

Beneath the Mohorovicic discontinuity, velocities of compressional waves range from 8 km/sec upwards. Few minerals are known to have such velocities at the relevant pressures. In particular, the framework silicates of low density, such as quartz and feldspars, fail to satisfy the seismic requirements although they are common at the surface. Dense phases, relatively low in silica, such as olivine, pyroxene, and garnet, have the required elastic properties.

At depths between about 400 and 1000 km the seismic velocities increase with depth at an unusually rapid rate. An analysis by Birch⁽⁶⁾ indicates that the velocity gradient is too large to be attributed to compression of a homogeneous material. This region of the earth must then be characterized by a change in composition, phase, or both. Using an equation of state derived from finite-strain theory, Birch extrapolated the elastic properties of the material below 1000 km to low pressure and found that the seismic velocities were higher than those found in dense silicates. The elasticity of oxides such as MgO or Al_2O_3 is consistent with the extrapolated data. The most plausible interpretation of this result is that the lower portion of the earth's mantle is composed of dense polymorphs of silicates, which are unknown at the earth's surface.

HIGH-PRESSURE GEOCHEMISTRY

There is no rigorous relation between pressure and depth in the earth. The usual approximation is to regard the earth as composed of a heavy liquid and to calculate the pressure as if it were hydrostatic. This approximation may fail badly near the surface, but at depths greater than, say, 20 km it becomes fairly accurate because the mean pressure becomes large compared with the strength of the rocks. This "lithostatic" approximation leads to a calculated pressure of about 9 kilobars at the depth of the Mohorovicic discontinuity in continental regions. At a depth of 400 km the pressure is about 140 kilobars, and at 1000 km it is roughly 400 kilobars. This, then, is the range of pressures in which several interesting geophysical phenomena take place. The upper end of the pressure range is unfortunately not yet attainable in apparatus which generates static pressure.

Most materials of geochemical interest are silicates, and reactions among them take place sluggishly. Temperatures of 1000°C or more are often required if reactions are to occur in hours rather than weeks. This means that high pressures and temperatures must simultaneously be maintained for long periods of time. High pressures generated by shock waves do not last long enough for reaction to take place. In most cases the phases present at high pressure and temperature can be quenched in and identified after the pressure has been released.

The first apparatus used in high-pressure geochemistry was an adaption of the 12 kilobar equipment used by Bridgman in much of his work. Modifications include the transmission of pressure by an inert gas rather than an oil, and enlargement of the bore of the pressure vessel to accommodate an internal furnace. Apparatus of this type has been described by Yoder.⁽⁷⁾ The pressure range was later extended by a similar modification of Bridgman's 30-kilobar apparatus.⁽⁸⁻¹⁰⁾

Equipment of this sort is capable of high precision in the measurement of both pressure and temperature. Pressure can be determined to within a few bars by the change in resistance of a coil of manganin wire, and temperature can be closely measured with thermocouples. But this type of apparatus is inconvenient to use, and simpler, if less accurate, equipment has been developed. The earliest of these was a modification of Bridgman's anvil apparatus for use at high temperatures.⁽¹¹⁾ This equipment is exceedingly simple to build and operate; it suffers from the disadvantages

that the pressure on the sample may not be uniform and that it is heated by an external furnace. The latter feature limits its temperature of operation to about 900°C.

A number of these disadvantages have been overcome in the "single stage" apparatus developed by Boyd and England.⁽¹²⁾ Their design has evolved from earlier equipment developed by Coes [described by Roy and Tuttle⁽¹⁾] and by Hall⁽¹³⁾. Talc is used to transmit the pressure, which must be calculated from the load on the piston. A correction is required for friction against the wall of the pressure vessel and for the finite strength of the talc; the first effect can be reduced by lubricating the walls with lead foil. The correction is determined by calibration against the bismuth I-bismuth II and thallium II-thallium III transitions. The first takes place at about 25 kilobars according to Bridgman, and the second at about 37 kilobars according to Boyd and England.⁽¹²⁾ Both pressures correspond to room temperature.

An attractive feature of this apparatus is that it can serve as the basis for equipment designed to operate in the range up to 100 kilobars. But the problem of simultaneous measurement of high temperatures and pressures in such equipment is not completely solved. Temperatures are measured with thermocouples, but the junction is subjected mechanical distortions as well as high pressure. These may affect its calibration by an unknown amount. The mechanical strength of the pressure medium undoubtedly decreases at high temperatures, which means the correction to the pressure determined by calibration at room temperature is too large. Comparison with results obtained in other apparatus suggests that errors in pressure and temperature due to these effects are small above 20 kilobars and 1000°C, but there is evidence the pressure calibration depends on both temperature and pressure.⁽¹⁴⁾ Pressures and temperatures have been found to be highly reproducible from run to run.^(14, 15)

None of the equipment discussed above can achieve pressures above 50 kilobars at high temperatures. The modified anvil apparatus can go higher than this at temperatures below 600°C, but only the "single stage" can reach pressures above 30 kilobars at temperatures above 1000°C. Efforts to extend the pressure range are being made in several laboratories devoted to geochemical research, but routine work above 50 kilobars has not yet been achieved. Research in this direction will surely continue because of interest in the properties of the earth at depths greater than 400 km.

AMPLITUDE OF VERTICAL MOVEMENTS IN GEOLOGICAL TIME

The first experimental indication that rocks now exposed at the surface have been subjected to great pressures in the past came from determination of the stability relations of the pyroxene jadeite, $\text{NaAlSi}_2\text{O}_6$.⁽¹⁶⁾ Nearly pure jadeite has been found in California, Japan, and Burma; if the mineral formed within its field of stability at temperatures above 100°C, pressures of at least 5 to 10 kilobars must have prevailed. A similar conclusion resulted from a study of the much more widespread mineral kyanite, Al_2SiO_5 .^(10, 14) Pressures of about 10 kilobars are necessary to form it stably at 300° to 500°C. It can be inferred from these results that pressures of the order of that at the base of the crust were involved in the production of jadeite and kyanite.

Experimental data for garnets and for certain pyroxenes near enstatite, MgSiO_3 , in composition have yielded similar results.⁽¹⁷⁾ Many garnets consist principally of solid solutions between almandine, $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$, and pyrope, $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$. Almandine is stable at relatively low pressures, but garnets containing over 50 per cent pyrope probably required pressures above 10 kilobars for their formation. Such garnets prove to be fairly common in nature. Enstatite can contain no more than 1 to 2 per cent