

THE GEOSPHERE

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Keywords: Earth's interior, crust, mantle, core, lithosphere, asthenosphere, isostasy, seismic waves, earthquake, Moho, mantle plume

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Summary

Direct observation of the hidden layers of the Earth is limited to the uppermost 30 to 40 kilometers of the crust. Mines, drill holes, rock fragments incorporated in igneous intrusions, and the exhumation of metamorphic rocks are the only means of direct observation we have of the Earth's interior. Early insights into the deeper portions of the crust were provided by gravity data, which indicated that mountainous regions must be underlain by a thick root of relatively light rocks. Thus, in a crude way, the Earth's surface topography is mirrored by the base of the crust. These observations led to the principle of isostasy, which states that the crust floats upon the underlying mantle. Since oceanic crust is thinner and denser than continental crust, it sits at a lower elevation, consistent with the principles of isostasy.

Knowledge of the Earth's interior layers comes primarily from the interpretation of seismic energy, which is propagated in all directions away from an earthquake site. Of the several types of waves formed, P-waves and S-waves are the most important. P-waves are the fastest seismic waves, and typically travel through crustal rocks at

velocities of about 7 km sec^{-1} and their velocity increases up to 13 km sec^{-1} in the Earth's interior. They can travel through both solids and liquids. S-waves, on the other hand, have velocities ranging from 4.5 km sec^{-1} in crustal rocks to about 7 km sec^{-1} in the Earth's interior, and are not transmitted through liquids.

The varying behavior of P- and S-waves as they penetrate the Earth's interior reveals the existence of the Earth's three principal layers, a metallic inner centre, or core, surrounded by a solid layer, known as the mantle, which is overlain by a thin outer layer, or crust. The existence of the crust-mantle boundary was deduced when it was realized that seismic waves in continents undergo a rapid increase in velocity at a depth of about 40 km, reflecting a change in density. The boundary between the crust and mantle is named the Moho after its discoverer, Andrija Mohorovicic. About 100 km below the surface, the systematic increase with depth in P- and S-wave velocities is interrupted by a zone of low seismic velocity indicating the presence of a weaker layer, known as the asthenosphere, the upper portion of which is thought to contain a small percentage of melt. The rigid lithosphere is mechanically detached from the asthenosphere, allowing plate tectonics to take place. The plastic nature of the mantle allows it to convect, although the precise nature of this convection is not understood. The results of seismic tomography, which can identify relatively warm and cold regions in the mantle, suggest a complicated form of convection.

The boundary between the mantle and core is defined by the bending inwards of P-waves, and the blockage of S-waves, forming shadow zones on the Earth's surface where these waves are not detected. Both these features indicate the presence of a liquid layer at this depth. The core-mantle boundary is placed at a depth of 2900 km. Calculations indicate that the core material has a density between 10.0 and 13.0 g cm^{-3} , and the composition is thought to be similar to iron-rich meteorites, which, like the Earth's core, are thought to represent the primitive composition of the inner part of the solar system. An iron- and sulfur-rich liquid dominates the outer core. Convection in the outer core and the spiraling flow of liquid is thought to be responsible for the Earth's magnetic field. The increase in P-wave seismic velocity at 5100 km depth suggests that the Earth's inner core is solid and may be rotating.

1. Introduction

The mass of the Earth is $5.97 \cdot 10^{24} \text{ kg}$ and is calculated from the gravitational attraction between the planets, the length of the Earth year, and the length of an Earth day. Since the Earth's volume is $1.09 \cdot 10^{12} \text{ km}^3$, the average density of the solid Earth is 5.52 g cm^{-3} . This value is the greatest of the terrestrial planets, the densities of which range from 3.93 (Mars) to 5.52 g cm^{-3} . The Earth's uncompressed density (i.e. the density of the Earth if its gravity did not compress it) is 4.2 g cm^{-3} . This value is much greater than that of crustal rocks (2.5 to 3.0 g cm^{-3}), and implies that the interior of the Earth is significantly different in density and composition from its surface.

Direct evidence of the composition of the Earth's interior is derived from drilling or from sub-surface mining and is, therefore, confined to the upper 10 km of the Earth's crust. Consequently, knowledge of the Earth's interior predominantly relies on indirect means. Although most of the recent advances in our understanding have been derived from interpretations of various types of seismic data, some of the earliest insights were

the result of the study of the Earth's gravity. Over the past 100 years, improved data collection and analytical techniques have resulted in a surprisingly thorough knowledge of the Earth's interior. The data indicate that the Earth can be subdivided into three layers: (a) the crust, the outermost and thinnest layer (<1 % of the Earth's volume), which consists of hard, strong but relatively light (less dense than the Earth's interior) materials composed chiefly of feldspars, quartz and pyroxenes. The crust has an average thickness of 30 to 40 km beneath the continents, while beneath the oceans its thickness is 7 to 8 km; (b) the mantle, which extends to a depth of 2900 km and makes up 83% of the Earth's volume, is composed of dense silicate and oxide minerals that contain iron and magnesium, such as olivine and pyroxene. As the Earth's temperature and pressure increase with depth, the strength of mantle rock varies and results in layering within the mantle; and (c) the core, which occurs below the mantle and extends to the Earth's centre, 6370 km below the surface. It is composed largely of metallic iron.

The data further indicate that the Earth has a rigid shell, known as the lithosphere (after the Greek "lithos," meaning rock), which includes all the crust and the uppermost part of the mantle. The lithosphere typically varies in thickness from about 75 km beneath oceans to about 125 km under the continents. The mantle is solid, but because it is close to its melting point, it is soft. The mantle convects, as buoyant portions of the mantle rise towards the surface and denser portions sink. In detail, however, the nature of this convection remains unknown. The core may be subdivided into an inner solid core, and an outer liquid core. Spiraling columns of iron-rich liquid in the outer core are responsible for the Earth's magnetic field.

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Editorial note: This article is complementary to *Internal Forces* and *Plate Tectonics and Landform Evolution*. Further information can be found especially in *Volcanic and Magmatic Rocks*.

Biographical Sketches

Jaroslav Dostal received his initial education in geology at Charles University in Prague, Czechoslovakia. He was a lecturer at that university before emigrating to Canada where he received his doctoral degree from McMaster University in Hamilton, Ontario in 1974. After a year of postdoctoral studies at Dalhousie University, Halifax, Nova Scotia, he was hired by Saint Marys University in Halifax where he is now a professor of geology. Dr. Dostal has also worked as a researcher at the Université de Montpellier, and the Université d'Aix-Marseille, France, and the Università di Modena, Italy. He has authored or co-authored over 150 papers in academic journals as well as more than 200 conference abstracts and other publications.

Brendan Murphy is an Irish citizen who completed high school and his B.Sc. degree in Ireland, before emigrating to Canada in 1975. He acquired an M.Sc. from Acadia University in Wolfville, Nova Scotia, in 1977 and a doctorate degree from McGill University (Montreal, Quebec) in 1982. In 1982, he joined St. Francis Xavier University, where he is now a professor of geology. He has published over 100 scientific articles in academic journals, book chapters, monographs, or geological field guidebooks, and has authored or co-authored more than 120 conference abstracts.

Damian Nance is a citizen of both the United Kingdom and the United States. He received his education in geology in England with a B.Sc degree from the University of Leicester in 1972 and a doctoral degree from Cambridge University before emigrating to Canada in 1976 to teach at St. Francis Xavier University in Nova Scotia. In 1980, he joined Ohio University where he is now a professor of geology. He has published over 150 scientific articles in academic journals, books and government documents, and has authored or co-authored more than 180 conference abstracts.