Ultrasonic Velocities and Related Elastic Properties of Hawaiian Basaltic Rocks[1]

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LABORATORY MEASUREMENTS of the compressional-wave and shear-wave velocities of various rock types give a useful basis for understanding the geological significance of observed variations in seismic-wave velocities associated with the crust and upper mantle (Birch, 1961, 1964).

The rocks exposed at the surface in Hawaii provide excellent material for testing the velocity-density relationships and the anisotropic effects in rocks believed to form the crust and the upper mantle under the ocean floor. These rocks exhibit wide ranges of porosity, density, and mineralogical composition, and their physical properties represent a number of emplacement environments.

The Hawaii Institute of Geophysics program for measuring the elastic properties of the Hawaiian rocks is confined as yet to normal pressure and temperature conditions, but it is planned to expand the program to include studies under high pressure and temperature conditions to match those at depth down to the level of the lower crust and the upper mantle.

The following paragraphs present the results of measurements of density and ultrasonic velocities for some selected Hawaiian rocks which are significant in the interpretation of the crustal and upper mantle structure from seismic and gravity observations.

METHOD OF MEASUREMENT

The pulse technique of measuring compressional-wave velocities described by Birch (1960) was the one employed in the present investigation. Shear-wave velocities were measured using the technique described by Jamieson and Hoskins (1963). Their method involves the use of P-wave transducers, the conversion of the P-wave pulse into an S-wave pulse through a pyrex glass prism, transmittance of the S-wave through the sample, and reconversion of the S-wave into a P-wave through a similar prism. Barium titanate transducers were employed in making all measurements. In addition to cores, samples cut into cuboids of suitable dimensions (2 × 2 × 2 inches) were used for measuring velocities in three mutually perpendicular directions.

RESULTS AND DISCUSSION

The elastic properties of some of the Hawaiian basaltic rocks that were studied are given in Table 1. The rocks represented are tholeiitic and alkaline olivine basalts, trachyte, amphibolite, ankaramite, dunite, and eclogite. Basalts represent the largest group of rocks studied. The maximum compressional-wave velocity (7.0 km/sec) under surface conditions is found in an amphibolitic intrusive dike rock having a density of 3.0 gm/cc. This rock is found in the Koolau caldera. Another specimen (eclogite), also from the Koolau caldera, has a rather low density (2.81 gm/cc) and velocity (6.2 km/sec). In hand specimen the eclogite appears to be porous (>5%), and under the microscope it shows some alteration zones formed as a result of reaction with the magma during its eruption. Without this contamination the eclogite would have had a density and velocity equivalent to that found for the amphibolitic rock of the Koolau caldera. The significance of high density (3.0 gm/cc or higher) and high velocity (7.0 km/sec or higher) values is evident in that these materials truly represent, in terms of seismic velocities, the constituents of mantle-like material in this caldera. An ultrabasic rock with a surface density of 3.0 gm/cc and velocity of 7.0 km/sec, when placed in the upper mantle environment under the oceans (approximately a depth of 10–12 km), would have a velocity of 7.5–7.8 km/sec.

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TABLE 1

ELASTIC PROPERTIES OF SOME HAWAIIAN BASALTS

SAMPLE	V_p* km/sec	V_s km/sec	ϵ (DENSITY) g/cc	κ (BULK MODULUS) dynes/cm² $\times 10^{-11}$	μ (MODULUS OF RIGIDITY) dynes/cm² $\times 10^{-11}$	E (YOUNG'S MODULUS) dynes/cm² $\times 10^{-11}$	$\frac{K}{\mu}$	σ (POISSON'S RATIO)
Olivine basalt	4.95 4.63 4.82	2.56	2.0	3.15	1.31	3.45	2.40	0.317
Olivine basalt	4.65	2.50	2.30	3.05	1.47	3.80	2.07	0.292
Olivine basalt	5.65 4.38 5.47	3.10	2.36	4.03	2.27	5.23	1.78	0.264
Olivine basalt (ankaramite)	5.08	3.02	2.40	4.6	2.18	5.56	2.11	0.296
Olivine basalt	5.52	2.76	2.60	5.27	1.98	5.27	2.63	0.330
Eclogite	6.06 5.82 5.86	2.94	2.81	6.29	2.43	6.45	2.59	0.328
Amphibolite	6.90 6.75 6.76	3.53	2.95	8.5	3.67	9.63	2.32	0.312
Hawaiite	4.20	2.51	2.59	2.4	1.63	4.0	1.48	0.224
Trachyte	5.18	2.83	2.60	4.22	2.08	5.4	2.15	0.298

* The three values of V_p are for transmission in three mutually perpendicular directions of propagation through the same specimen.

Figure 1 shows the velocity-density relation of the Hawaiian basalts and other volcanic rocks. These are primarily olivine basalts with varying amounts of olivine and other ferromagnesian silicates. The velocities of the olivine basalts vary from 4.5–6.5 km/sec with corresponding changes in densities from 2.2–2.8 gm/cc. As will be seen, the values are largely dependent on vesicular structure, the amount of interstitial glass present, and the amount of olivine present.

Figure 2 shows the variation in ultrasonic velocities in four olivine basalts of comparable density but having different percentages of olivine. The inclusions of dunites and olivine-rich rocks in some of the volcanic flows on the island of Hawaii, especially in the 1801 flow, are not uncommon, and have been described by Ross et al. (1954). These rocks, composed principally of olivine, give velocities of 6.5–7.2 km/sec (density 2.8–3.1 gm/cc) under atmospheric conditions of temperature and pressure. Of all the Hawaiian rocks whose transmission velocities have been measured (including eclogite), the dunites and olivine-rich inclusions give the highest values. The measured seismic velocities of the upper mantle under the Hawaiian Archipelago (Furumoto and Woollard, p. 315 in this issue; Eaton, 1962) are of the order of 8.2–9.0 km/sec. Eaton's deduced velocity distribution under a typical volcano is based upon local earthquake data on Hawaii. The values reported by Furumoto et al. are based upon explosion seismic refraction measurements. Inasmuch as most of the magmas connected with Hawaiian volcanic eruptions are believed to originate at the depths of earthquake foci at or about 60 km, the seismic velocities below the Moho are important from the point of view of the chemical composition of the upper mantle. Although it is not the purpose of this report to discuss the pros and cons of various models of the upper mantle, it can be said that the presence of olivine-rich nodules in some of the Hawaiian flows, the increasing transmission velocity of the olivine basalts (ankaramite) with increasing olivine content (see also Birch, 1961), and the seismic velocities of the layer below the Moho discontinuity (8.2–9.0 km/sec) all indicate that the upper mantle below the Hawaiian Archipelago is most probably composed of material resembling dunite. The planned high pressure and temperature measurements of velocities of the dunites and olivine-rich basalts at the Hawaii Institute of Geophysics should clarify some of the unsolved questions.

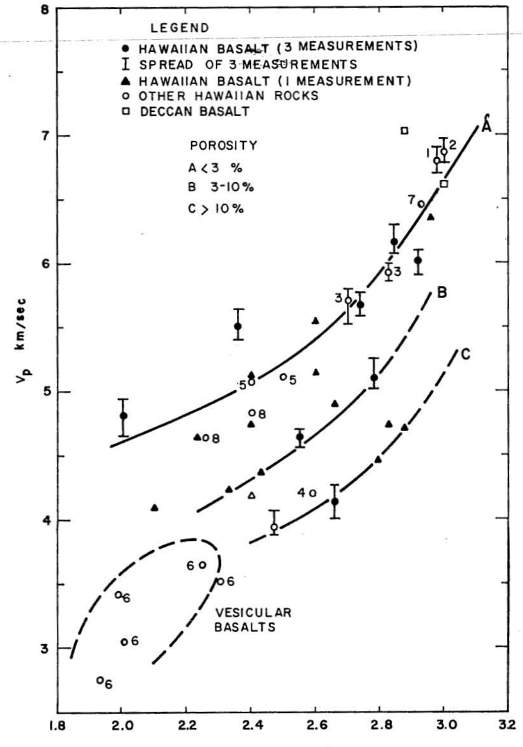

FIG. 1. Velocity versus density relationship in Hawaiian rocks. *1* and *2*, amphibolitic rocks; *3*, eclogite; *4*, hawaiite; *5*, ankaramite; *6*, vesicular basalt; *7*, pyroxenite; *8*, tholeiite.

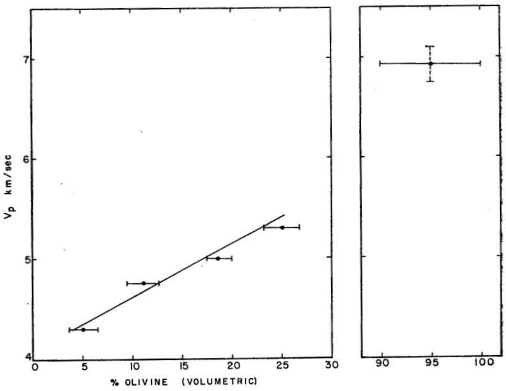

FIG. 2. Velocity versus olivine content in basalts.

Amphibolitic rocks (Fig. 1, *1* and *2*) and an eclogite (Fig. 1, *3*) having higher densities than basalt show higher velocity values, as stated earlier. Although the curves of Figure 1 have been drawn on the basis of apparent porosity values as deduced from wet and dry density determinations, these are obviously not all true porosities and permeability is a parameter that is also incorporated. The effect of this factor will require further study. In gross form, though, the velocity-density relationships shown for volcanic rocks are essentially correct. As might be expected, the velocity in a rock is significantly lowered when the porosity increases. The dispersion in the three curves can be attributed to the differences in mineral composition, crystallinity of the material constituting the rock, the size and geometry of vesicles present, and the undetermined effect of permeability due to microfractures.

Horizontal variations in seismic velocities of the upper layers of the basaltic lavas on the Hawaiian Islands, as observed by the Hawaii Institute of Geophysics group (Furumoto and Woollard, p. 315 in this issue) and others, are real and thus signify variations not only in mineralogical composition and density but in vesicularity and permeability as well. Problems pertaining to the degree of vesicularity to be expected at depth can best be understood by studying the variation in seismic velocity in material of variable vesicularity and density. The ideal approach to the solution of this prob-

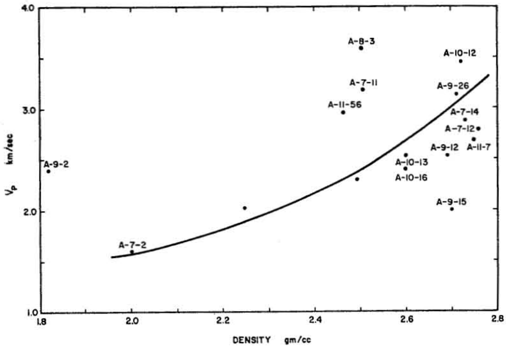

FIG. 3. Velocity versus density in cores from Alae Crater, Hawaii.

lem would be to drill through lava material and obtain the cores to examine vesicularity, density, chemical composition, and other physical properties. Figure 3 shows the physical measurements on some drill cores obtained from Alae Crater, island of Hawaii, by the U. S. Geological Survey Volcano Observatory scientists. Although there is a direct relationship between the velocity and density of these cores there is significant variation in the velocities of cores (Fig. 3, *A-9-15, A-10-16, A-10-13, A-9-12, A-11-7, A-7-12,* etc.) with little or no change in density (2.6–2.7 gm/cc). The chemical composition of these cores is about the same (Dallas Peck, personal communication), but there is a large variation in the glass content in the rock material. Because the modulus of rigidity of glass is much lower than the average value of equivalent crystalline rock material, the velocity of propagation of elastic waves will be lowered as the percentage of glass increases. The relationship between velocity and glass content for these cores is shown in Figure 4. The low velocities of the Pacific Ocean upper crustal layer (3.8–4.2 km/sec) reported by Raitt (1956), and by Shor and Pollard (1964), and verified by the unpublished studies by Western Geophysical Company, suggest that the glass content may be influencing the seismic velocity to a large extent. Certainly, the work by J. Moore of the U. S. Geological Survey (personal communication) indicates essentially zero porosity for basalts extruded on the ocean floor. Quick chilling could produce interstitial glass, however.

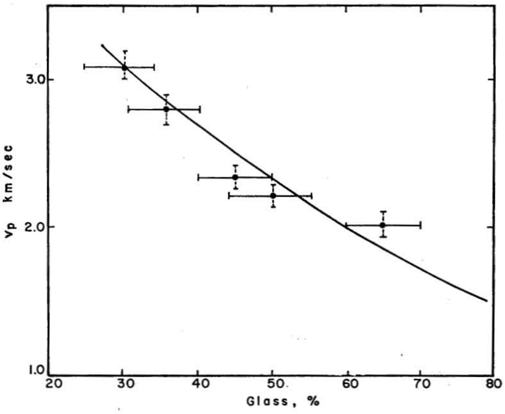

FIG. 4. Velocity versus glass content in cores from Alae Crater, Hawaii.

ANISOTROPY

There is a significant degree of anisotropy in the transmission of compressional waves in Hawaiian rocks. This is shown in Table 1 and Figure 1, where velocities obtained in three perpendicular directions through the same sample are recorded. In some rock types there is as much as 8–10% difference between the maximum and minimum velocities observed. Although anisotropism in vesicular lavas is related to dimensional orientation of the vesicles, in whole rock material it is related principally to mineral orientation. Both olivine and plagioclase feldspars are of special interest in the interpretation of seismic refraction data. This portion of the study now underway at the Institute of Geophysics is still in its initial stage.

SUMMARY

1. Density, rock structure, porosity, permeability, and glass content control the seismic velocities of the vesicular basaltic lavas.

2. Density, glass content, and mineralogical composition of the non-vesicular flows and intrusives control their seismic velocities and related elastic properties.

3. The alkalic basalts (e.g., trachytic type) have a low velocity of transmission as compared with the tholeiitic olivine basalts.

4. The average value of Poisson's ratio for Hawaiian basalts is 0.29.

5. Dunites and olivine-rich inclusions in the Hawaiian basalts have the highest transmission velocities observed in this study. This material is most probably derived from the upper mantle.

6. The Hawaiian rocks exhibit significant degrees of anisotropy due to the differences in the mineral composition and orientation, and the geometry and orientation of the vesicles.

ACKNOWLEDGMENTS

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