RECENT GEOCHEMICAL RESEARCH AT HIGH PRESSURES

by

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INTRODUCTION

Investigations of the stability relations of silicates at high temperatures and atmospheric pressure were begun about 1900. These studies have been fundamental to our understanding of the origin and evolution of volcanic rocks and other rocks of igneous origin which solidified near the surface. Deep-seated igneous rocks and many metamorphic rocks cannot be completely understood on the basis of such experimentation, however. Geochemical research at high pressure is needed to advance our knowledge of the processes which produce most of the material making up the earth.

Studies of mineral stability at high pressures indicate that some rocks, now exposed at the earth's surface, acquired their present mineralogy at high pressures. The data give a measure of the amplitude of the vertical movements which have affected the crust of the earth in geologic time. The unexpected result is that these movements have been a few tens of kilometers, i.e., of the order of the thickness of the crust itself.

High-pressure geochemical research has also been important as a supplement to seismology. The velocities of elastic waves in the earth provide a most important body of information about its constitution. Considerable ambiguity remains, however, and this can be removed to some extent by chemical considerations. Geochemical studies will aid in interpreting the Mohorovicic discontinuity at the base of the crust and the rapid increase with depth of the seismic velocities between 400 and 1000 km. In addition, measurement of the effect of pressure on melting points, in conjunction with seismic evidence of the essential solidity of the outer part of the earth, set a limit to the temperatures between depths of 30 and 100 km.

The following section of this review is concerned with observational seismology and its interpretation in terms of laboratory measurements of the velocities of elastic waves in rocks. This is followed by a discussion of the methods and apparatus of high-pressure geochemistry, and then by discussions of various parts of the earth's interior together with relevant experimental data. This paper is largely concerned with experiments made at pressures about 10 kilobars; Roy and Tuttle[1] have reviewed earlier work at lower pressures.

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This review is premature in the sense that many important investigations are unfinished and many problems have yet to be investigated. But this is characteristically the case in a field which has recently been opened and which is advancing rapidly. The methods used, the principles involved, and the information sought are well illustrated by work which is now in more or less final form.

SEISMIC DATA

Two types of bodily elastic waves can be propagated in an isotropic elastic medium. Their velocities as functions of depth form one of the most important bodies of information about the interior of the earth. If V_P denotes the velocity of compressional waves and V_S that of shear waves, the theory of infinitesimal elasticity yields the relation

$$V_P^2 - \frac{4}{3}V_S^2 = K_S/\rho \quad ,$$

where K_S is the adiabatic bulk modulus and ρ is the density. The quantity K_S/ρ , sometimes called the elastic ratio, is very nearly equal to $K_T/\rho \equiv (\partial P/\partial \rho)_T$. Here P is pressure and K_T the isothermal bulk modulus. $(\partial P/\partial \rho)_T$ can be derived from conventional measurements of static compressibility; a correction amounting to a few per cent is needed to convert the results to adiabatic conditions, but it is easily made to sufficient accuracy. Comparison of laboratory and seismic results then leads to notions about the constitution of the earth's interior.

This method of analyzing seismic data suffers from the disadvantage that the observed velocities must be subjected to mathematical manipulations, often with compounding of observational errors. At shallow depths, V_P is much better known than V_S, but the greater accuracy of V_P is lost in forming the quantity K_S/ρ. These objections have been overcome by direct measurements of V_P at pressures up to 10 kilobars by an ultrasonic pulse technique. Such measurements were first made by Hughes and his collaborators.[(2-4)] More extensive results, both with regard to number of types of rock investigated and with regard to attention to anisotropy of the specimens, has recently been published by Birch.[(5)] Some 200 individual specimens are included in the latter study. The velocities are determined by measuring the transit times of ultrasonic pulses in cylindrical specimens of rock. The data are accurate to a few parts in a thousand; this accuracy is ample since different cylinders cut from the same chunk of rock may differ by more than 1 per cent.

Seismically determined velocities of compressional waves in the earth's crust range from somewhat more than 5 km/sec near the surface to 7 km/sec or so at depth. A large number of common types of rock have velocities in this range, and no difficulty is encountered in reconciling these data with plausible compositional models of the crust. On the other hand, no unique model can be found from seismic data alone. There is also ambiguity in the seismic results themselves. The increase in velocity with depth in the crust may be uniform or it may take the form of stepwise jumps at the interfaces between uniform layers.

It is clear, however, that in "normal" continental regions of moderate elevation a more or less abrupt increase in velocity takes place at a depth of 30 to 35 km. This is the Mohorovicic discontinuity, which by definition marks the base of the crust. Beneath the oceans it is found at depths (below sea level) of 10 to 15 km, and its depth may exceed 60 km beneath high mountain ranges. An outstanding problem is its sharpness; present seismic data cannot distinguish between a true discontinuity in the mathematical sense and a transition spread over an interval a few kilometers thick.