THE MANTLE OF THE EARTH

by Don L. Anderson

In the first decade of this century physicists discovered that the atom had a massive central core which they called a nucleus, and geophysicists discovered that the earth had a massive central nucleus which they called a core. The study of the interior of the atom, the smallest building block of matter, and the study of the interior of the earth, the largest piece of matter to which man has direct access, have proceeded rapidly for the last 60 years. We now have exquisitely detailed information about the interior of both the atom and the earth.

Although the study of the atom and the study of the earth have proceeded independently, they are conceptually very similar, and advances in the one field often have direct and sometimes surprising pertinence to the other. In neither case can the interiors of the objects of study be observed directly. Their properties are deduced or inferred from physical effects. For example, the atomic nucleus was discovered by the scattering of electron beams; the earth's core was discovered by the scattering of seismic waves.

Advances in the understanding of matter have led to advances in our understanding of the composition and physical state of the earth's interior. The behavior of material at great depth in the earth is one of our best guides in the study of effects of high static pressure and high temperature on the properties of solids, a currently active branch of solid state physics and materials science .The anomalous behavior of the mantle at a depth of about 400 kilometers stimulated much research in the polymorphism of solids.

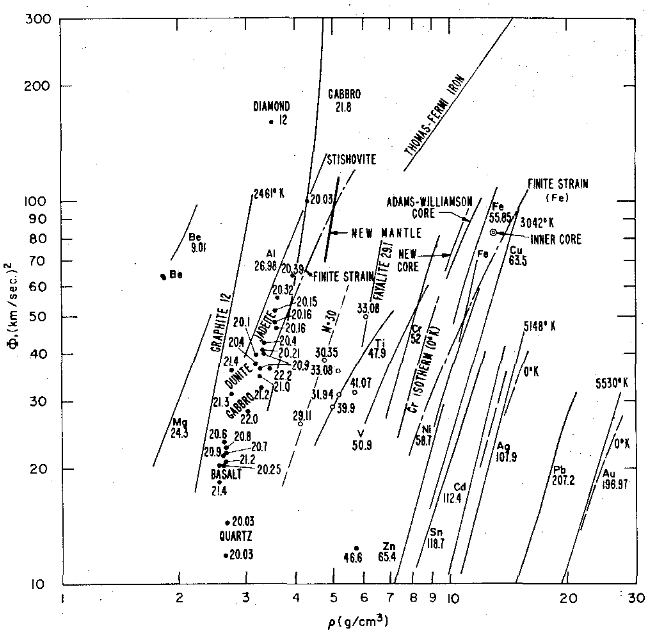
When atomic physicists were able to tap the energy of the nucleus, they made available to the geophysicist a seismic energy source much less temperamental and more predictable than earthquakes. For the first time the study of the earth could proceed as a controlled experiment. The ability of the geophysicist to detect and measure very small ground motions was an important part of the nuclear test ban negotiations and, in essence, made the geophysicist the watchdog of the progress of physics in other countries.

INFORMATION FROM SEISMIC WAVES

Earthquakes radiate elastic waves in all directions, and the time they take in travelling from the earthquake focus to various parts of the earth's surface is the basic information from which the structure of the earth's interior is inferred. Clearly, the location of the earthquake both in time and space must be known in order to infer the path of the seismic wave and the time it takes in its journey. However, the seismic waves themselves are the best source of information regarding the location and time of the earthquake. The accuracy of location depends on the accuracy with which the velocities in the earth are known. This seismic uncertainty principle is responsible for a certain fuzziness in our models of the earth's interior and in our maps of the distribution of earthquakes .

Earthquakes are not point sources in space or time. Furthermore, their occurrence in time and space cannot be predicted. The study of earthquakes and the use of earthquakes to study the earth therefore amounts to a continuous monitoring program. Neither earthquakes nor seismometers are uniformly distributed over the surface of the earth, so many years of monitoring are required to build up an adequate description of the earth's interior.

Buried nuclear explosions provide a quite satisfactory point source of seismic energy. Since nuclear tests are well located and well timed, they have been a boon to seismologists. With the ambiguities of the source removed, a more detailed picture of



A comparison of laboratory shock wave data for rocks and seismic data (where ϕ is the square of the hydrodynamic sound velocity and ρ is density) shows that the mantle has a mean atomic weight near 23 and that the core is slightly less dense than pure iron.

the earth can be drawn. The development of nuclear weapons has had other fallout for geophysics. No nuclear test ban treaty can be effective unless underground tests in other countries can be monitored. This monitoring requires the installation of very sensitive seismometer networks in many parts of the world. The more seismometers that are operating, the more accurately can natural events— as well as artificial explosions— be located, and the more precise becomes our understanding of the structure and physical properties of the earth's interior. Thus the physicist's ability to split the atom has contributed substantially to the study of the earth's interior.

There is still a third area in which developments in atomic physics have had direct impact on geophysics. People who put nuclear devices in big holes in the ground like to know how the intense shock waves are affecting their "container." To answer this question they have supported shock wave research on rocks. During the passage of a shock wave the rock is exposed to extremely high pressures and temperatures and, in a well-controlled experiment, the physical properties of the rock under these extreme conditions can be measured. Pressures of the order of several megabars and temperatures of the order of thousands of degrees Kelvin can be routinely generated in these shock wave experiments which use shaped charges of conventional explosives.

Static high-pressure equipment using large presses can go up to about 100 kilobars, which is equivalent to only about 300 km deep in the earth or 1/20th of the way to the center. Measurements of the elastic properties of rocks have only been made up to about 15 kb, which corresponds to a depth not much below the crust of the earth. Since seismic experiments involve elastic properties throughout the earth, large extrapolations have been required to convert seismic data to standard conditions and, hence, discuss the composition and temperature of the interior. Geophysicists have therefore been concerned for some time both with theoretical equations of state which will allow them to compute the effects of temperature and pressure on the density and elastic constants of silicates and oxides and with the stability of complicated crystal lattices. Shock wave data on rocks can be compared fairly directly with data available from seismology, and we are now making rapid progress in our ability to infer the composition and physical state of the material at all depths in the earth's interior. By comparing the shock wave data with the seismic data (left) we can estimate the mean atomic weight of the mantle and core. We conclude that the mantle is a magnesium-rich silicate and that the core is probably iron mixed with some lighter material.

Unfortunately, shock waves supply only one elastic constant--the compressibility—and the effects of temperature can only be treated approximately. There is still considerable interest in the lower-pressure experiments and in theoretical equations of state. Silicates are structurally complicated, however, and the interatomic forces between constituent ions are not as clear-cut as in simple ionic crystals, so no one has carried out a complete lattice dynamical or quantum mechanical calculation for any common rock-forming mineral. Even pressures in the core are too low for applicability of simplified statistical treatments such as the Thomas-Fermi equation of state. Semi-empirical equations of state, such as the finite strain equations of Birch and Murnaghan, have therefore been widely used by geophysicists both to extrapolate low-pressure data and to indicate how ultrahigh-pressure equations of state must be modified to have the proper low-pressure behavior.

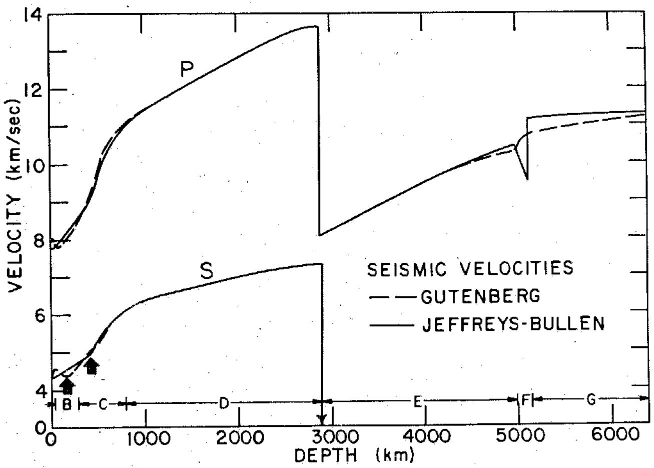
The major subdivisions of the earth's interior (determined from variations in the velocity with which compressional waves travel through the earth) are the crust, mantle, and core. Within these subdivisions, from the center out, there are the solid inner core, a transition region between inner and outer core, the liquid outer core, a transition region between the liquid core and the solid mantle, the lower mantle, a transition region which separates normal silicates from their high-pressure polymorphs, the upper mantle, and the crust.

The upper mantle varies locally and is different under oceans than it is under tectonic areas and stable continental shield areas. The graph at right gives the structure of the upper mantle and transition region in the western part of North America, a tectonic area. This structure resulted from a detailed study by Lane Johnson of the apparent velocities of seismic waves across the large crossed array in Arizona. This array was set up by the Air Force as part of the nuclear test detection program, and the data are routinely sent to Caltech's Seismological Laboratory.

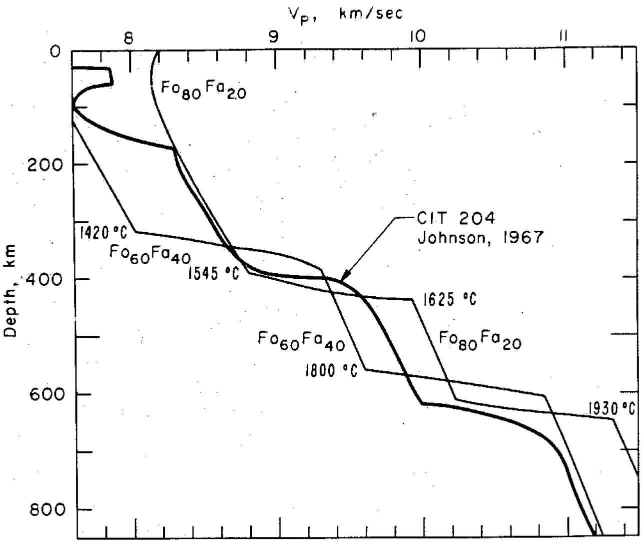
LOW-VELOCITY ZONE

We are not sure what causes the pronounced low-velocity zone at the 100 km depth; it may represent a different mineral assemblage than the adjacent regions of the mantle, or the material in this zone may be partially molten. It may also be caused by a particularly large thermal gradient in this region of the earth, a thermal gradient so large that the effects of pressure are completely cancelled out.

The low-velocity zone is also present in oceanic areas but is virtually absent in stable shield areas. Seismic waves, particularly shear waves, that penetrate this zone are attenuated very rapidly. In some volcanic regions shear waves cannot even get through this zone, suggesting that it is almost totally molten and is, in fact, the source of magma for the volcanos. In Hawaii some volcanic eruptions are preceded by earthquake activity in the low-velocity layer, which again suggests that this low-velocity layer is at least partially molten.



The major subdivisions of the earth's interior are determined from variations in the velocity of compression waves traveling through the earth: (B) upper mantle; (C) transition region; (D) lower mantle; (E) liquid outer core; (F) transition region; (G) solid outer core.



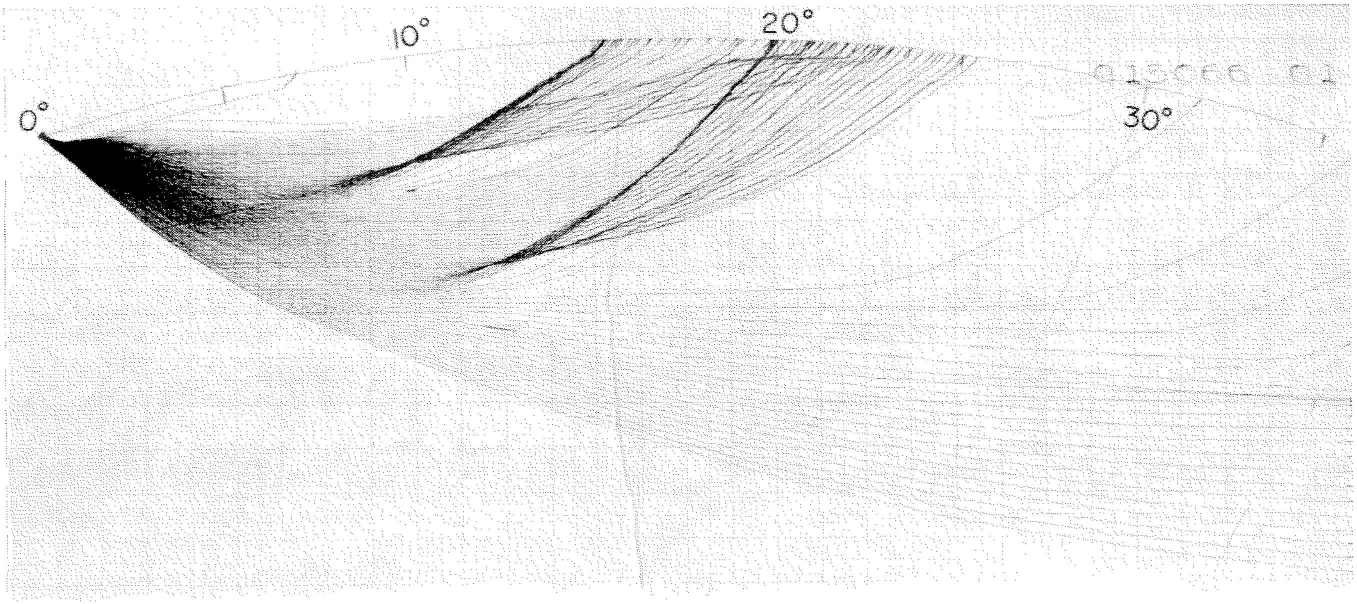
The structure of the upper mantle and transition region in western North America (heavy line) is compared with theoretical mantle models (light lines) that take into account temperature, pressure, and phase changes.

The low-velocity zone is terminated fairly abruptly at about 150 km, indicating a sudden change in the physical state or the composition of the material at this depth. The magnitude and abruptness of the velocity change argue for a compositional change. Perhaps the lighter fraction of the mantle, which also has a lower melting point, has migrated upward, leaving behind a refractory residue which not only has higher velocities but is further from its melting point.

The low-velocity zone may represent a great reservoir of magma held in a solid matrix, as water is held in a sponge. Since molten rock is enriched in radioactivity, a partially molten zone is self-perpetuating. The conductivity of rock is so low that internally generated heat is effectively held in the earth unless the molten rock is allowed to escape to the surface or to shallow depths. This apparently happens in zones of crustal weakness and results initially in lines of volcanos and ultimately in the formation of new crust.

The formation of continents may be due to the upper mantle turning itself inside out in this way. Stable regions of the earth's crust, such as the Canadian Shield, lack a low-velocity zone and apparently have long since depleted their underlying mantle of its magma and its radioactive source of internal heating, and are therefore quiescent.

Low densities are usually associated with low seismic velocities. If the trend in density is similar to the trend in velocity, then the upper mantle in oceanic and tectonic areas would be unstably stratified.



Plot of waves in the upper mantle radiating from a point source shows effect of refraction through various regions.

From about 150 to 400 km in depth the seismic velocities increase at the rate one would expect from the effects of self-compression. Near 400 km the velocity begins to increase very rapidly; this is the transition region. Seismic waves are bent very strongly when they go through such a region. Seismologists can only observe the wave when it finally reaches the surface of the earth, and it has taken them many years to untangle the spider web pattern of ray paths through the upper mantle (above).

Scientists at Caltech's Seismological Laboratory were unraveling the seismic rays in this transition region at the same time that important high-pressure measurements were being made in Japan and Australia. Scientists in these countries were subjecting olivine, a prime candidate for the main mineral of the upper mantle, to pressures of the order of 100 kb. Olivine has a very open-packed crystal structure, as do most common silicates, and it had been predicted that it would collapse under high pressure to a form approximately 10 percent denser. The high-pressure experiments verified this prediction and provided the information necessary to calculate the details of the transition. Furthermore, thermochemical data now made it possible to predict the pressure at which this new phase would collapse still further to an even denser high-pressure phase.

The depths at which these transformations occur depend on both the temperature and the composition of the olivine. Olivine occurs as pure forsterite (Mg_2SiO_4) and pure fayalite (Fe_2SiO_4), and all intermediate compositions are possible. Most olivines are magnesium-rich, and the olivine in the mantle is probably 60 to 80 percent forsterite (Fo_{60} Fa_{40} to F_{80} Fa_{20}). The remarkable similarity between these theoretical mantles and the new seismic results leaves little doubt that two successive phase changes are indeed taking place and that these phase changes dominate events in the transition region.

MORE QUESTIONS

The factors controlling the distribution of earthquakes have intrigued seismologists for many years. By far the greatest number of earthquakes occur in the crust. In some tectonic regions the distribution with depth approximates a decreasing exponential curve interrupted by small maxima near 80, 180, 350, and 600 km. The deepest known earthquake occurred near 700 km. Each one of these depths is near a prominent feature of the new velocity depth curve. No such correlation existed for previous mantle models.

The location of tectonic belts and great fracture and ridge systems suggests that the earth is subjected to some worldwide stress system. Are these stresses most effectively concentrated where the elastic properties are changing most rapidly? The ability of a solid to creep—its viscosity, if you will—seems to be well correlated with its elastic properties. Is the mismatch in ability of the earth to deform at various levels responsible for deep-focus earthquakes? Or is the mantle out of the thermodynamic equilibrium in tectonic regions, and do the phase changes themselves cause earthquakes? Or is it the readjustment of the earth to these phase changes that is the source of earthquakes?

As usual, the result of a scientific study generates as many questions as it answers.