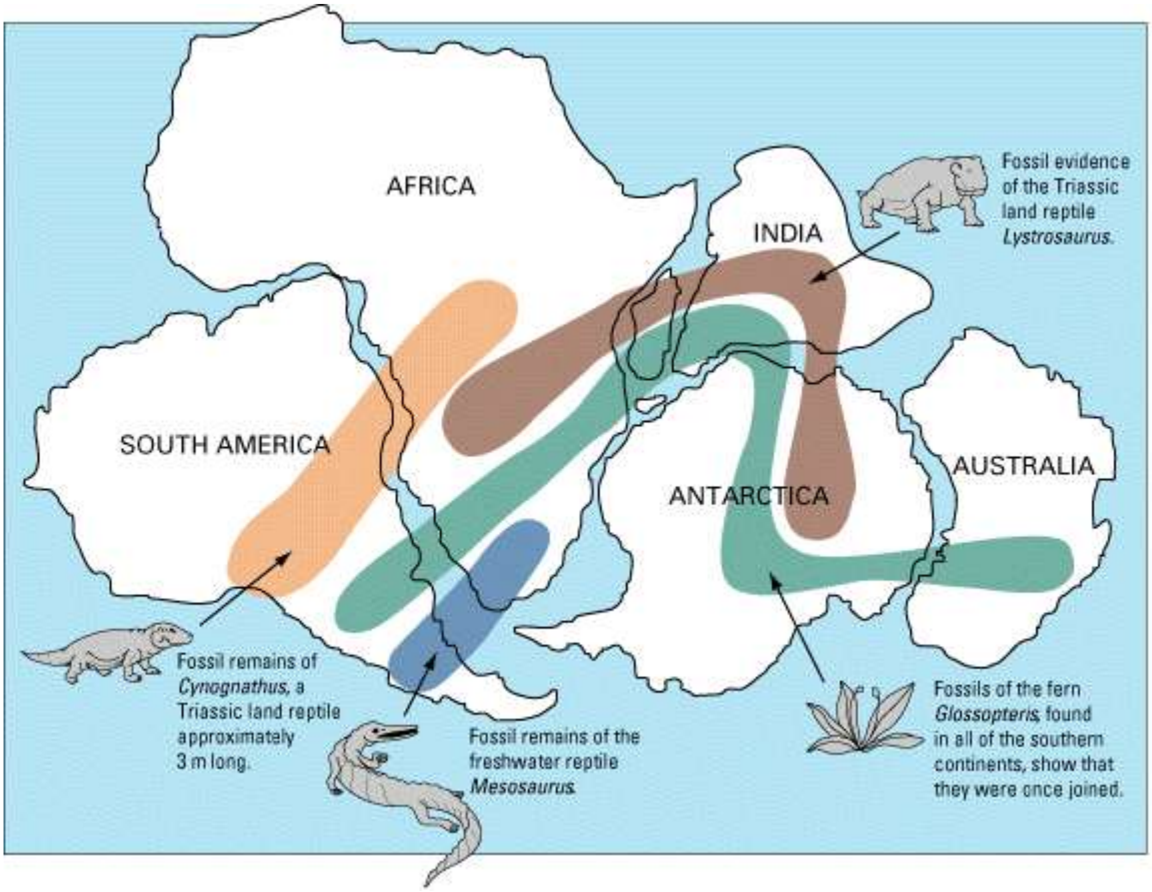
Our oceans were formed in part by outgassing, but this could not have been the only source. There is too much water on earth to be accounted for by outgassing. A likely alternative source of water is comets. Comets are “dirty” ice balls, comprising about 80% ice and 20% rocky-metallic materials. Early in the history of the solar system, they were found much more frequently in the solar system’s inner regions than they are today. It is now largely accepted among scientists that comet bombardment accounts for some fraction of the earth’s oceans, though the precise value of that fraction is unknown.

Solar system objects such as Mercury, our moon, and some of the moons in the outer region of the solar system are heavily cratered, the remnants of impacts during the final stages of their formation. Yet the earth is not. It might seem logical to assume that this is due to the fact that, unlike the other bodies, the earth has an atmosphere and oceans. Perhaps erosion has worn down the craters so that they are no longer visible today. But this is not the case. Rather, the craters have been removed by plate tectonics, another geological evolutionary mechanism produced by the heat of radioactive decay.

It you look at the globe, the continents of Africa and South America seem to fit together like two pieces of a jigsaw puzzle. The continental shelves of these continents are an even better fit. Early in the twentieth century, Alfred Wegner, a German meteorologist, became intrigued by this. He was struck by the similarities in the geological formations and the fossil records at the edges of these widely separated continents. Wegener noted that the locations of certain fossil plants and animals on present-day, widely separated continents would form definite patterns (shown by the bands of color in the following figure) if the continents were rejoined. He proposed the theory of continental drift, hypothesizing that at one time in the past the continents were connected and have since drifted apart.

Wegner’s idea was initially ridiculed by the scientific community. No one could conceive of a mechanism whereby entire continents could be caused to move across the face of the earth. However, as the ocean floors began to be studied in more detail in the late 1950s and early 1960s, scoffers became supporters. Geophysicists developed a theory known as plate tectonics, based on the plastic properties of the earth’s upper mantle, to explain continental drift. The evidence in favor of the theory soon became overwhelming.

On the ocean floor, about halfway between Europe and Africa to the east and North and South America to the west, is the Mid-Atlantic Ridge. Dating of rocks at the ridge shows them to be very young. As you move out from the ridge in either direction, the rocks are measured to be progressively older. It is clear that the continents of Europe and Africa are moving apart from North and South America. The speed at which they are moving apart has been measured by satellite observations to be about an inch or so a year. In other parts of the globe, the continents are moving together and, in still other parts, moving anti-parallel to one another, all at similar speeds. If we extrapolate the motions of the continents backwards in time, we find that about 200 million years ago all of the continents were together in a single continent today called "Pangaea."



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The continents rest on huge plates that are being driven across the earth's surface by convection currents in the upper mantle beneath them. Where the plates collide, one of the plates is driven under the other and forced down into the mantle and subsequently melted. The other plate is driven upward, forming mountain ranges. At the boundary where two plates move apart, molten material rises up, forming new rocks. In this way the crust of the earth is continuously being destroyed and reformed. Although there are some rocks as old as four billion years, most are much younger. The craters formed in the very early history of the earth no longer exist because the ground they formed on no longer exists. It has been recycled by plate tectonics.

The boundaries of the plates are regions of extreme geological activity: volcanoes and earthquakes. As can be seen on the below map, Japan is on the boundary of two plates. Another consequence of plate tectonics is that India, which was once an island, has collided with the underside of Asia, forming the Himalayan Mountains. The Mediterranean Sea is gradually being squeezed closed. Los Angles, parts of southern California, and the Baja peninsula are located on the Pacific plate and are slowly moving north with respect to the North American plate, on which the rest of

California is located. This boundary, known as the San Andreas Fault, is a well-known earthquake-prone region of the globe.

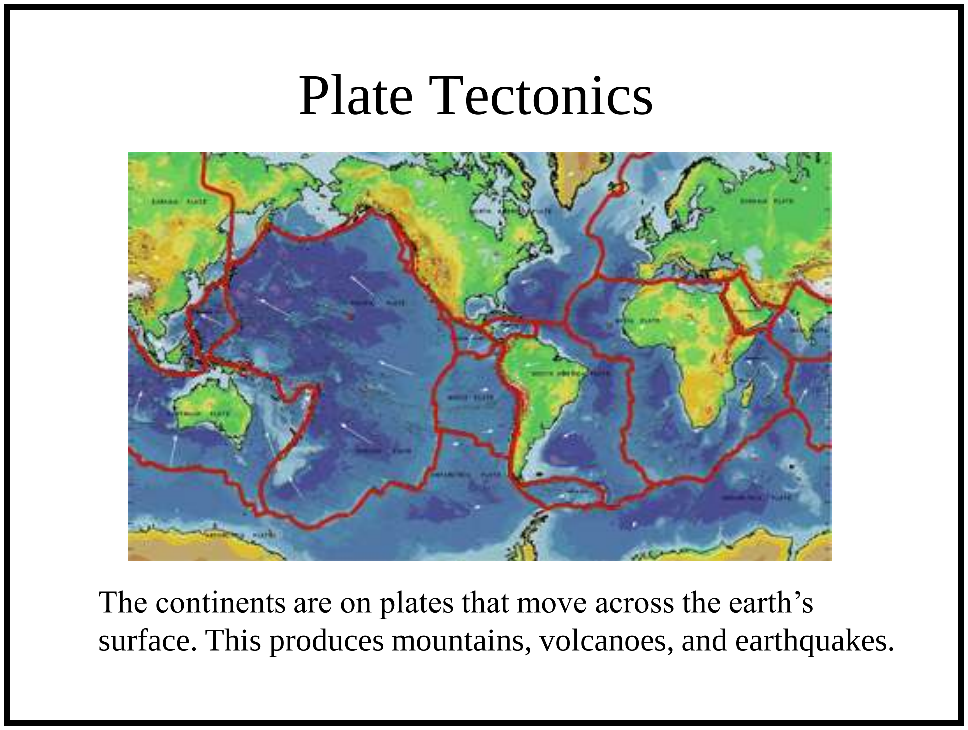

Plate Tectonics

The continents are on plates that move across the earth's surface. This produces mountains, volcanoes, and earthquakes.

The Origin of the Moon

Various theories of the origin of the moon have been suggested over the years. One, the fission theory, proposed that the moon separated from the earth when the earth was just forming. Another, the capture theory, maintained that the moon formed somewhere else in the solar system and was later captured by the earth. Still a third, the coaccretion theory, suggested that the moon and the earth formed by the usual accretion process but as two separate bodies in orbit around each other rather than as a single body. It was hoped that the rocks brought back from the moon by the Apollo mission astronauts would settle the question of the moon's origin. However, the exact chemical nature of these rocks is inconsistent with the predictions of any of the three theories described above. Therefore, all three are incorrect.

Once it was clear that none of our pre-existing theories were correct, astronomers began working on other theories that would be consistent with the chemical nature of the moon rocks. The most widely accepted theory today is the giant-impact theory. It proposes that very early in the history of the earth, after chemical differentiation had begun, the earth was struck a glancing blow by a Mars-sized object. Molten and vaporized material from the object and from the earth's mantle was blasted into space by the collision. Some of this material escaped, some fell back to earth, and some went into orbit around the earth. The material in orbit then formed the moon by accretion.

Relative to the earth, the moon is deficient in iron and in volatile materials such as water. The giant-impact theory can readily explain this. Because the moon was formed by materials from the outer part of the colliding body and from the earth's mantle, it would be expected to be iron-poor. Also, the high temperatures resulting from the collision would have vaporized the water, eliminating it from the subsequent accretion process. Computer simulations indicate that such a sequence of events would be consistent with known physical laws, provided the mass of the colliding object and the angle of impact lie within certain ranges. Although we may never know for sure if this is the correct account of the origin of the moon, at this time it is the only theory consistent with the data.