

Structure of the earth

Journey to the center of the earth

In 1864, the French writer Jules Verne published his novel *Journey to the Center of the Earth*. What is this story about? The geologist Lidenbrock and his nephew Axel find a coded itinerary to the center of the Earth and immediately set out for it. The expedition begins in an Icelandic crater, leads through narrow passages, palatial caves and an underground sea. At the end, the Stromboli volcano spits the travelers out again. It is a journey through the layers of rock and at the same time a mixture of scientific knowledge of the time, vivid fantasy and science fiction. Today we know that Verne's ideas about the journey to the center of the earth are not possible. Instead, our ideas of places unknown to us have catapulted from the center of the earth to outer space with the findings of cosmology, the exploration of space, and the discovery of new planets, stars, and galaxies. But Verne's novel was a reflection of its time, as the work of James Hutton and the publication of Charles Lyell's *Principles of geology* in the 1830s certainly had an influence on Jules Verne, as did Charles Darwin's work on the origin of species, published just a few years before Verne's novel. The knowledge of the inner structure of the earth was hardly available at that time.

In this post, I want to take you on a scientific journey to the center of the Earth. Maybe this journey is not as imaginative as Jules Verne novel, but the scientific findings are not less exciting.

Inner structure of the earth

Let's start with the structure of the earth. The inner structure of the earth, which is mainly studied by geophysics, consists, in an idealized way, of concentric spherical shells, each of whose material has a distinctly different density. The earth has a radius of about 6,350 km and is divided into a core, a mantle and the crust (Fig. 1):

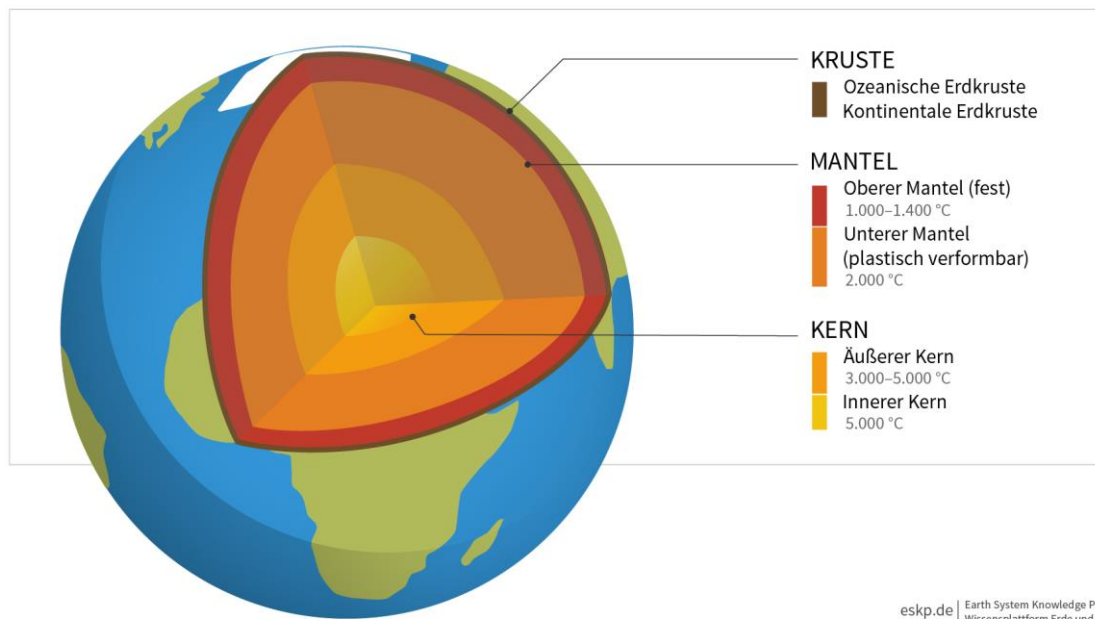


Abb. 1: structure of the earth

Due to different components, temperatures and differences in pressure, we can divide the three shells into six layers of the Earth: oceanic and continental crust, upper and lower mantle, and the outer and inner core. These layers of the Earth have different states of aggregation - i.e. solid and liquid - and have different depths. For example, the Earth's crust, with a maximum thickness of 80 kilometers, is much narrower than the nearly 3,000-kilometer-thick mantle.

The surface of the earth is the uppermost part of the earth's crust. Although it consists overall of solid, brittle rock, the structure of this layer - i.e. the thickness and density - can vary depending on the location, but the temperature is comparable. The earth's crust is divided into oceanic and continental crust. The continental crust, with a depth of up to 80 kilometers, is thicker than the oceanic crust, which has a maximum depth of 8 kilometers. This is mainly due to the fact that it contains high mountains. It is thickest where the highest mountains in the world are located - the Himalayas in Asia.

The Earth's mantle is divided into an upper and lower mantle.

The upper mantle is maximum 660 km thick and has a solid to viscous consistency. It can be divided into two layers: The upper part of the upper mantle is solid and therefore, together with the Earth's crust, is called the lithosphere, meaning 'stony shell'. However, the lithosphere is not rigid. Instead, it is subdivided into plates and moves on top of the underlying viscous region, the lower layer of the Earth's upper mantle. The viscous region is also called the asthenosphere, meaning 'powerless shell'. Temperatures here are so high that rock from the upper mantle melts and behaves like a lava lamp: The rock material heats up, rises toward the Earth's crust, cools there again, and finally sinks back toward the center of the Earth.

Then - separated by a transition zone - the lower mantle region begins. It extends about 2900 kilometers deep into the Earth's interior. In contrast, the lower mantle is solid, since the pressure here is considerably higher at 1,000 - 1,500 kbar.

The earth's core can also be separated into two layers, an inner and an outer one. The boundary layer between the lower mantle and the outer core is called the "D-layer". It is about 200 kilometers thick and lies at a depth of about 3000 kilometers. Pressure and temperature rise dramatically here. Experts speak of 5000 degrees Celsius. Here, the rock begins to become liquid. It consists mainly of the elements nickel and iron. In this electrically conductive liquid, which is hardly more viscous than water, flow movements can intensify electric currents and form magnetic fields. This is where the earth's magnetic field is created. The outer core of the earth reaches to a depth of about 5150 kilometers.

At 6300 degrees and a pressure as at the earth's surface of 1 bar, iron would be a gas. At the center of the earth (at a depth of 6378 kilometers), however, the pressure is 3,600 kbar and even at a temperature of 5000 degrees, nickel and iron then form a solid metal sphere that rotates. As a comparison: In our atmosphere there are temperatures of 14°C on average and a pressure of about 1 bar, i.e. 0.001 kbar.

The heat in the inner core of the earth is generated by the radioactive decay of elements and is the motor for the movements in the earth's interior, for the enormous forces that threaten us in the form of earthquakes or volcanic eruptions, but also provide us with energy.

Fig. 2 provides a tabular overview of the individual layers of the earth with their physical properties.

Erdschicht	Tiefe unter der Erdoberfläche	Temperatur	Druck	Aggregatzustand
Kontinentale Erdkruste	30-80 Kilometer	max. 1.100°C	10-15 Kilobar	fest
Ozeanische Erdkruste	5-8 Kilometer	max. 1.100°C	10-15 Kilobar	fest
Oberer Erdmantel	max. 660 Kilometer	1.200-1.500°C	300-500 Kilobar	fest/zähflüssig
Unterer Erdmantel	bis etwa 2.900 Kilometer	1.900-3.700°C	1.000-1.400 Kilobar	fest
Äußerer Erdkern	max. 5.100 Kilometer	3.000-5.000°C	etwa 2.500 Kilobar	flüssig
Innerer Erdkern	bis 6.371 Kilometer (Erdmittelpunkt)	bis 5.700°C	etwa 3.600 Kilobar	fest

Zur Orientierung für dich: In unserer Atmosphäre herrschen Temperaturen von durchschnittlich 14°C und ein Druck von etwa 1 Bar, also 0,001 Kilobar.

Abb. 2: layers of the earth with their physical properties

Basics of seismology

How do we know about the structure of the earth?

Unlike in Jules Verne's novel, we are not able to walk inside the earth. We can fly to the moon, but a journey to the center of the earth will probably always remain science fiction. Even at a depth of just a few kilometers, any drilling rig becomes soft because it cannot withstand the enormous pressure and high temperature. Nevertheless, researchers know very well how the earth is structured - but from where? This is where the findings and methods of geophysics come in. It studies the physical properties and processes of the Earth's crust and interior, but in a broader sense it also includes the physics of the oceans (oceanography), the atmosphere (meteorology, aeronomy) and the planets of the solar system. It also explores various technical methods to explore the spheres of the Earth. A method of geophysics that proves what the interior of our Earth looks like will be presented.

Similar to an X-ray machine, geologists can look inside the Earth without having to cut it open. Their "X-rays" are earthquake waves, also called seismic waves: When there is a strong shaking in one place, the vibrations propagate through the entire body of the earth, much like sound waves in the air. However, these waves do not always travel at the same speed: In dense and hard material, the vibrations are transmitted faster than in lighter and softer material. If they encounter a layer of rock with a higher density, they can also be refracted or reflected back, like light rays on a pane of glass. And some waves can travel only in solids or viscous materials and cannot pass through liquids at all.

Every time a large earthquake occurs somewhere on Earth, the vibrations from the earthquake propagate like waves in a pond, penetrating both the interior and the surface of the Earth.

There are several types of seismic waves, which are distinguished by their propagation characteristics. The two main types are body waves and surface waves (Fig. 3). Body waves can travel through the interior of the earth; surface waves are bound to the earth's surface and propagate much like ripples in a pond into which a rock is thrown. Earthquakes generate both body waves and surface waves.

Verschiedene Typen von Erdbebenwellen

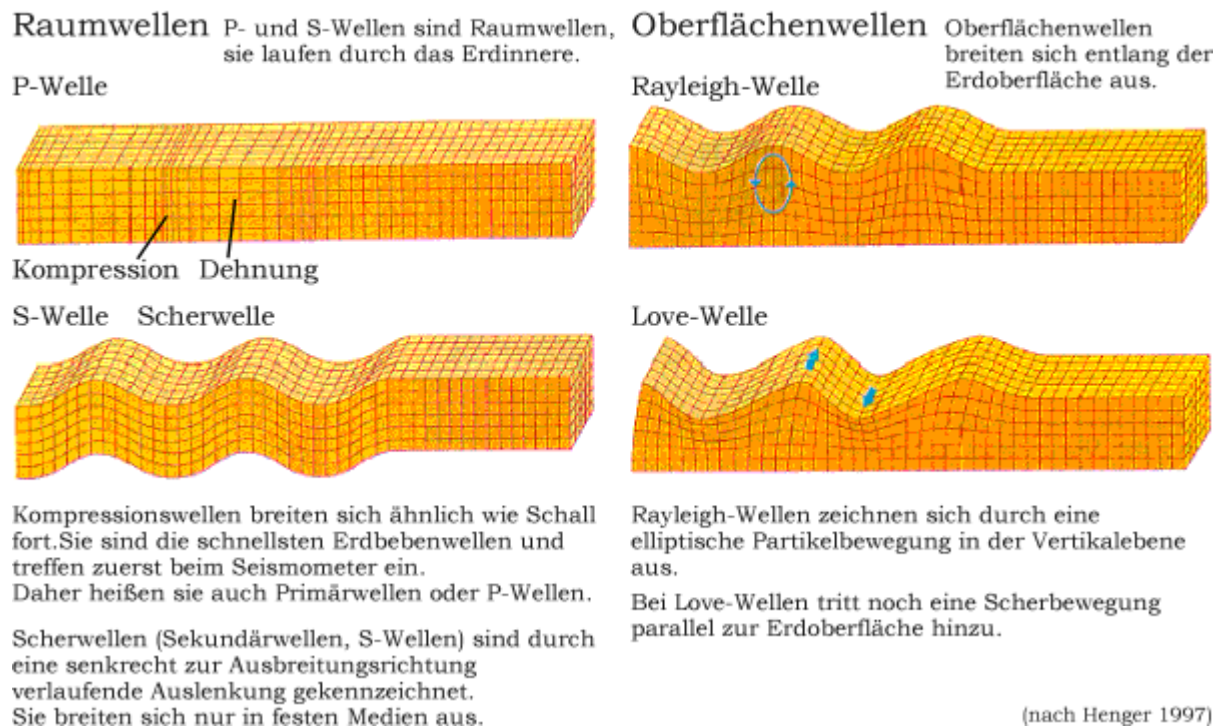


Abb. 3: Types of seismic waves

There are two types of body waves: First primary waves or P-waves, and secondary waves or S-waves. These two main types of seismic waves provide information about the aggregate state of a rock, since, for example, S-waves, unlike P-waves, cannot propagate in liquids and gases. Due to the different states of aggregation between the earth's crust, mantle and core, seismic waves propagate at different speeds. P waves travel at a speed of 5.5 km/second in the crust, 8-12 km/second in the mantle, and 10 km/second in the core, but only about 1.5 km/second in water. Therefore, they are the first to reach a particular earthquake detector (hence the name primary wave or P-wave). P-waves are longitudinal waves, i.e., they oscillate in the direction of propagation. As with sound waves in the air, here the particles in the ground are pushed and pulled, moving in the direction of propagation of the wave.

After the P-wave, the next wave to arrive at a seismic station is the secondary wave or S-wave. S-waves can only propagate in solid materials, not in liquids. These waves move the ground perpendicular to the direction of propagation. S-waves are much slower than P-waves, with speeds of only about 3.0 km/second in the crust and up to 6 km/second in the mantle.

In addition to P and S waves, there are two other types of waves that are grouped together as surface waves.

One type of surface waves are Love waves, named after the British mathematician Augustus Edward Hough Love, who in 1911 was the first to establish a mathematical model for the propagation of these waves. They are the fastest surface waves, but

propagate more slowly than S-waves. The ground motion is back and forth in a horizontal direction.

The second important type of surface waves are Rayleigh waves, named after Lord Rayleigh, who mathematically predicted the existence of these waves in 1855, even before they were actually observed. In Rayleigh waves, the ground rolls in an elliptical motion similar to ocean waves. This rolling moves the ground up and down as well as back and forth in the direction of the wave's propagation. Most of the shaking felt during an earthquake is usually Rayleigh waves, whose amplitudes can become much larger than those of the other types of waves.

These earthquake waves are recorded by a worldwide network of highly sensitive measuring devices called seismographs (Fig. 4).

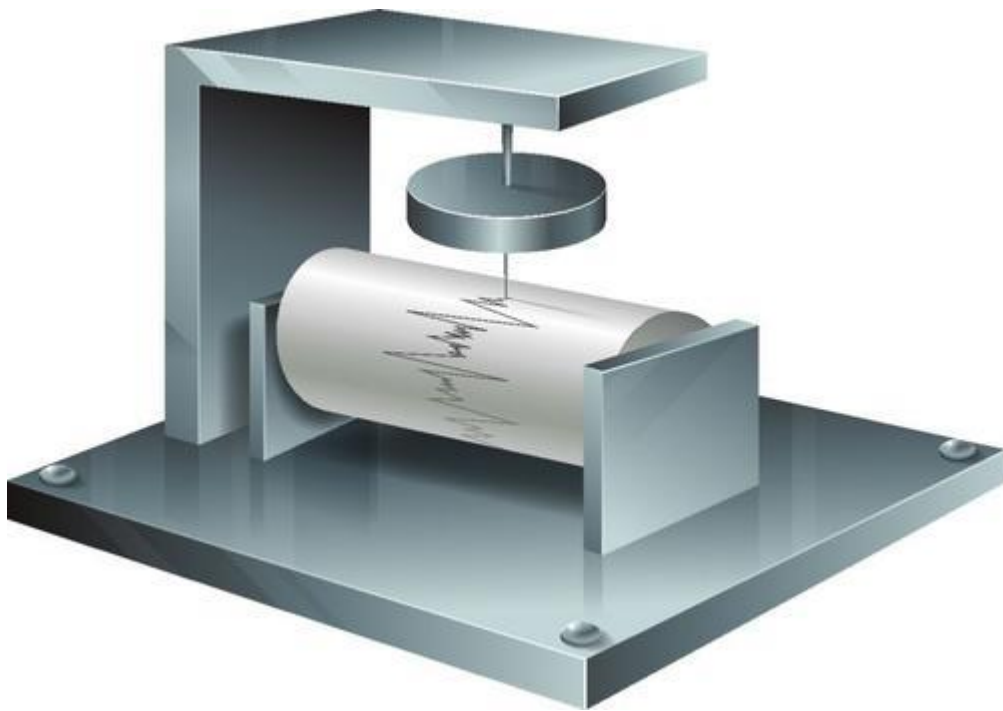


Abb. 4: Sesmograph

From the patterns in these diagrams, researchers can read the nature of the waves and their speed, and trace the path of the waves through the globe. The propagation of space waves in the Earth's interior is usually described using a ray approximation as in geometrical optics. A seismic wave is refracted "away from the perpendicular" with increasing propagation velocity, and "toward the perpendicular" with decreasing (Fig. 5).

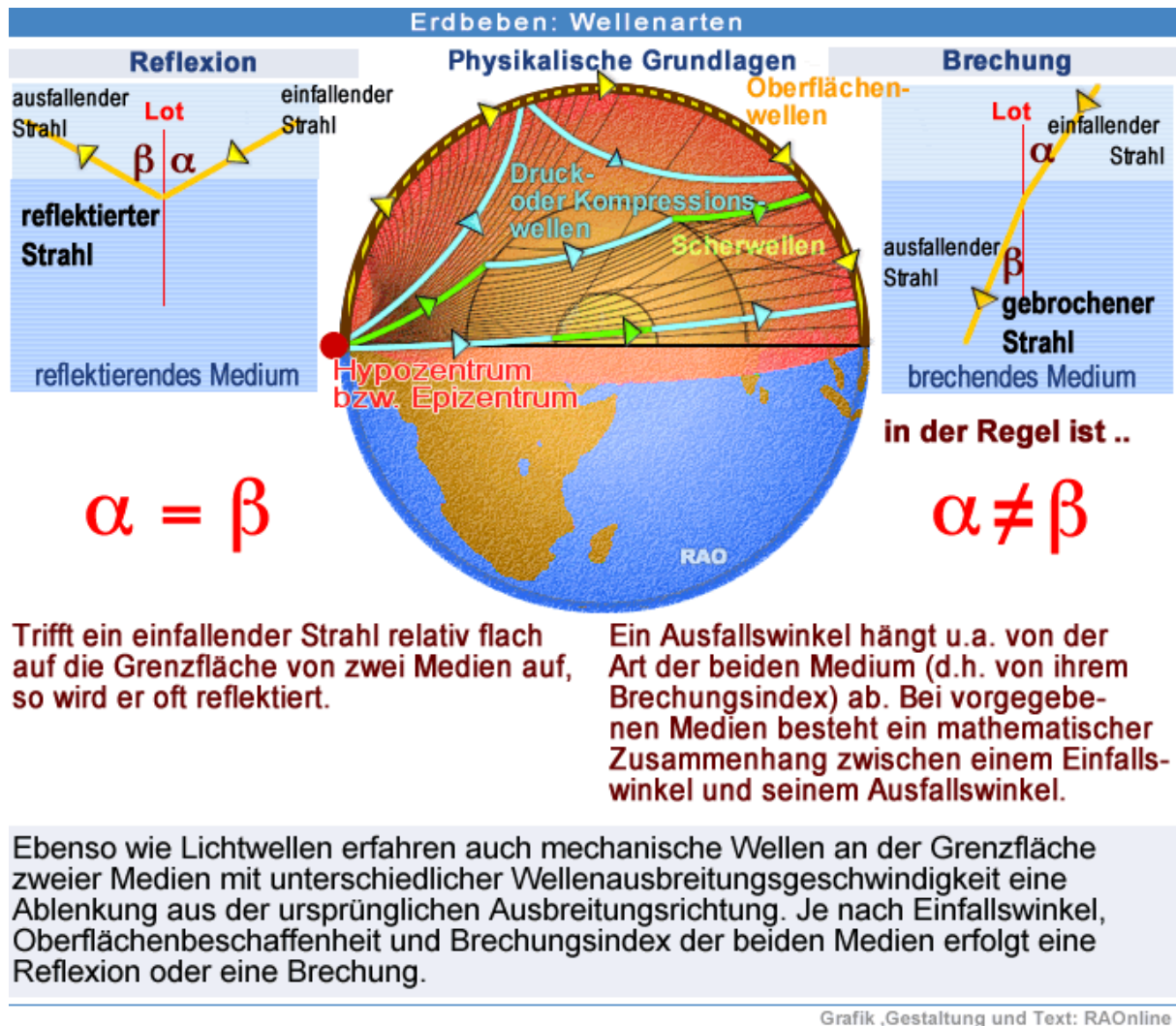


Abb. 5: Path of the earthquake waves through the globe.

Within the Earth's interior, the speed of propagation changes with depth, both continuously and - at discontinuities - abruptly.

By interpreting the wave propagation during earthquakes, insights into the internal structure of the Earth could be gained. For example, since S-waves are extinguished at a depth of 2,900 km, it could be concluded that the outer core of the Earth must be liquid. S-waves only appear again in the inner, therefore solid, core of the earth. In general, by observing the propagation speed and direction of space waves, conclusions can be drawn about the physical properties of the material in which the waves travel.

Further methods to determine the internal structure of the earth

Another way to find out the internal structure of the Earth is to apply Newton's law of gravity and know the mass of the Sun, the mass of the Earth, and the volume of the Earth. Thus, one can calculate that the average density of the Earth is about 5.5 g/cm^3 , which is 5.5 times as dense as water. The rocks of the Earth's crust usually have a density of only 2.7 g/cm^3 (granites and gneisses) to 3.0 g/cm^3 (basalts). But the crust makes up only a tiny percentage of the Earth's volume, so this does not matter.

The mantle, on the other hand, makes up most of the Earth's volume, and the density of the rocks of the mantle ranges from 3.3 g/cm^3 in the upper mantle to 5.5 g/cm^3 near the boundary between the core and the mantle. If the entire crust and mantle have a lower density than the Earth's average of 5.5 g/cm^3 , and more than half of the volume of the volume has already been accounted for, then this means that the remaining volume of the core must have a much higher density to arrive at the overall average of the Earth's density. Using the seismic wave velocities, we can calculate that the density of the outer core is about 10 g/cm^3 and the innermost core is 13 g/cm^3 (13 times as dense as water, Fig. 6). This indicates that the pressure in the inner core is about 4 million times the pressure of air at sea level, and that the temperatures are above 7000°C !

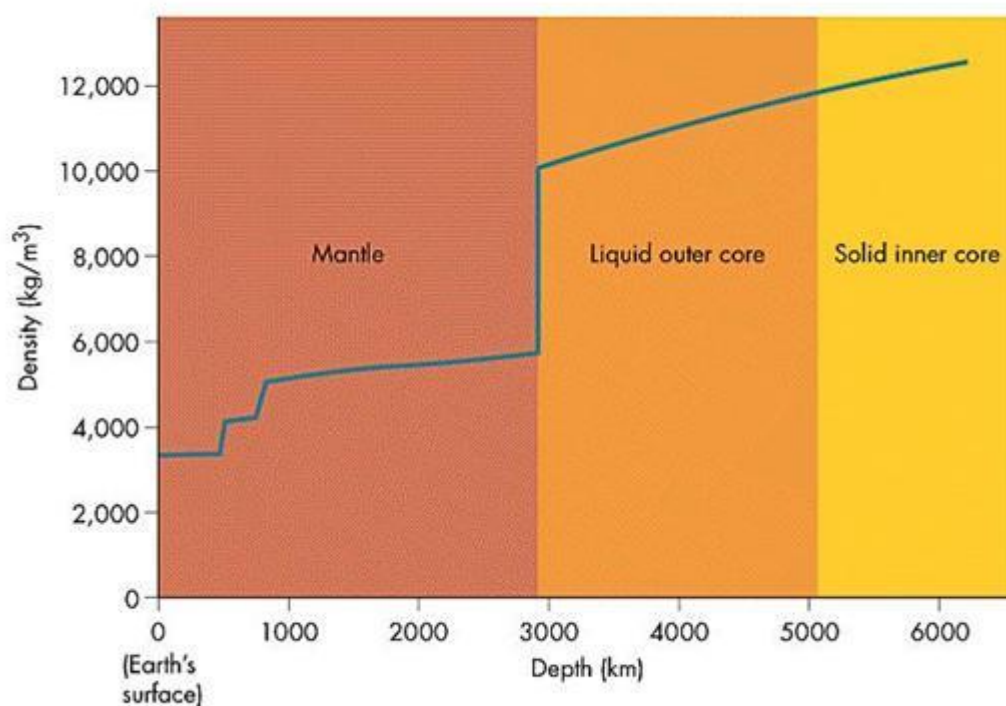


Abb. 6: Density of the earth

Another area is the Earth's magnetic field (Fig. 7). Since the important experiments of Michael Faraday, we know that the Earth has a magnetic field that propagates into space and has many important effects. One of its most important benefits is that the field protects us from the ionized radiation of the solar wind, which is blocked by the magnetic field and flows around us through space.

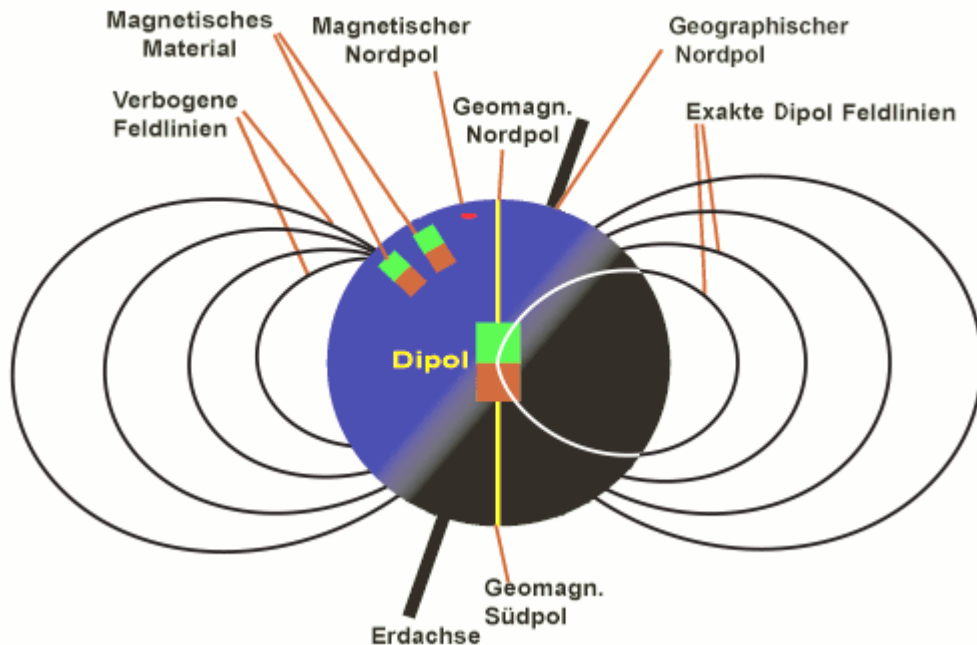


Abb. 7: Geomagnetism

What causes the Earth's magnetic field? It can't be a simple bar magnet like we know from physics class, because solid metal magnets lose their magnetization above 650 °C, and we've just shown that the Earth's interior is much hotter than that. Instead, it must be some kind of electrical geodynamo, similar to the dynamos that generate electricity in a hydroelectric plant.

There, the force of water is used to spin coils of conducting metal wires through a magnetic field, producing electric current. If the Earth's core were spinning rapidly (as the Earth spins) and were made of a conductive metal, it would also generate a magnetic field.

So the Earth's magnetic field is only possible if the Earth's core is made of a good conducting metal.

Meteorites also provide valuable information about the internal structure of the Earth (Fig. 9).

Meteorites regularly fall to Earth and provide us with samples from other planetary bodies as well as the material of the original solar system before there were planets. The three main types of meteorites are 1) chondritic meteorites, which are from the earliest solar system and provide the data from which we can infer the characteristics and age of the early solar system; 2) stony meteorites, which are rich in magnesium

silicates, the same composition as the rocks of our own mantle, and are thought to be remnants of the mantle of another planet that broke up; and 3) iron-nickel meteorites, which are a very rare and special type of meteorite, with only 6% of known meteorites having this composition (Fig. 9).

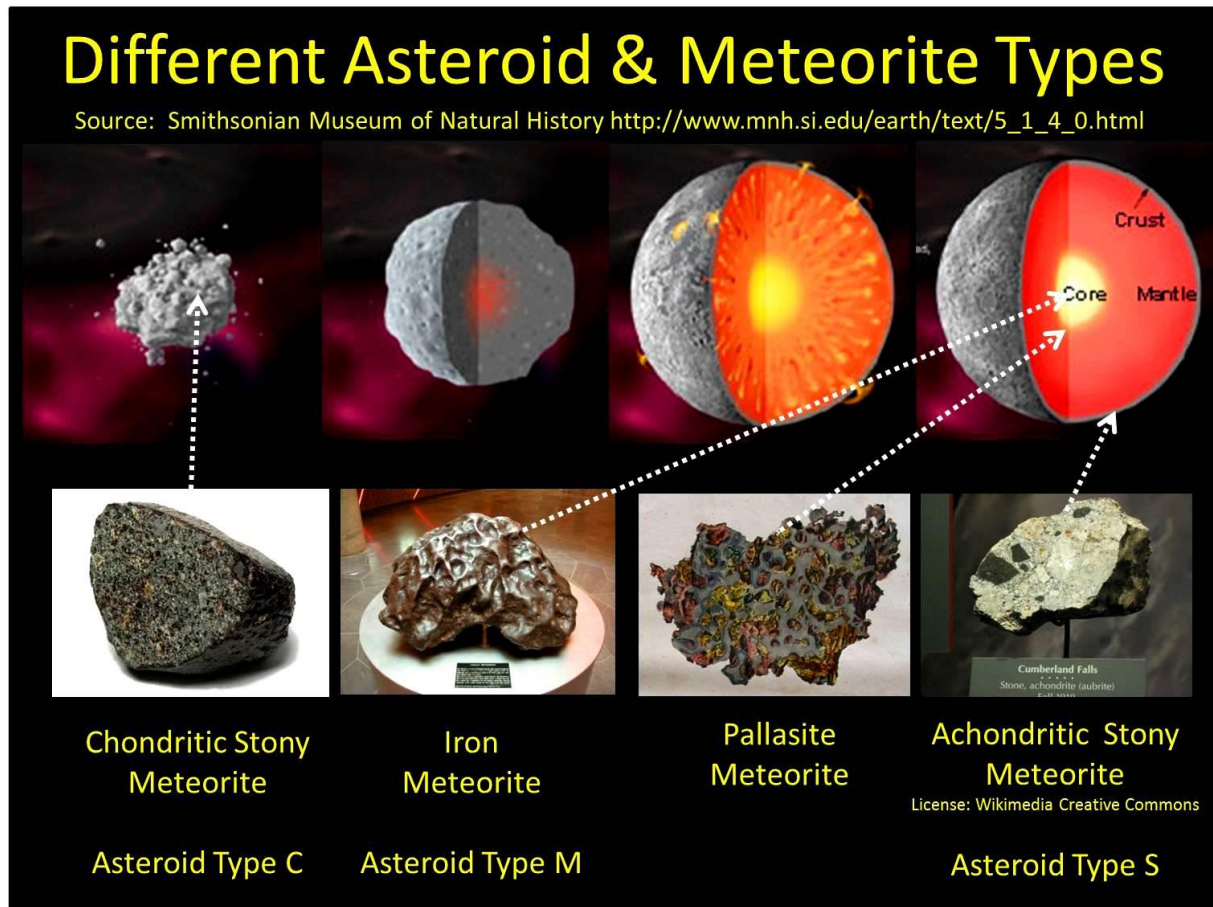


Abb. 8: Types of meteorites

As their name implies, iron-nickel meteorites are composed mainly of iron, with about 5-25% nickel and small amounts of cobalt and other rarer elements. Thus, they are much simpler than the stony meteorites and chondrites, which contain many different chemicals and minerals. The most interesting aspect of iron-nickel meteorites, however, is that they provide samples of what the core of many planets (including ours) is made of. When analyzing the spectra of certain asteroids (of the so-called M-type), it turns out that they have the same composition as iron-nickel meteorites. From the geochemical traces trapped in them, we know that iron-nickel meteorites originally formed the core of certain large protoplanets that have since decayed. They also contain isotopes of aluminum-26, the radioactive heat source that caused the protoplanets to melt and allowed the denser materials (iron and nickel) to sink into the core and separate from the mantle during planetary differentiation.

Iron and nickel are thus the only metals found in the solar system that are dense enough to form the rocks in our core (when subjected to the pressures and

temperatures in our core), and most importantly, iron and nickel are good electrical conductors, so when they are melted, they convect and create Earth's magnetic field.

The heavy elements on ours have sunk downward into the Earth's interior, and the light ones have remained at the rim, at the crust. But since the chemistry of the crust is known - that's the ground beneath our feet - and at the same time we know from the meteorites what the overall mixture once looked like, we can deduce what metals and minerals are in the Earth's interior.

Of course, there are also holes drilled through the earth's crust (Fig. 9). The deepest hole in the world is on the Kola Peninsula in Russia. Scientific drilling started in 1970. Researchers wanted to bring rock samples from the earth's interior to the surface. But at a depth of a good 12 kilometers at a temperature of almost 200 degrees Celsius, the drilling equipment became soft and the electronics failed. The Russian deep drilling program had to be discontinued in 1989. But at 12262 meters, it remains the deepest borehole in the world to this day. Over 45,000 rock samples were taken from the earth's crust during this time. Their exploration will take decades.

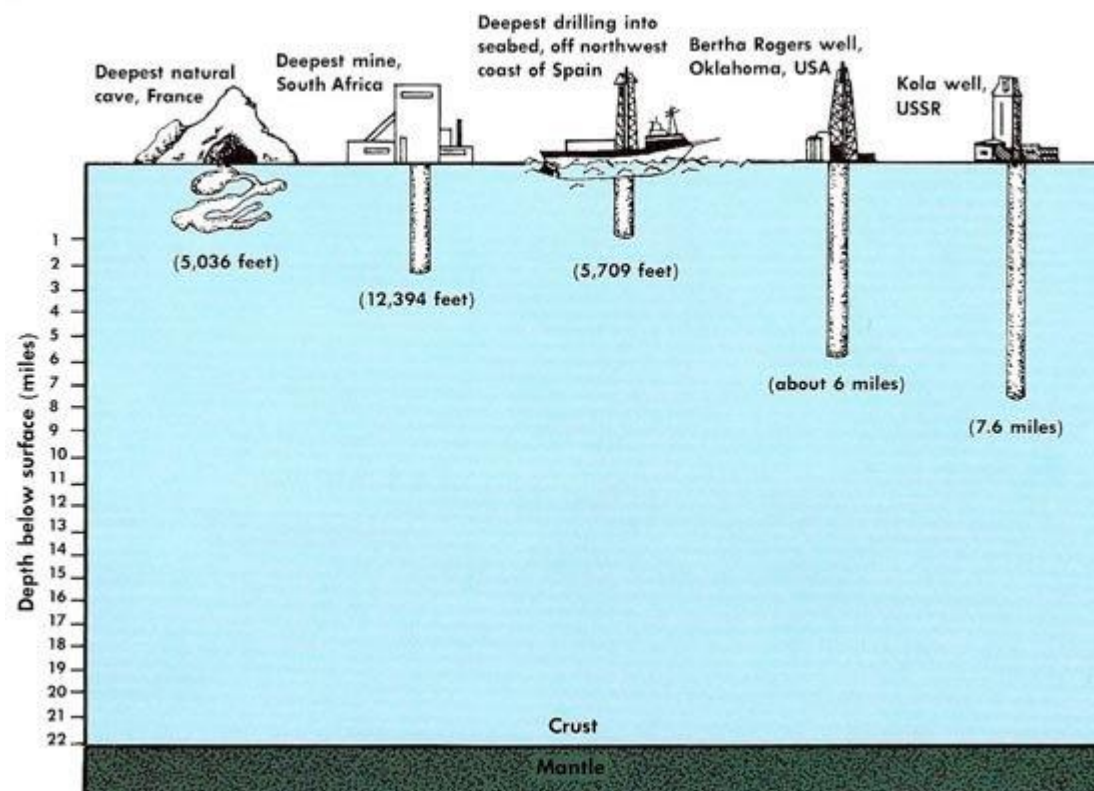


Abb. 9: Drilling into the earth's interior

In this way, the researchers learn a lot about the Earth's interior - for example, at what depth there are layers of rock or metal and whether they are solid, viscous or thin.

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