A Journey to the Center of the Earth

Solid State Geophysics at Caltech

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A real understanding of how the earth "operates" may ultimately lead to prediction and perhaps control of the surface manifestations of its processes

A century has passed since the publication of Jules Verne's prophetic science fiction novels. In that time the adventures of Verne's heroes—Captain Nemo's beneath the sea, and Michael Arden's from earth to moon—have nearly all been overshadowed by the massive technical accomplishments of this century. All, that is, except for Professor Von Hardwigge's, which Verne described in his fanciful *A Journey to the Centre of the Earth*, published in 1864. And it is improbable that we will ever duplicate that feat.

Although the center of the earth is relatively close at hand—a mere 4,000 miles away—because of the very high pressures and temperatures there and the character of the intervening material, it is unlikely that man will ever have direct access to this subterranean world. Reliance on indirect evidence as to its nature is in fact what seismology and geophysics are all about.

During the last decade, the revolution that has swept through the earth sciences has redirected our studies of the earth's interior. It has embodied recognition of the movements of large plates over the earth's surface, their continuing creation from molten rock at the ridges of the oceans, and, finally, their subduction into the earth beneath the great trenches. Specifically, much current research is focused on obtaining data regarding the temperature distribution and mineralogy of the earth's mantle and providing a viable theory for explaining the driving mechanism of plate motions, which are reflected in continental drift.

Aside from our intellectual curiosity as to the nature of the static environment and dynamic processes taking place in the earth's interior, a real understanding of how the earth "operates" may ultimately lead to prediction and perhaps control of the surface manifestations of these processes—the earthquakes and volcanic explosions that can so drastically affect man and his cultural works.

Even with our present limited knowledge of the origins of the vertical motions of the continental crust and the horizontal motions of the sea floor, what we know about the processes of the emplacement of igneous (molten) rocks has already provided important strategies for exploration for mineral raw materials and for continuing supplies of fossil fuels, fissile elements, and geothermal resources. Indeed, in many respects, the future needs of our technologically oriented society will to some degree be met by our ability to understand the nature of, and processes existing in, the earth's interior.

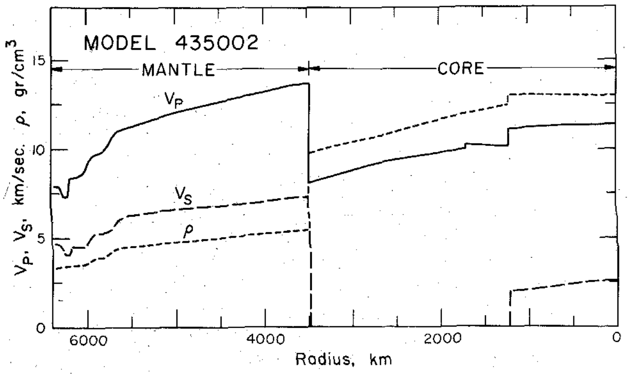
Although the external shape, mass, and moment of inertia of the earth were fairly well established at the time Jules Verne was writing, the fact that the earth has a 3,500-km-radius liquid core (presumably of iron plus lighter elements) was not defined seismologically until 1912, when it was done by Beno Gutenberg, then a young geophysicist working in Göttingen, Germany. The gross picture of the earth's interior that has evolved is that of a liquid outer core (which is the source of the magnetic field) enveloping a small, 1,300-km-radius solid inner core, and a 2,900-km-thick rocky mantle made up of a mineral composition such as $(Mg,Fe)_2 SiO_4$. Only the top of the surface layer, or crust, 10 to 30 km thick, which overlaps the mantle, has been directly explored by man.

Over the last two decades major advances have increased our knowledge of the figure of the earth, particularly the shape of the sea floor, and the global features of its gravity field. Scientists have also made a series of incredibly detailed measurements of the variation of elastic (compressional and shear) wave velocities with depth.

The detailed picture that my seismologist colleagues have given us presents a profound challenge to the solid state geophysicist to provide an explanation of the elasticity and density profiles of the earth in terms of chemical composition, changes of phase (that is, rearrangement of atoms) and reactions between minerals induced by the tremendous pressures and temperatures in the interior of the earth. He must also provide the basic information on material properties—such as thermal diffusivity and viscosity—that is required for theories describing the creation, subsequent horizontal motion, and the final digestion of lithospheric plates into the hot mantle.

To measure such properties as density and compressional- and shear-wave velocity over the range of pressures existing in the earth (reaching 3.7 megabar, or 54 million pounds per square inch at the core) presents a formidable task. The temperatures for the center of the earth have been estimated to run anywhere from 4,000 to 10,000°K. High-pressure apparatus in which minerals can be exposed to static pressures of 30 kilobar (the equivalent of the pressure in the earth at a depth of some 100 km) have provided much important data about the mineralogy and physical properties for the crust and upper mantle.

The current research frontier in solid state geophysics is being pursued by several groups in the United States, Japan, and Australia, using such apparatus. These groups are also testing new equipment that employs a weak solid (such as sodium chloride) to achieve quasistatic pressures of up to 300 kbar (300 times 14,504 pounds per square inch, or the pressure at a depth in the earth of 1,000 km) using containers constructed of carbides or diamonds. Because of the massive amount of material required to contain such pressures, it is difficult to determine the pressure actually achieved, although chemical reactions, density, and electrical resistance are measured.



A recent earth model computed from seismological data by Don L. Anderson and T. Jordan. Data used include classical body-wave travel-time, spectra of the earth's free oscillations, velocities of world-encircling surface waves, and the mass and moment of inertia of the earth.

At Caltech we have taken a rather different approach to the study of the materials that are likely to make up the lower mantle and core of the earth—shock waves. Fundamentally, generating extreme pressures with shock waves relies on the use of inertial rather than static forces. The pressure gradient between one atmosphere (15 pounds per square inch) and multimegabar (many millions of pounds per square inch) high-pressure environments occurs within the 0.05-mm-thick shock-front zone instead of within a massive static apparatus. The shock waves we are able to induce in minerals—when we achieve the pressures of interest—propagate at speeds of from 2 to 20 mm per microsecond. Thus, typical shock transit times for 0.5-cm-thick samples range from 0.25 to 2.5 microseconds. With high-speed photographic or electronic instrumentation it is possible to observe the shock-front boundary within transparent or semi-transparent crystals; and electrical and optical properties can also be extracted from the shock-induced, high-pressure environments at essentially the speed of light.

Virtually all of our knowledge, direct or indirect, of the pressure-density-energy relations (or equations of state) for a host of elements, compounds, and—most importantly for geophysical purposes—minerals has come from shock-wave research. Many of our earlier studies were carried out using high explosives to generate the shock waves.

During the past five years our group at the Seismological Laboratory has been largely concerned with measuring equations of state of mantle minerals to shock pressures of up to 700 kbar. To date, our principal research tools have been two guns powered by chemical propellants and used to launch projectiles to speeds of nearly three kilometers per second at a series of target materials. In these experiments, projectile velocity and the resultant shock velocity in the target sample allow simple calculation of the shock (inertial) pressure. Since the projectile and shock velocities can be measured to better than one percent, the resulting pressures—as well as the density and internal energy—are determined on an absolute basis to nearly that accuracy. This attractive feature overcomes one of the major difficulties of pressure calibration of static apparatus; however, the price paid is that it is the internal energy and not the temperature that is explicitly determined. Theoretical calculation of the shock temperature turns out, in fact, to be a difficult problem for very large compressions.

We have found over the pressure range available to our present apparatus that almost all the common silicate minerals studied to date undergo very marked phase

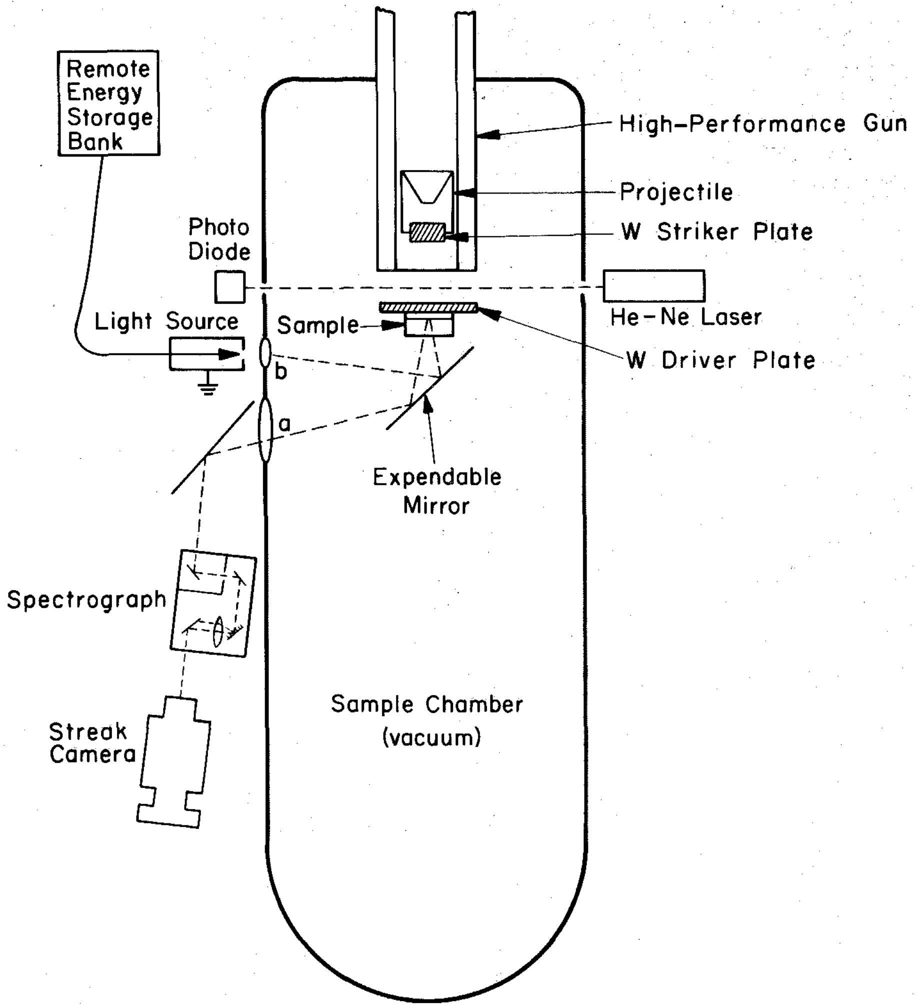
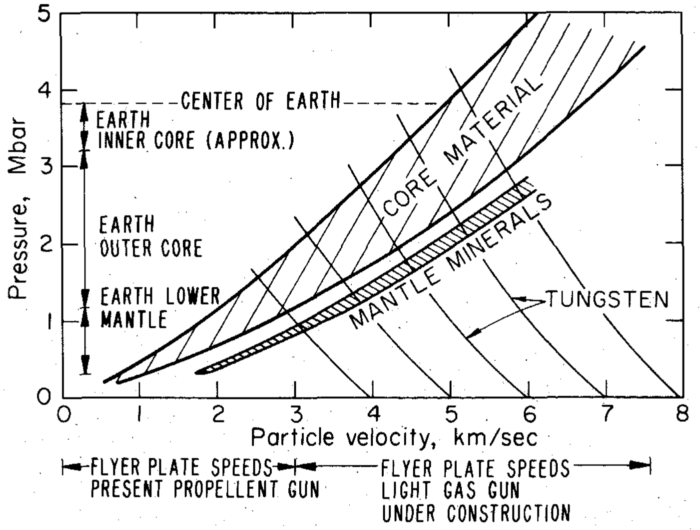


Diagram of the spectrographic system used to measure the adsorption spectra of minerals during shock loading to pressures in excess of 500 kbar. As the shock wave propagates through the sample, light from an intense spark source is reflected from a mirror within the sample and is recorded by a high-speed time-resolving (streak) camera.

changes involving equivalent zero-pressure density increases of from 10 to 30 percent. Major changes in structure with compression have been discovered for such minerals as orthoclase, garnet, ilmenite, and pyrrhotite.

Although the general nature of these new mineral structures was predicted on crystal chemical grounds, we are currently exploring their exact nature to see if the changes can be related to the complicated velocity and density structure of the earth's mantle. This amounts to a whole new field of study—very-high-pressure silicate mineralogy—in which silicon ions are surrounded by six or more oxygen ions instead of the four present in ordinary silicates.

In addition to studying the pressure relations of the major mantle minerals—olivine, pyroxene, and garnet—we are continuing a program of shock-recovery experimentation on a variety of rock-forming minerals. We want to observe, under controlled conditions, the post-shock changes in mineral structure that occur when meteorites impact onto planetary surfaces. Space exploration has demonstrated that meteorite impact is the principal cause of many of the large-scale surface structures on the moon, Mars, and



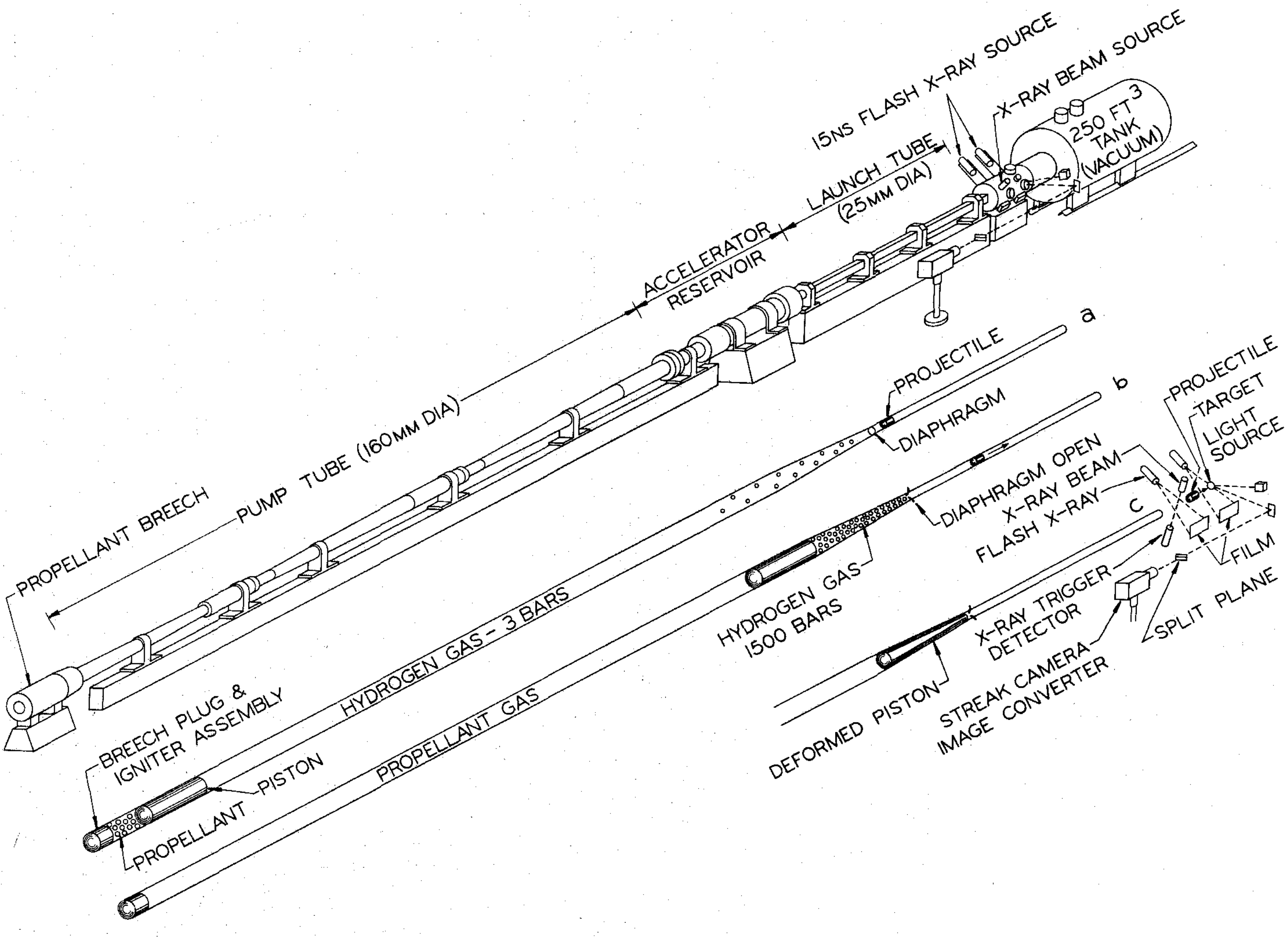
Pressure-particle velocity curves for various mantle and core materials in relation to the performance of propellant and light-gas guns now in use. The intersection of positive-sloping (sample) curves with negative-sloping driver plate (tungsten) curves centered at various projectile velocities determines the induced shock state upon impact. The range of properties for hypothetical core and mantle materials is indicated.

Mercury. Our interest in describing the meteorite impact process has recently led us to obtain the first shock-wave data for lunar rock and soil.

About a decade ago light-gas gun techniques (largely developed at NASA's Ames Research Center and used to launch small models of reentry vehicles into various planetary atmospheres) began to be utilized for the launching of projectiles against targets to generate plane shock waves. The use of these guns to launch impactor plates to speeds of nearly eight kilometers per second has effectively permitted a new region of ultrahigh pressures to become accessible to the laboratory experimenter. Pressures in excess of two megabars in silicate materials and nearly four megabars will now be available for the study of candidate materials of the earth's core as well as for obtaining new insights into the physics of the interior of the major planets.

A diagram of an Ames model launcher, recently converted into a shock-wave apparatus by Norman Keidel and his colleagues in the Caltech Central Engineering Shop, is shown below. This large two-stage apparatus is currently being installed in the Helen and Roland W. Lindhurst Laboratory of Experimental Geophysics, and it will be operated along with the existing single-stage propellant guns by Harold Richeson and David Johnson.

In this way we will be taking a journey to the center of the earth—though only within centimeter-sized samples and for total voyages of less than one microsecond. □



A diagramatic view of the two-stage light-gas gun used for shock-wave research on earth materials. The total length of the apparatus is 106 feet, total weight approximately 35 tons. (a) When the chemical propellant ignites, a 20-kg plastic piston compresses hydrogen in the pump tube. (b) As the projectile enters the high-pressure reservoir section, the diaphragm ruptures and the projectile begins to accelerate down the launch tube. (c) As a result of the deformation of the plastic piston in the high-pressure reservoir, gas pressure is maintained on the base of the projectile as it is accelerated, until it clears the launch tube. After leaving the launch tube, the projectile, which has a tungsten plate in its nose, intersects a continuous X-ray beam and triggers two 15-nanosecond flash X-ray sources. The resulting X-ray shadowgraphs permit the projectile velocity to be measured. When the projectile hits the sample, the streak camera is activated, recording the shock-wave velocity through the sample.