EARTH AS A PLANET

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Keywords: solar system, Moon, Mercury, Mars, Venus, geoid, plate tectonics, magnetic field

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Summary

Although Earth is an ordinary planet, it is the only place known to have supported the evolution of life. Formed about 4.5 billion years ago, it has developed a unique dynamic system that couples the behavior of slow rock convection in its interior with the growth of continents, oceans, and the atmosphere. With the advent of space travel during the second half of the twentieth century, it is now possible to view Earth's properties in comparison with those of neighboring planets. New data from the solar system have inspired giant advances in understanding global geology, and in particular, have raised awareness of the special position held by Earth.

1. Introduction

Earth (Figure 1) is one of nine planets orbiting around a 4.5 billion year old medium-sized star we call the Sun. It takes 365.26 days to make one rotation, while spinning on its axis once every 23.93 hours. Earth's orbit lies almost 149.59 million kilometers (or 1 astronomical unit, AU) from the Sun in between those of Venus and Mars. Together with Mercury, closest to the Sun, Venus, Earth, and Mars make up a group called the "terrestrial planets." The Earth is the largest, densest, and most massive of these four rocky planets and the only world where water exists not only as a surface liquid, but also as a solid and gas. The outer planets, Jupiter, Saturn, Uranus, and Neptune are

made predominantly from hydrogen (although Uranus and Neptune contain a large proportion of ice) and are known as the "gas giants." Distant Pluto, which spends most of its time in the far reaches of the solar system, is a rocky body that may once have been a moon from another planet or the remnants of a partially formed planet dating from the early solar system. Table 1 shows the major physical properties of Earth compared with the other terrestrial planets.

Figure 1. Earth taken by the Apollo 17 astronauts in 1972 showing Africa, Saudi Arabia, and Antarctica. Source: NASA.

2. Earth

2.1. The Origin of Earth

The solar system is thought to have formed around about 4.5 billion years ago from a huge cold cloud of gas and dust called the "solar nebula." With 90 percent of the mass at its center, the cloud shrank and was heated by gravitational compression, forming the Sun. The accretion of matter around the central mass began to form individual collections of material called "protoplanets," before the solar wind drove outward the lighter elements (such as hydrogen and helium), causing the distribution of masses and

densities we see in the solar system today. It is not known whether the early Earth started out hot or cold, as this depends on whether it accreted slowly (100 million to 1 billion years) or quickly (100 000 to 10 million years). Scientists now lean towards a fast accretion theory, which would mean that the Earth remained molten throughout much of its early history.

The early Earth would have been an unsorted mixture of materials, growing in size as it gathered up smaller objects in its path. During this time the heavier materials sank towards the center, creating the core, and the lighter materials rose to the surface, creating the mantle and the crust. This process of separation is called differentiation, and is thought to have played a key role in the formation of all the terrestrial planets.

Physical property	Earth	Mercury	Venus	Mars
Mass (Earth=1)	1.000	1.000	0.815	0.107
Mass (kg)	5.976×10^{24}	0.330×10^{24}	4.871×10^{24}	6.421×10^{23}
Equatorial radius (km)	6378	2437.6	6051.3	3398
Equatorial radius (Earth=1)	1.000	0.382	0.949	0.532
Mean density (g cm^{-3})	5.52	5.43	5.42	3.94
Equatorial gravity (m s^{-2})	9.78	3.70	8.87	3.72
Equatorial escape vel. (km s^{-1})	11.2	4.25	10.4	5.0
Orbital period (days)	365.25	87.97	224.7	686.98
Sidereal rotation period	23.934 hr	58.65 days	243.01 days	24.622 hr
Obliquity	23.45°	0.5°	-2.6°	23.98°
Mean surface temperature (°C)	15	125	468	-55
Mean surface pressure (bar)	1	$<10^{-12}$	90	0.007
Atmosphere	N_2, O_2, Ar, CO_2	H_2, He, O_2	CO_2	CO_2
Mean distance from the Sun (km)	149.60×10^6	57.91×10^6	108.20×10^6	227.94×10^6

Table 1. The physical properties of the Earth compared with the other terrestrial planets

2.2. Earth's Interior

Since we cannot sample it directly, we have to investigate the interior of our planet using indirect methods, of which the most efficient is through the study of earthquakes. When Earth suffers an earthquake, seismic waves travel away from its source, or focus (Figure 2). Primary, or P, waves squeeze and compress the rock or fluid they travel through along the direction of motion, in the same way that sound waves in air disturb the atmosphere. Secondary, or S, waves move by creating a sideways shear motion, producing a kind of snake-like wiggle, and can travel through rock but not fluids. P waves move faster than S waves, but both sets slow down when moving through hotter material and are reflected or refracted at the boundary between layers of different materials. A third type of wave, the surface wave, travels along Earth's surface and the

outermost layers of the crust. Surface waves come in two varieties: Love waves (named after their discoverer, Augustus Love), which are horizontal ripples, and Rayleigh waves (named after the English physicist John William Strutt, Lord Rayleigh) which are vertical. Since the speeds of seismic waves change as they move through Earth, earthquakes can therefore be used as probes to investigate conditions deep under the surface.
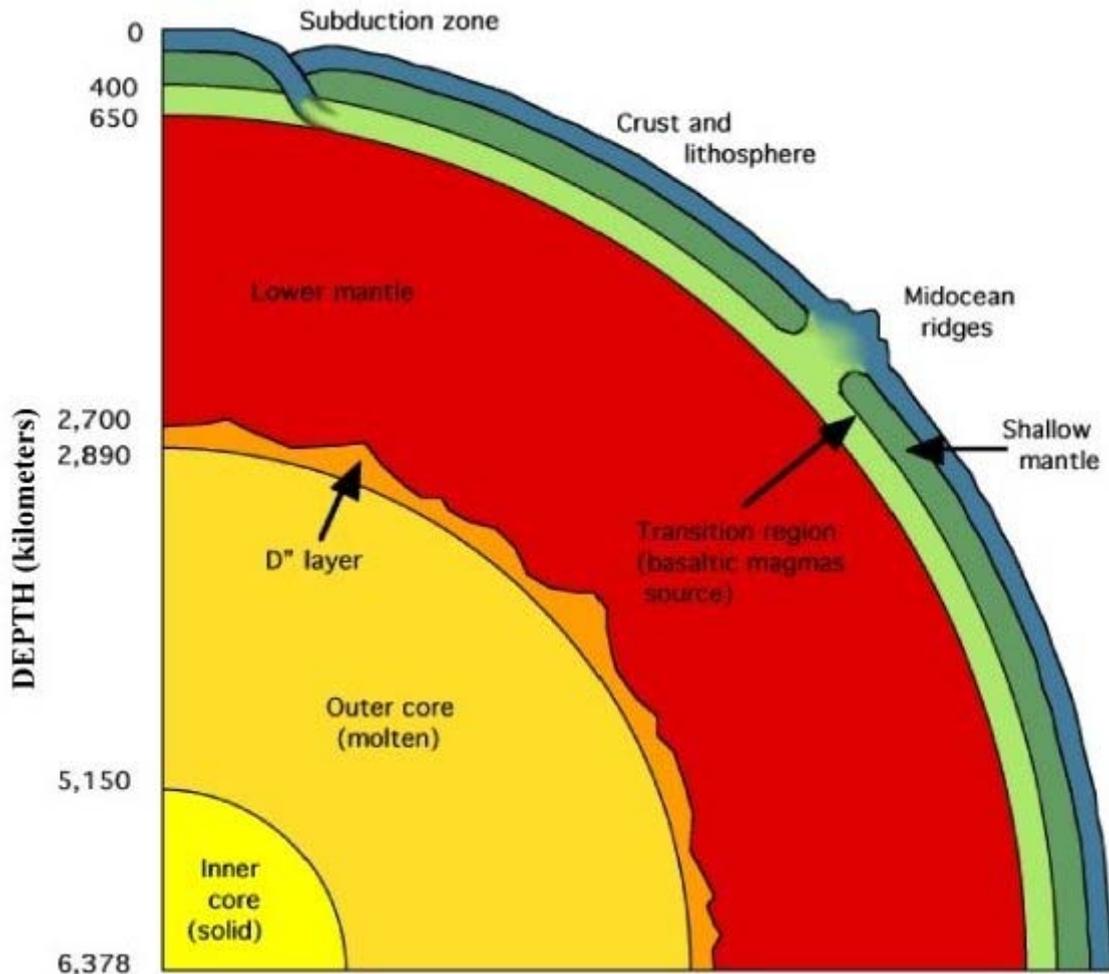

Figure 2. Seismic activity caused by earthquakes has been used to probe Earth's interior

The principal divisions of the Earth's interior into core, mantle, and crust have been known for nearly 100 years (see *The Composition of the Earth: Rocks and Minerals*). In 1906, the British geologist Richard Oldham found that at a certain depth P waves slowed dramatically and S waves stopped completely. This is the boundary to the Earth's liquid core and occurs at a depth of 2980 km. The core has now been found to have a solid inner section (frozen due to the intense pressure), which "floats" in the center of the outer core. The inner core rotates with respect to the mantle, a feature that helps to explain how the Earth's magnetic field creates and reverses its polarity. Soon after Oldham made his discovery, the Yugoslavian seismologist Andrija Mohorovičić found that seismic waves show a sharp increase in velocity around 60 km beneath the surface. This is the Mohorovičić discontinuity, or "Moho" for short, and marks the

boundary between the mantle and crust. Several other layers have now been found, subdividing the mantle into upper and lower parts at depths of about 410 and 670 km. There is also a 200 to 300 km thick layer (the so-called "D-layer"), just above the core, and this may represent dense material that sank through the mantle, but was unable to sink into the core.
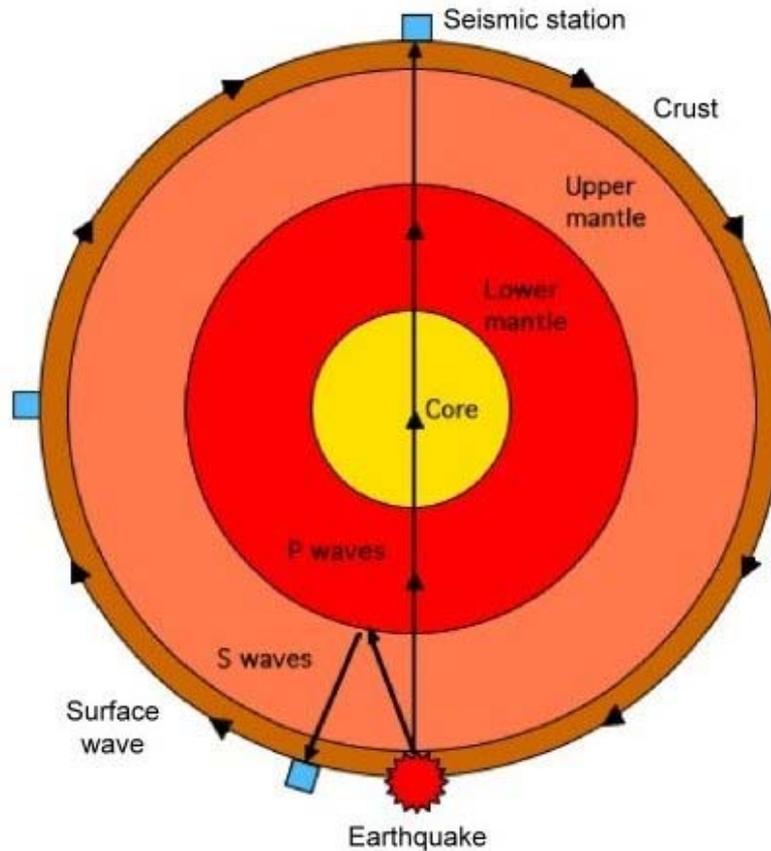

Figure 3. The major layers within the Earth's interior. Each has distinct physical and possibly chemical properties.

So what are these layers actually made of? The inner core, which is smaller than the Moon, but three times as dense, is possibly made of pure iron and nickel (Figure 3). The outer core is less dense than molten iron and probably contains some lighter elements such as sulfur, carbon, or oxygen. The majority of the Earth's bulk is in the mantle, which is made up of silicate materials like basalt, olivine, and pyroxene. We can sample these materials directly where they are exposed in eroded mountain belts or brought to the surface as volcanic eruptions. The crust is of course part of what we stand on, and is made up of a many different types of rocks. The average thickness of the continental crust is 20 to 50 km and of the oceanic crust is 5 to 10 km. The oceanic crust is fairly young, no older than 200 million years, and is constantly being renewed by networks of volcanoes on the ocean floor at a rate of about 17 km^3 per year. The continental crust is far older, up to 4.1 billion years and is enriched with many incompatible elements (that is, those that do not combine easily with others) such as uranium (U), potassium (K), and lead (Pb).

2.3. Plate Tectonics

If we look closely at the globe, one striking observation is that most of the continents appear to fit together like pieces in a jigsaw puzzle. For example, the western coast of Africa matches surprisingly well with the eastern coast of South America. This fact was noticed by Alfred Wegener who, in 1912, proposed that the continents had once been joined together into a single land mass called "Pangea" (meaning "all-Earth") and over time had drifted apart into their present positions. His theory however gained little recognition because of a lack of geologic evidence. In the 1960s greater understanding of the ocean floor and the discovery of mid-ocean ridges, island arcs, and oceanic trenches, led Harry Hess, and later Robert Dietz, to propose that the sea floor was being constantly renewed by mantle upwelling. Their theories suggested that the mantle undergoes a thermal convection, causing the crust to be pulled and pushed apart by a process now known as sea floor spreading. It also became apparent that the crust is divided into large tectonic plates, the boundaries of which were characterized by intense volcanism and seismic activity.
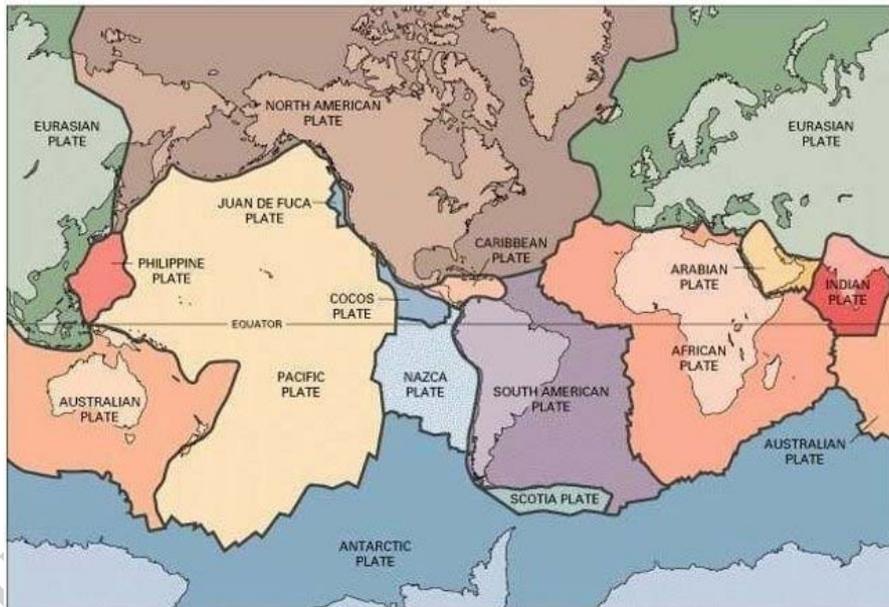

Figure 4. The Earth is split up into 12 major lithospheric plates, which "float" upon the part of the upper mantle called the asthenosphere. Source: USGS.

The crust is made up of about twelve major plates (Figure 4), which are rigid lithospheric blocks that "float" on part of the upper mantle called the "asthenosphere." Plates come in two varieties, the oceanic plates which are about 60 km thick, and the continental plates which are about 100 to 200 km thick. There are three types of plate boundaries (Figure 5): 1) boundaries of divergence or spreading, such as the Mid-Atlantic Ridge, where plates spread apart and new crust is made; 2) fracture zones, or transform faults, where two plates slide against one another in opposite directions, often causing violent earthquakes; and 3) boundaries of convergence, or subduction zones, where plates move toward each other with the leading edge of one plate (usually the lower density continental plate) overriding the other (the higher density oceanic plate)

and forcing it down into the mantle where it is reabsorbed. The convergence of two low-density continental plates causes the crust to remain afloat and thicken, creating huge mountains like the Himalayas.
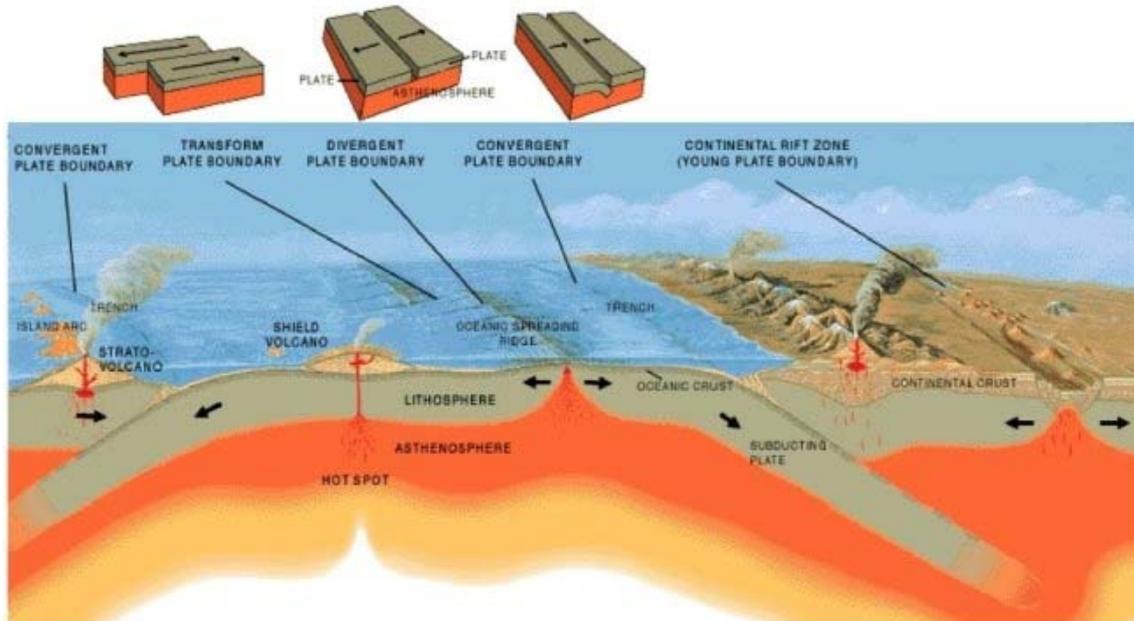

Figure 5. A cross-section of the main types of plate boundary. Source: USGS.

2.4. The Geoid

Earth's surface is covered by irregularities such as tall mountains and deep canyons. If we remove these anomalies, we get a smoothed-out shape of the Earth called the geoid, defined as the perfect ellipsoid the planet would assume if it were made completely of liquid.

A knowledge of the exact shape of the geoid is essential for accurate map making and navigation, and until the late 1950s only a few percent of Earth's land surface had been accurately mapped to scales of less than a kilometer or so. By studying changes in gravity at different locations around the globe, scientists found that Earth was not perfectly spherical but had a bulge at the Equator. Observations of the satellite Vanguard I, launched in 1958 by the United States, showed that its orbit varied because of differences in the shape of this bulge.

Later data from orbiting satellites showed that the South Pole is closer to the center of the Earth than the North Pole, and that there are regions around the globe of very slight flattening and bulging, giving the geoid a lumpy shape (Figure 6). Although these geoid "highs" and "lows" are due to differences in the density of the mantle, they show only a poor correspondence to areas of present-day tectonism (that is, the continents and subduction zones). They do, however, show a good correlation to regions where subduction zones and continents existed in the past. This suggests that internal processes, like the loss of heat from the mantle, take many millions of years to adjust compared with changes in the positions of crustal plates.
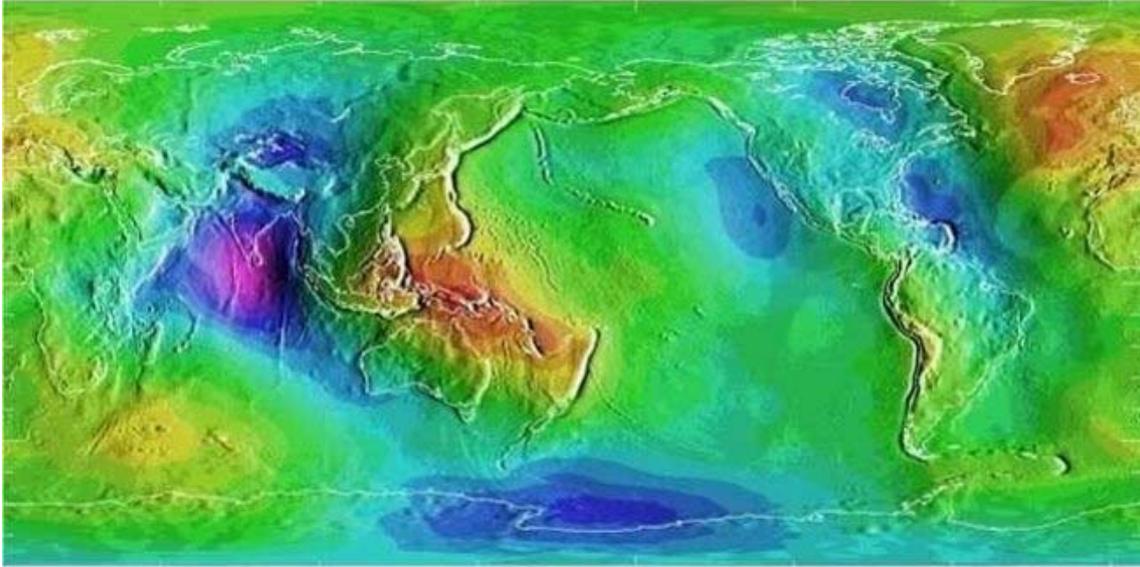
Figure 6. Satellite tracking data has revealed that our planet displays geoid highs (reds) and lows (blues). The highs correspond to subsurface concentrations of dense rocks and the lows to accumulations of less-dense rocks, probably within the mantle. Source: NASA.

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Biographical Sketch

Antony Brian is a planetary scientist in the Department of Geological Sciences at University College London. His research is focused on the geology of the terrestrial planets and he is currently involved with the NASA–USGS Venus Mapping Program, which aims to produce detailed geologic maps of the entire Venusian surface.