Internal structure of the Earth

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THE chemical and physical properties of the Earth's interior are subjects that influence many areas of the physical sciences but they are, in general, only amenable to indirect study. With the exception of rare inclusions in volcanic rocks there are no samples of the Earth from depths greater than about 50 km, a tiny fraction of its 6,370-km radius. Most information comes from observations of the propagation of seismic waves, with additional constraints being applied by properties such as mass, moment of inertia, electrical conductivity and the presence of a magnetic field. One of the more important traditions in seismology, continued on page 121 of this issue¹ by Peter Shearer, is the characterization of distinct layers in the terrestrial onion. What this layering represents is one of the fundamental questions in Earth sciences.

Seismology as a science dates from the late nineteenth century and it was in 1909 that Mohorovičić discovered² the presence of a velocity discontinuity at about 35 km below the surface in Central Europe. The presence of two (compressional) P-wave and (shear) S-wave arrivals at certain distances from the earthquake indicated that some waves pass down into a high-velocity layer and arrive earlier than those passing through the (relatively slow) upper continental crust. At about the same time³ it was found that P waves passing through the centre of the Earth arrived later than anticipated and that S waves did not arrive at all. By 1914 the presence of a core in the Earth, the outer part of which is liquid (does not transmit S waves), and the gross division of the Earth into crust (0–35 km under continents, 0–10 km under oceans), mantle (35–2,900 km) and core (2,900–6,370 km depth) was well established⁴.

Because it could easily be shown that the overall density of the Earth cannot be obtained by simple self compression (with depth) of the rocks found at the surface, explanations of the three main regions centred on their having different chemical compositions⁵ — a silica-rich crust, a magnesium-iron-silicate mantle and an iron-nickel metal core. These gave about the right density and corresponded to some of the major groups of meteorites thought to represent primordial material of the Solar System. Equation-of-state data for iron (beginning with those of Bridgman⁶) confirm that an iron-rich core containing a few per cent of a light element such as oxygen or sulphur has about the right properties.

Actual experimental results at high pressure lagged behind the early advances in seismology, however, and seismologists

were busy delineating even more Earth structure (see figure). An inner (possibly solid) part to the core was established by Lehmann⁷. As accurate data on the mantle accumulated it became apparent that there is a transition zone of rapidly increasing P- and S-wave velocity between 300 and 900 km depth in the mantle^{8,9} which could not be due to self compression (from 100 to 300 kilobars pressure approximately) and required a change in mineralogical state or chemical composition through this region. Volcanic rocks originating at great depth (recognized because, for example, they bear diamonds) commonly contain fragments of the mantle with about 70 per cent olivine, $(\text{Mg,Fe})_2\text{SiO}_4$, and smaller amounts of pyroxene and garnet.

The variation of compressional P-wave velocity with depth according to refs 9 and 11. The region from 0 to 1,000 km depth has been expanded for clarity.

After Jeffreys's seismological results⁹ were presented, Bernal¹⁰ suggested that, because olivine is probably an important component of the mantle, the rapid increase in velocity between 300 and 900 km depth could be due to the transformation of this mineral to the spinel structure, a transformation that had already been experimentally produced in the analogous germanate. The question of whether or not the discontinuities involve simple isochemical transformations of this type or arise from changes in bulk composition is crucial to understanding the dynamic and chemical history of the Earth. Although the mantle is convecting vigorously, small compositional differences would be sufficient to inhibit convective exchange and isolate the lower regions from most volcanic and other plate tectonic processes.

Refinement of the Jeffreys Earth model has led to replacement of the transition 'zone' by two worldwide seismic discontinuities within the mantle at about 400 and 670 km depth. These each exhibit increases of about six per cent in P-wave velocity with increasing depth and are only a few kilometres wide. Correlations of density with elastic properties indicate

that the 400- and 670-km discontinuities each reflect density increases of about 8 per cent, enough to prevent convective exchange if they are attributable to changes in composition, but not if due to phase transformations¹². Other discontinuities of lesser extent and magnitude have been proposed, most notably those at about 220 km and 520 km that Shearer discusses in this issue¹. By amassing years of long-period (20-second) seismograms from the Global Digital Seismograph Network (GDSN) in a coherent display, he finds that there are distinct phases associated with 400-, 520- and 670-km discontinuities but none associated with a 220-km discontinuity, indicating that the latter is not a globally coherent feature. The magnitude of the discontinuity at 520 km is about half that at 400 km.

Are the discontinuities compositional or due to isochemical phase transformations? The crust-mantle discontinuity (Moho) corresponds to increases in P-wave velocity from about 7 to 8 km s⁻¹ and is generally accepted as being compositional, the mantle being dominated by $(\text{Mg,Fe})_2\text{SiO}_4$ and the crust by more silica-rich minerals. Recent high-pressure experimental studies¹³ have shown that $(\text{Mg,Fe})_2\text{SiO}_4$ olivine does transform to a different structure (modified spinel) at pressures (140 kbar) corresponding to the 400-km discontinuity, the differences in elastic properties and density being of about the right magnitude¹⁴. A second weaker transformation¹⁵ from modified spinel to spinel structure at about 180 kbar may be the explanation for the 520-km discontinuity, and the reaction of spinel structure to $(\text{Mg,Fe})\text{SiO}_3 + (\text{Mg,Fe})\text{O}$ has recently been found to occur at about the right pressure to explain the 670-km discontinuity¹⁵. Thus, the mantle may be of approximately constant composition from 35 to 2,900 km depth and convecting through most of its thickness. □

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