THE MANTLE AND ITS PRODUCTS

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Summary

The most widespread and voluminous melts on Earth are basaltic in composition, and these result from partial melting of mantle material. Mantle melts can be generated by: (a) decompression melting, (b) increase in temperature, and (c) addition of volatiles. In the first of these models, upward migration of buoyant, solid, mantle material causes decompression melting, considered to be the main mechanism for generating large volumes of basaltic liquids at ocean ridges and above mantle plumes. In the second model, the temperature of the mantle can be raised above the mantle solidus. Heat transfer by the movement of hot material, as one example, can take place in upwelling plumes. In the final model, introduction of volatiles (mainly H_2O, CO_2) can significantly depress the mantle solidus. This type of melting, important in subduction zones, is caused by decarbonation and dehydration reactions involving volatile-bearing minerals, especially amphiboles, contained within a subducted slab. Depending on the degree of partial melting and pressure (= depth), a variety of different mantle melts can be produced. High degrees will generate picritic basalts, intermediate degrees will generate tholeiitic basalts and low degrees can generate alkali basalts. If volatiles, especially CO_2, are present, lamprophyres, kimberlites and carbonatites can be produced.

1. The Layered Earth

Earth, like most of the innermost planets in the solar system, is layered. It can be divided into core, mantle, and crust. Of these zones, the mantle is by far the largest and contains 84% of the volume of Earth, thus exceeding the volume of the crust and core

combined. In addition, the mantle contains 68% of Earth's mass. Starting at the base of the crust the mantle extends downwards to the outer part of Earth's core until it reaches a depth of about 2900 km at the core–mantle boundary. Because of its inaccessibility, our knowledge of the chemical composition and mineralogical make-up of the mantle is based on both direct and indirect observations combined with modeling and with melting experiments. A summary of Earth's internal structure is given in Table 1.

Region	Depth (in km)	Percentage of Earth's mass
Oceanic crust	0–10	0.10
Continental crust	0–40	0.40
Upper mantle	10–400	10.30
Transition zone	400–660	7.50
Lower mantle	660–2890	49.20
Outer core	2900–5150	30.80
Inner core	5150–6370	1.70

Table 1. Summary of Earth's interior

During its history, Earth has undergone differentiation, which is a process in which materials have separated on the basis of their melting points and densities. The mantle can thus be thought of as that part of the Earth that remains after the lighter material has risen to the surface to form the continental crust and the atmosphere, and the heavier material has sank to the interior to form the core. It is possible to divide the mantle vertically into layers on the basis of density and seismic wave velocities. A threefold division of the mantle into upper mantle, transition zone, and lower mantle is adopted here. Each of these layers is the result of compositional and/or mineralogical changes with depth.

The upper part of the mantle has an average density of about 3.5 gm cm^{-3} and in it are contained both the lithosphere and asthenosphere. The lithosphere is that part of the mantle that forms a cold, rigid layer, and in it is contained the crust. This part of the Earth transmits stress and forms the many plates that cover the surface of Earth. The underlying asthenosphere behaves as a fluid over geological time and extends from a depth of about 70 km to about 200 km. Sometimes called the "low velocity zone," the asthenosphere has anomalously low seismic velocities, a property that has been attributed to the presence of a very small fraction of permanent melt. The rocks in this zone are closer to their melting points than other parts of the mantle, and this part is probably made up of a slush of liquid plus crystals. The so-called "transition zone" is that part of the mantle where both seismic velocities and densities increase rapidly between 400 km and 660 km, features which can be attributed to phase changes in which minerals collapse under pressure and form denser mineral assemblages. The discontinuity at 400 km is probably because of the change from an olivine structure to a spinel structure, while the 660 km discontinuity is probably the result of the breakdown of minerals to those of perovskite-structured, and dense oxide minerals.

The lowermost mantle extends from 660 down to about 2891 km, and is characterized by a linear increase in density with depth. The discontinuity at 660 km was once

considered an obstacle to slabs of oceanic lithosphere that had been subducted into the mantle, but evidence from seismic tomography (a technique in which seismic waves can be used to produce three-dimensional images of Earth's interior) suggests that its role in acting as an impermeable barrier may have been over-emphasized. It now appears that material can be subducted all the way down to the core–mantle boundary. The basal part of the mantle or D″ layer forms the lowermost 200 to 300 km of the mantle, and might well contain some of the earliest phases to condense out of the solar nebula, including such minerals as perovskite and melilite. It has an irregular contact with the core, perhaps produced by thermal upwelling from the core into the mantle. The core–D″ boundary represents the largest density contrast in the Earth. Strategically situated at the core–mantle boundary, the D″ layer acts as a collecting point for light material that leaves the core, and heavy material that settles out of the mantle. Thus the bulk chemical composition of this lowermost part of the mantle probably represents a highly variable zone in terms of its chemical composition. Because of the substantial amount of heat leaving the core, the D″ layer is also a lower thermal boundary layer for the base of the mantle.

2. Mineralogy and Chemical Composition of the Mantle

Because it is impossible to obtain samples of the mantle directly, Earth scientists have to resort to a variety of methods to evaluate both its mineralogy and chemical composition. Using chemical data obtained from meteorites (especially the group of meteorites known as "chondrites") it is possible to make estimates of the chemical composition of the mantle by extracting both crust and core from estimates of primitive Earth. Geophysical information such as gravity, heat flow, seismic data, and electrical conductivity can also help place constraints on the mineralogy and chemical composition of the mantle. Although such approaches have helped in understanding the gross structure of the mantle, a large part of our knowledge of the mineralogy and chemical composition of the mantle is based on fragments that have been transported to the surface by deep-seated, highly explosive igneous melts. These fragments can take the form of so-called "mantle nodules," or as individual minerals (xenocrysts), which are found mainly in kimberlites, and alkali basalts. These fragments provide scientists with direct samples that can be investigated in the laboratory. The range of mantle xenoliths found in kimberlites is much more varied than those found in basalts, perhaps because basaltic melts form at much shallower levels than kimberlites, and hence sample a much more restricted part of the mantle. A further indirect approach to understanding the make-up of the mantle is to evaluate the compositions of melts known to have been derived by partial melting of the mantle, and from these infer the make-up of the mantle source.

Based on mantle nodules and geophysical data, the bulk of the minerals that make up the mantle are oxygen-rich Fe^{++} and Mg compounds. Such minerals include olivine and orthopyroxene. Some mantle nodules can also contain clinopyroxene. As a broad generalization most mantle nodules are peridotites—defined as ultramafic rocks containing greater than 40% olivine. Minerals stable under mantle conditions are given in Table 2, and the different rock types that form the mantle are given in Table 3 (see *Occurrence, Texture, and Classification of Igneous Rocks*)

Main minerals
Olivine (Mg, Fe)$_2$SiO$_4$
Orthopyroxene (Mg,Fe)$_2$Si$_2$O$_6$
Clinopyroxene Ca(Mg,Fe)$_2$Si$_2$O$_6$
Plagioclase CaAl$_2$Si$_2$O$_8$
Spinel (Mg,Fe)(Al,Cr)$_2$O$_4$)
Garnet (Mg,Fe)$_3$Al$_2$Si$_3$O$_{12}$
Main volatile-bearing minerals
Mg calcite (Ca,Mg)CO$_3$
Dolomite Mg Ca(CO$_3$)$_2$
Magnesite MgCO$_3$
Amphibole (Ca,Na,K)$_{2-3}$(Mg,Fe,Al)$_5$(Al$_{1-2}$Si$_{6-7}$O$_{22}$)(OH,F,Cl)$_2$
Phlogopite K(Mg,Fe)$_3$(AlSi$_3$O$_{10}$)(OH,F,Cl)$_2$

Table 2. Minerals stable under mantle conditions

lherzolite olivine + orthopyroxene + clinopyroxene (+ garnet or spinel or plagioclase) *harzburgite* olivine + orthopyroxene *wehrlite* olivine + clinopyroxene *dunite* nearly all olivine

Table 3. Ultramafic rocks that make up the mantle

The uppermost mantle probably has a mineralogical composition similar to that of a garnet lherzolite containing 60% olivine, 30% pyroxene, and 10% garnet. Other minerals such as plagioclase feldspar and spinel can also be present, and since these minerals along with garnet are stable under different conditions of pressure they can be used to place constraints on the depth of the sources from which the mantle nodules came. In the spinel–garnet transition a reaction takes place between clinopyroxene and spinel to generate garnet and olivine. At lower pressure, olivine and feldspar react to form spinel, clinopyroxene, and orthopyroxene. Plagioclase feldspar is stable at conditions < 30 km depth, spinel < 75km and garnet >75 km. At a depth of greater than about 400 km the garnet lherzolite assemblage changes into an assemblage of high-pressure minerals. Table 2 shows the important minerals that are stable under mantle conditions along with those rich in volatiles, such as water and carbon dioxide. A more exotic group of minerals that have been found in mantle nodules is the crichtonite group, along with other minerals such as apatite, perovskite, ilmenite, rutile, and diamond.

The total volatile content of the mantle is generally considered to be low, and for most practical purposes the mantle can be treated as an anhydrous assemblage. However, there is mineralogical evidence for the presence of volatiles in the mantle. Phlogopite and amphibole found in some lherzolite nodules confirm the presence of hydrous phases in the mantle. It is difficult to assess how much water is present in the mantle, but most estimates are generally less than a few tenths of 1%. Minerals can also contain volatile species other than water. Carbon dioxide is fixed in carbonate minerals such as calcite, dolomite, and magnesite. The presence of carbon dioxide in the mantle is not only supported by the presence of carbonate minerals, but also by the presence of CO_2-rich fluid inclusions in such mantle minerals such as olivine and pyroxene. Mica, amphibole, and apatite are additionally important because they can contain large ion lithophile elements such as K, Ba, and Rb, as well as P, which are elements needed to produce alkaline melts at low degrees of partial melting.

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Biographical Sketch

Keith Bell obtained a B.Sc. from the University of Leeds in 1961, and a D.Phil from the University of Oxford in 1964. He then held postdoctoral positions in the Department. of Geological Sciences at the University of Texas in Austin, and in the Department of Physics at the University of Toronto. Since 1971 he has been a professor in the Department of Earth Sciences at Carleton University in Ottawa, Canada. From 1991 to 1995 he was director of the Ottawa-Carleton Geoscience Center. His main interests involve the isotope geochemistry of carbonatites and alkaline rocks, the chemical evolution of the mantle, and the role of plumes in generating volatile-rich melts. He has also published papers on the application of Pb isotopes as a tool in mineral exploration in glaciated terrains. He has edited a book *Carbonatites: Genesis and Evolution*, and has co-edited the IAVCEI Proceedings volume, No. 4, *Carbonatitic Volcanism*. He is on the editorial boards of *Lithos* and the *Journal of African Earth Sciences*.