Compressional Wave Velocities in Possible Mantle Rocks to Pressures of 30 Kilobars

NIKOLAS I. CHRISTENSEN

Department of Geological Sciences and Geophysics Program
University of Washington, Seattle, Washington 98195

The velocities of compressional waves are reported to hydrostatic pressures of 30 kbar for pyroxenites, eclogites, and a dunite. The data above 10 kbar, when corrected for length changes, permit the determination of pressure coefficients of compressional wave velocities, which range from 0.010 km s^{-1} $kbar^{-1}$ in eclogite to 0.014 km s^{-1} $kbar^{-1}$ in pyroxenite. It is shown that pressure coefficients of velocity for rocks determined below 10 kbar are generally unreliable due to the influence of porosity. The pressure coefficient of velocity measured for the dunite agrees well with similar data from single-crystal olivine; however, pressure coefficients of velocity for the pyroxenites are significantly lower than measurements for single-crystal bronzite.

In recent years considerable effort has gone into laboratory investigations of wave velocities and the related elastic properties of rocks and rock-forming minerals. Velocities for a large variety of rocks have been reported to pressures of 10 kbar [e.g., *Birch,* 1960; *Simmons,* 1964; *Christensen,* 1965]. Similarly, velocities in many single crystals and hot-pressed aggregates of geophysical importance have been studied to pressures of a few kilobars [e.g., *Anderson et al.,* 1968; *Manghnani,* 1969; *Chung,* 1971; *Kumazawa and Anderson,* 1969; *Graham and Barsch,* 1969]. The results of these studies are important to geophysics in that they provide data for the interpretation of seismic velocities within the earth in terms of chemical composition and crystal structure.

Wave velocity data for rocks to 10 kbar have been particularly useful in the interpretation of oceanic and continental crustal composition [e.g., *Birch,* 1958; *Ringwood and Green,* 1966; *Christensen,* 1970] and have provided the important relationship between density, velocity, and mean atomic weight [*Birch,* 1961], which has been used extensively in estimating mantle composition. However, the interpretation of rock velocities is complicated due to complex mineralogy, chemistry, porosity, and preferred mineral orientation common to most rocks. For example, the effect of porosity has been shown by *Birch* [1960, 1961] to produce a significant lowering of velocities at pressures below approximately 2 kbar for many rocks. At pressures usually between 2 and 10 kbar, rock velocities appear to be primarily related to the elastic properties of their mineral components; however, it is not clear what influence porosity has on velocity in this pressure range [*Birch,* 1969], and because of this it is tenuous to extrapolate rock velocity data much beyond 10 kbar.

To overcome some of the problems inherent in direct studies of rock elasticity, many investigations have concentrated on measurements of the elastic properties of single crystals and hot-pressed polycrystalline aggregates. These studies offer certain advantages in that the measurements are for a single-crystal structure rather than a composite of crystal structures typical of most rocks, and it is usually possible to use techniques that provide higher degrees of accuracy and precision of the data. However, the elastic properties of hot-pressed polycrystalline aggregates are also significantly influenced by anisotropy, porosity, and residual strain arising from their fabrication process [*Spetzler et al.,* 1972]. Extrapolation of single-crystal data to high pressure is also subject to uncertainty because of theoretical problems in averaging directional elastic properties in anisotropic media [*Thomsen,* 1972; *Birch,* 1972].

Clearly, it is desirable to obtain elastic wave data on naturally occurring mineral aggregates at hydrostatic pressures above 10 kbar. In this study, compressional wave velocities and their pressure derivatives are reported to 30 kbar for five rocks of probable mantle composition. Compressional wave velocities for these rocks are compared with extrapolated velocities of single crystals and similar rocks that have been studied at lower pressures.

EXPERIMENTAL DETAILS

A modified Bridgman-Birch 30-kbar pressure system was used to generate the hydrostatic pressures. Details of similar systems have been described by *Bridgman* [1938] and *Birch et al.* [1957]. A simplified diagram illustrating the operation and construction of the pressure-generating unit is shown in Figure 1. The high-pressure cylinder is slightly conical on its external surface and is driven into a massive support cylinder having a matching conical inner surface by the lower 500-ton press. This produces external pressure on the high-pressure cylinder. The upper 125-ton press drives a packed piston down into the pressure vessel, thereby producing the desired pressure within the cylinder. The upper and lower jacks are operated simultaneously by two 20,000-psi air pumps connected to a single oil reservoir. The press frame, consisting of three plates and six connecting tie rods, serves to contain the thrusts of the upper and lower jacks and locate the assembly.

The tapered pressure vessel is approximately 30 cm long and has a 1.9-cm bore. The electrical leads, which pass through a closure at the lower end of the vessel, are required for measuring the pressure and travel times of the compressional waves. The pressure was measured by observing the change in electrical resistance of a coil of manganin wire located within the pressure chamber. The coil was initially calibrated by Harwood Engineering Company of Walpole, Massachusetts, and calibrations were made independently in our laboratory by observing the change in electrical resistance at the freezing pressure of mercury and the lowest solid-solid transition of bismuth. The pressures reported in this paper are estimated to be accurate to 1%.

The pulse transmission method described in detail by *Birch* [1960] was used to obtain the velocities. Barium titanate transducers of 2-MHz frequencies generated and received the compressional waves. The samples were cylindrical, 1.27 cm in diameter and 3 cm in length, and were jacketed with Cu foil to exclude the pentane and 2-methylbutane pressure medium. The first arrivals received from the samples were matched with similarly shaped first arrivals obtained from a calibrated variable-length mercury delay line.

In velocity measurements to 10 kbar the break of the initial rise from the sample, and thus the ease of matching the delay line signal with the signal from the sample, becomes better defined with increasing pressure. This is probably due to many factors, including closure of pore space in the sample and improved bonding at high pressure between the transducers and the sample. In the runs to 30 kbar the quality of the signal continued to improve beyond 10 kbar to approximately 18 kbar, where a slight decrease in amplitude of the initial rise accompanied increasing pressure. However, even at 30 kbar the initial onset of the first motion was found to be superior to signals commonly observed in rocks at pressures below 2 kbar. The accuracy of the measurements above 2 kbar is estimated to be 0.5%. The precision, which is important in obtaining the pressure derivatives of the velocities, is better than 0.1%.

DESCRIPTION OF SAMPLES

Large blocks of pyroxenite, dunite, and eclogite visibly free of fractures were selected for the study. Particular attention was given in obtaining samples that were as free of secondary alteration as possible. Rocks with abundant pyroxene and olivine commonly possess strong preferred orientation, which often results in significant anisotropy [*Birch,* 1960; *Christensen,* 1966; *Christensen and Ramananantoandro,* 1971; *Babuška,* 1972]. Preliminary petrofabric analyses of the samples showed only weak pyroxene and olivine orientation. To establish the maximum anisotropy, three cores 2.54 cm in diameter and 7–8 cm in length were cut from each sample. Two directions from each sample were selected with the aid of the fabric diagrams to give maximum anisotropy, and velocities were measured to 10 kbar in the three cores from each rock. The results of the measurements at 10 kbar are summarized in Table 1. Separate cores were obtained for the 30-kbar measurements, the axes of which paralleled the cores that gave intermediate 10-kbar compressional wave velocities.

The pyroxenites differ somewhat in composition. Modal analysis of the Stillwater pyroxenite gives 97% bronzite, 1% olivine, 1% opaque, and less than 1% plagioclase and mica. The Twin Sisters pyroxenite contains approximately 82% enstatite, 18% olivine, and less than 1% opaque and serpentine. The anisotropy observed in the Twin Sisters

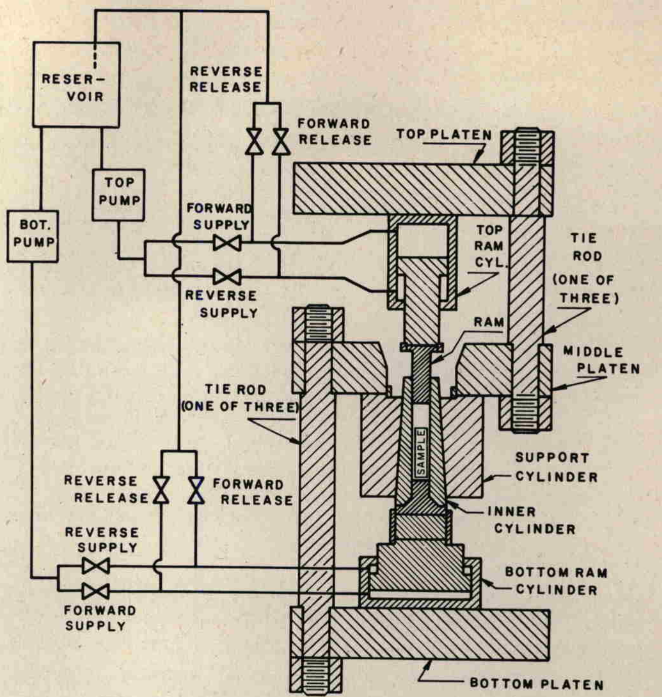

Fig. 1. Bridgman-Birch 30-kbar apparatus.

TABLE 1. Mean Velocities, Mean Densities, Calculated Elastic Constants, and Anisotropies at 10 kbar

Parameter	Pyroxenite, Stillwater, Montana	Pyroxenite, Twin Sisters, Washington	Dunite, Twin Sisters, Washington	Eclogite, Sunnmøre, Norway	Eclogite, Nové Dvory, Czechoslovakia
Compressional wave velocity, km/s	8.056	7.937	8.496	8.268	8.424
Shear wave velocity, km/s	4.622	4.453	4.834	4.617	4.639
Bulk density, g/cm^3	3.332	3.309	3.329	3.546	3.581
Compressibility, Mbar^{-1}	0.82	0.83	0.73	0.71	0.66
Lamé's constant, Mbar	0.74	0.77	0.85	0.91	1.00
Shear modulus, Mbar	0.71	0.66	0.78	0.76	0.77
Poisson's ratio	0.25	0.27	0.26	0.27	0.28
Seismic parameter, (km/s)^2	36.4	36.5	41.0	39.9	42.3
Young's modulus, Mbar	1.79	1.67	1.96	1.93	1.98
Bulk modulus, Mbar	1.21	1.21	1.37	1.42	1.51
Compressional wave anisotropy	0.7%	3.8%	0.3%	2.4%	0.8%
Shear wave anisotropy	0.5%	3.1%	1.5%	1.4%	1.9%