

# Velocity Structure of the Troodos Massif, an Arc-Derived Ophiolite

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## Abstract

The seismic velocity structure of a section of the Troodos Massif has been reconstructed in detail from values of compressional (Vp) and shear (Vs) wave velocities measured in the laboratory under elevated hydrostatic confining pressures for 74 samples obtained from drillhole CY-4 at Palekhoroi, Cyprus. The 2263 m thick section begins in sheeted dikes and continues through a gabbroic section into ultramafic rocks consisting of websterites, olivine websterites and minor lherzolites. The sheeted dike section shows strong velocity gradients with Vp increasing from 5.4 km/sec at the top to 6.8 km/sec at 630 m depth. Beneath the dike section, low velocity zones for both Vp and Vs originate from alteration of high level gabbros. Velocities from depths between 950 m and 1750 m agree well with oceanic Layer 3 velocities. The transition from gabbro to websterite and olivine websterite at 1750 m marks a sharp increase in velocity to Vs = 4.2 km/sec and Vp = 7.7 km/sec. These values fall within the range observed for the oceanic Mohorovicic discontinuity by refraction.

## Résumé

La configuration des vitesses séismiques d'une section du massif de Troodos a été reconstituée en détail à partir des vitesses des ondes compressives (Vp) et cisailantes (Vs) mesurées en laboratoire sous des pressions hydrostatiques confinantes élevées. Les 74 échantillons étudiés proviennent du forage CY-4, à Palekhoroi, Chypre. La section, épaisse de 2263 m, débute dans le complexe filonien et traverse des roches gabbroïques à ultramafiques, ces dernières étant constituées de websterites, de websterites à olivine et de peu de lherzolites. La portion du complexe filonien montre un fort gradient de vitesse caractérisé par Vp croissant de 5.4 km/sec au sommet à 6.8 km/sec à 630 m de profondeur. Sous le complexe filonien des zones à faibles vitesses Vp et Vs sont observées sur les gabbros supérieurs métamorphisés. Les vitesses mesurées pour les profondeurs comprises entre 950 et 1750 m sont très comparables à celles mesurées dans la couche 3 de la croûte océanique. La zone de transition, depuis les gabbros jusqu'aux websterites et aux websterites à olivine à 1750 m, est marquée par des accroissements importants des vitesses Vs (4.2 km/sec) et Vp (7.7 km/sec). Ces vitesses se situent à l'intérieur de l'intervalle des valeurs mesurées par sismique-refraction pour la discontinuité Mohorovicic océanique.

## INTRODUCTION

Beginning in the early 1970's, it became widely recognized that ophiolite complexes may represent on land exposures of oceanic crust and upper mantle (e.g., Coleman, 1971; Dewey and Bird, 1971; Moores and Vine, 1971). Although direct observations of the nature of the oceanic crust were limited to dredging and shallow drilling, the seismic structure of the oceanic crust was well known in many localities (Raitt, 1963; Shor et al., 1971). Thus, it was critical to examine the seismic properties of ophiolites and compare them with oceanic crustal structure determined by marine seismic investigations. Laboratory measurements of seismic velocities of major ophiolite lithologies (Peterson et al., 1973; Kroenke et al., 1976; Christensen, 1978) and rock suites from detailed traverses through complete or nearly complete ophiolite sections (Salisbury and Christensen, 1978; Christensen and Smewing, 1981; Christensen and Salisbury, 1982) demonstrated many similarities between ophiolite and oceanic crustal velocities. In addition, perhaps the most convincing evidence for ophiolite oceanic crustal models was the finding that seismic anisotropies of ophiolite ultramafic sections are similar to oceanic upper mantle anisotropies (e.g. Christensen and Salisbury, 1979; Christensen and Lundquist, 1982; Christensen, 1984).

Two major problems concerning the possibility of ophiolites as oceanic crustal analogs have persisted however. First, the thicknesses of crustal sections of many ophiolites, including the Troodos complex, appear thin compared with seismic measurements of oceanic crustal thickness (Christensen and Salisbury, 1975). Secondly, the chemistries of many ophiolites are calc-alkaline, suggesting that some may have originated in an island arc environment (e.g., Miyashiro, 1973). A probable origin at a spreading center located within an island arc for the Troodos ophiolite is supported by chemical studies of volcanic glass samples (Robinson et al., 1983).

In this paper, we investigate the detailed seismic and density structure of a major section of the Troodos ophiolite with the purpose of understanding the seismic structure of oceanic crust formed in an island arc environment. Seismic velocities at elevated pressures are presented along with densities for 74 samples from the sheeted dike section, the gabbroic section and the websterites and olivine websterites of drill hole CY-4 at Palekhori, Cyprus. Excellent depth control of the velocity and density profiles over the 2263 m thick section is made possible by the 99.9% core recovery. The high recovery also implies that the section is (relatively) free of open cracks and that laboratory measurements may be fairly representative of formation properties. Major velocity gradients and discontinuities in the Troodos ophiolite are found to have similarities with those in other ophiolites and some oceanic crustal seismic sections.

## MEASUREMENT TECHNIQUES

Minicores approximately 2.45 cm in diameter and 3 to 6 cm in length were taken from the main drill core at approximately 20 to 40 m intervals. Each sample was selected as carefully as possible to be representative of the depth interval from which it was obtained. The samples were weighed dry, then saturated with water and reweighed. The bulk density of each sample was determined from its mass and dimensions and the porosity was calculated from its wet and dry weights. The mineralogy of each sample was determined from thin section analysis.

Compressional and shear wave velocities were measured using the pulse transmission technique described in detail by Birch (1960). All velocities were obtained at room temperature using water-saturated samples. Transducers with resonant frequencies of 1 MHz were used to generate and receive the compressional and shear waves. The samples were jacketed with copper foil and 100-mesh copper screens were placed between the cores and jackets to provide space for water to drain from microcracks as the confining pressure was increased. Thus, pore pressure was lower than confining pressure during the pressure cycles.

## DATA AND DISCUSSION

Compressional and shear wave velocities, water saturated bulk densities ( $\rho$ ) and porosities ( $\phi$ ) are given in Table 1. In addition to the velocities, velocity ratios ( $V_p/V_s$ ), Poisson's ratios ( $\sigma$ ), bulk moduli ( $K$ ) and shear moduli ( $\mu$ ) are tabulated for various pressures. The elastic constants were calculated from the measured velocities and densities using the equations summarized by Birch (1961).

A stratigraphic section of the drill core along with measured densities and velocities from Table 1 are shown in Figure 1. Velocities at the top of the section were measured at a differential confining pressure of 90 MPa (0.9 kbar) while those shown at greater depths were at appropriate higher pressures. The lowermost velocities in Figure 1 are at confining pressures of 140 MPa (1.4 kbar). These pressures correspond to those extending from the lower portion of Oceanic Layer 2 to well into Layer 3. The velocity and density structures of the Troodos ophiolite shown in Figure 2 are based upon the relative abundances of each lithology as observed in the complete section of drill core. Also shown are envelopes defining the ranges of measured velocities and densities.

Based on the petrology of the drill hole and the velocity and density profiles of Figures 1 and 2, the ophiolite section sampled in hole CY-4 can be divided into four velocity zones. The uppermost consists of dike rocks. This zone is characterized by strong positive velocity gradients. Compressional wave velocities increase from approximately 5.4 km/sec at the top of the drill hole to 6.8 km/sec at a depth of 630 m and shear wave velocities

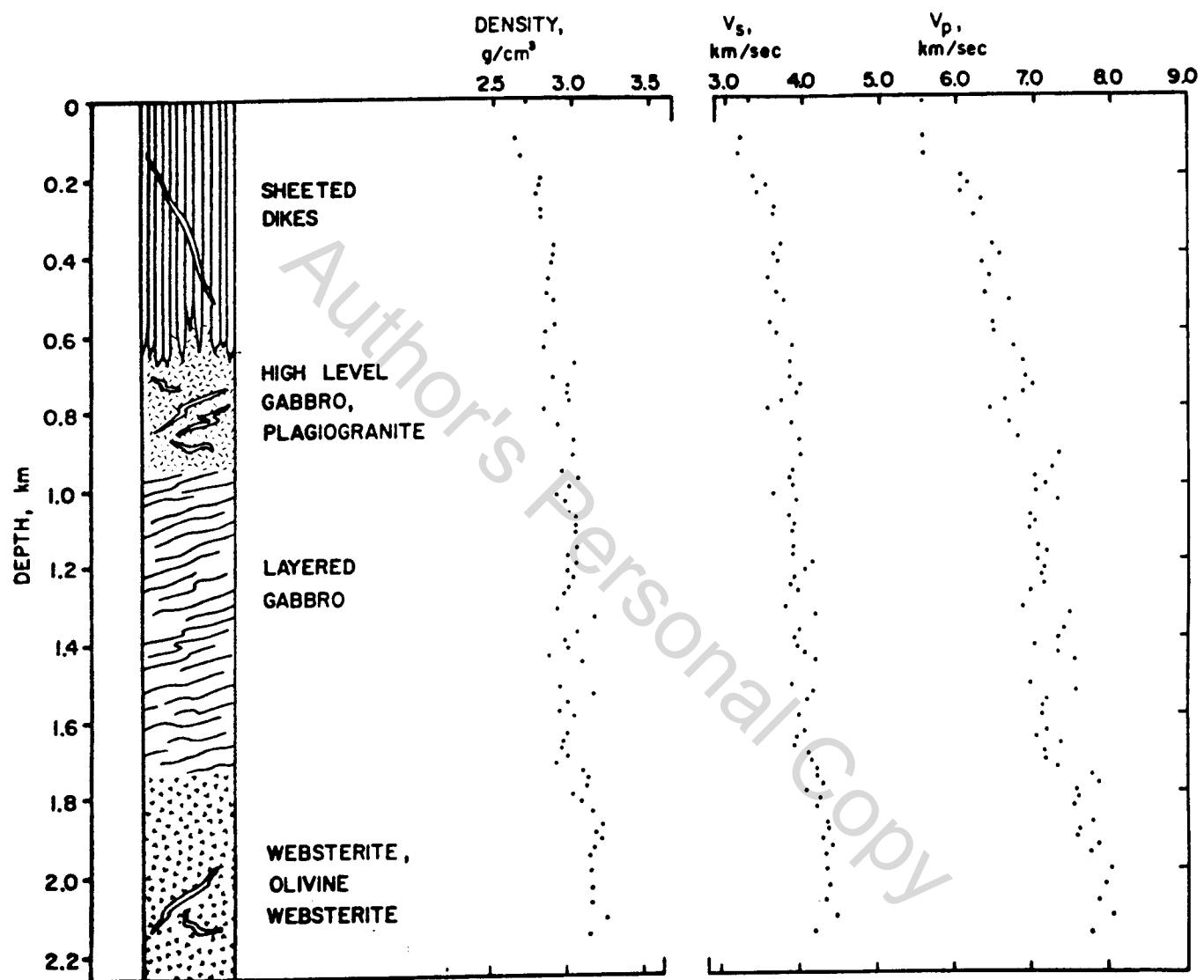
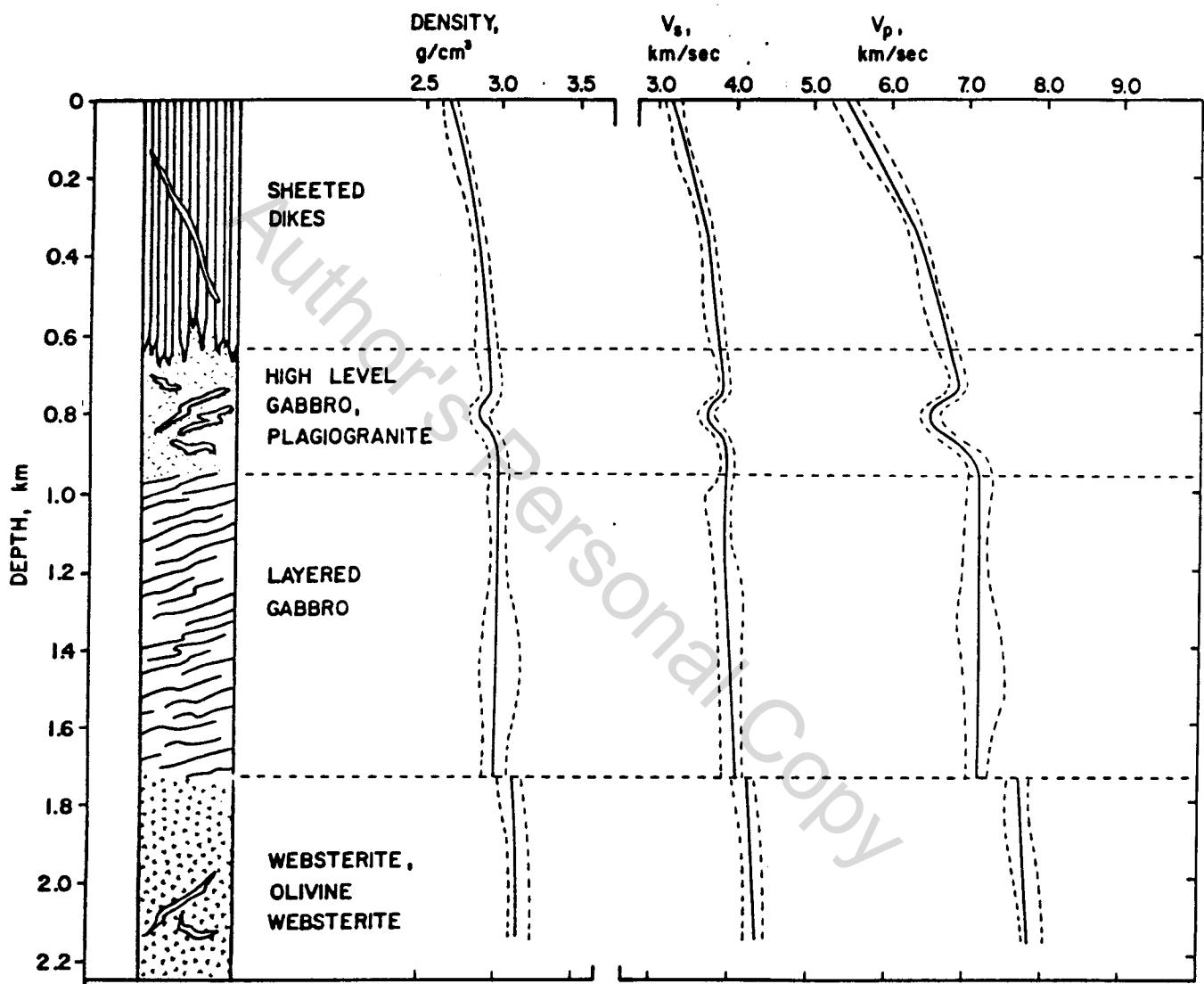


Figure 1: Density, compressional ( $V_p$ ) and shear ( $V_s$ ) wave velocities as a function of depth in hole CY-4.



**Figure 2:** Envelopes of Compressional ( $V_p$ ) and shear ( $V_s$ ) wave velocity and density versus depth in hole CY-4. Solid lines represent best fit to the data.

TABLE 1: Compressional (Vp) and shear (Vs) wave velocities, Poisson's ratios  $\sigma$ , bulk moduli (K) and shear moduli  $\mu$  versus pressure (P).

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 61.75 m	0.2	5.45	3.19	1.71	0.24	0.44	0.27
Diabase	0.4	5.49	3.24	1.70	0.23	0.44	0.28
$\rho = 2.70 \text{ g/cm}^3$	0.6	5.52	3.27	1.69	0.23	0.44	0.29
$\phi = 2.8\%$	0.8	5.54	3.29	1.68	0.23	0.44	0.29
	1.0	5.56	3.31	1.68	0.23	0.44	0.30
	2.0	5.64	3.34	1.69	0.23	0.46	0.30
	4.0	5.72	3.37	1.70	0.23	0.48	0.31
	6.0	5.77	3.38	1.70	0.24	0.49	0.31
CY-4 100.11 m	0.2	5.39	3.10	1.74	0.25	0.43	0.25
Diabase	0.4	5.46	3.14	1.74	0.25	0.44	0.26
$\rho = 2.63 \text{ g/cm}^3$	0.6	5.51	3.17	1.74	0.25	0.45	0.26
$\phi = 3.2\%$	0.8	5.55	3.18	1.74	0.25	0.45	0.27
	1.0	5.57	3.20	1.74	0.25	0.46	0.27
	2.0	5.65	3.24	1.74	0.25	0.47	0.28
	4.0	5.69	3.26	1.74	0.25	0.48	0.28
	6.0	5.70	3.27	1.74	0.25	0.48	0.28
CY-4 140.81 m	0.2	5.30	3.03	1.75	0.26	0.42	0.24
Diabase	0.4	5.43	3.09	1.76	0.26	0.45	0.25
$\rho = 2.66 \text{ g/cm}^3$	0.6	5.51	3.12	1.77	0.26	0.46	0.26
$\phi = 3.2\%$	0.8	5.56	3.14	1.77	0.27	0.47	0.26
	1.0	5.60	3.16	1.77	0.27	0.48	0.27
	2.0	5.68	3.21	1.77	0.27	0.49	0.27
	4.0	5.73	3.24	1.77	0.27	0.51	0.28
	6.0	5.76	3.26	1.77	0.26	0.51	0.29
CY-4 199.90 m	0.2	5.93	3.21	1.85	0.29	0.60	0.29
Diabase	0.4	5.98	3.27	1.83	0.29	0.61	0.30
$\rho = 2.81 \text{ g/cm}^3$	0.6	6.02	3.31	1.82	0.28	0.61	0.31
$\phi = 1.5\%$	0.8	6.04	3.34	1.81	0.28	0.61	0.31
	1.0	6.06	3.36	1.81	0.28	0.61	0.32
	2.0	6.14	3.40	1.81	0.28	0.63	0.33
	4.0	6.22	3.43	1.81	0.28	0.65	0.33
	6.0	6.28	3.45	1.82	0.28	0.67	0.34
CY-4 219.28 m	0.2	6.00	3.44	1.74	0.26	0.56	0.33
Diabase	0.4	6.06	3.47	1.74	0.25	0.57	0.34
$\rho = 2.79 \text{ g/cm}^3$	0.6	6.09	3.50	1.74	0.25	0.58	0.34
$\phi = 1.3\%$	0.8	6.11	3.51	1.74	0.25	0.58	0.34
	1.0	6.13	3.52	1.74	0.25	0.59	0.35
	2.0	6.19	3.56	1.74	0.25	0.60	0.35
	4.0	6.24	3.59	1.74	0.25	0.61	0.36
	6.0	6.26	3.60	1.74	0.25	0.62	0.36
CY-4 240.00 m	0.2	5.86	3.29	1.78	0.27	0.55	0.30
Diabase	0.4	5.93	3.34	1.78	0.27	0.56	0.31
$\rho = 2.77 \text{ g/cm}^3$	0.6	5.98	3.37	1.77	0.27	0.57	0.32
$\phi = 1.2\%$	0.8	6.01	3.39	1.77	0.27	0.58	0.32
	1.0	6.04	3.41	1.77	0.27	0.58	0.32
	2.0	6.10	3.45	1.77	0.27	0.60	0.33
	4.0	6.16	3.48	1.77	0.27	0.61	0.34
	6.0	6.26	3.60	1.74	0.25	0.62	0.36

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 279.50 m	0.2	6.20	3.55	1.75	0.26	0.61	0.35
Diabase	0.4	6.26	3.59	1.74	0.26	0.62	0.36
$\rho = 2.80 \text{ g/cm}^3$	0.6	6.29	3.61	1.74	0.26	0.62	0.36
$\phi = 0.4\%$	0.8	6.31	3.62	1.74	0.25	0.63	0.37
	1.0	6.33	3.63	1.74	0.25	0.63	0.37
	2.0	6.38	3.65	1.75	0.26	0.64	0.37
	4.0	6.43	3.67	1.75	0.26	0.66	0.38
	6.0	6.45	3.68	1.75	0.26	0.67	0.38
CY-4 299.57 m	0.2	6.09	3.54	1.72	0.24	0.57	0.35
Diabase	0.4	6.15	3.58	1.72	0.24	0.58	0.36
$\rho = 2.80 \text{ g/cm}^3$	0.6	6.18	3.60	1.72	0.24	0.59	0.36
$\phi = 0.7\%$	0.8	6.20	3.61	1.72	0.24	0.59	0.37
	1.0	6.21	3.62	1.72	0.24	0.59	0.37
	2.0	6.27	3.65	1.72	0.24	0.60	0.37
	4.0	6.32	3.67	1.72	0.25	0.62	0.38
	6.0	6.35	3.68	1.73	0.25	0.63	0.38
CY-4 377.50 m	0.2	6.38	3.61	1.77	0.26	0.67	0.38
Diabase	0.4	6.42	3.66	1.76	0.26	0.67	0.39
$\rho = 2.88 \text{ g/cm}^3$	0.6	6.45	3.68	1.75	0.26	0.68	0.39
$\phi = 0.3\%$	0.8	6.46	3.70	1.75	0.26	0.68	0.39
	1.0	6.47	3.71	1.75	0.26	0.68	0.40
	2.0	6.50	3.72	1.75	0.26	0.69	0.40
	4.0	6.55	3.73	1.75	0.26	0.70	0.40
	6.0	6.58	3.74	1.76	0.26	0.72	0.41
CY-4 399.11 m	0.2	6.47	3.51	1.85	0.29	0.73	0.35
Diabase	0.4	6.52	3.55	1.83	0.29	0.74	0.36
$\rho = 2.88 \text{ g/cm}^3$	0.6	6.55	3.58	1.83	0.29	0.74	0.37
$\phi = 0.6\%$	0.8	6.57	3.60	1.82	0.28	0.74	0.37
	1.0	6.59	3.62	1.82	0.28	0.75	0.38
	2.0	6.65	3.66	1.82	0.28	0.76	0.39
	4.0	6.69	3.68	1.82	0.28	0.77	0.39
	6.0	6.71	3.68	1.82	0.28	0.78	0.39
CY-4 420.81 m	0.2	6.27	3.63	1.73	0.25	0.63	0.38
Diabase	0.4	6.30	3.65	1.73	0.25	0.63	0.38
$\rho = 2.87 \text{ g/cm}^3$	0.6	6.32	3.67	1.72	0.25	0.63	0.39
$\phi = 0.6\%$	0.8	6.33	3.68	1.72	0.25	0.63	0.39
	1.0	6.33	3.68	1.72	0.24	0.63	0.39
	2.0	6.36	3.70	1.72	0.24	0.64	0.39
	4.0	6.40	3.72	1.72	0.25	0.65	0.40
	6.0	6.42	3.72	1.72	0.25	0.66	0.40
CY-4 459.60 m	0.2	6.31	3.49	1.81	0.28	0.67	0.35
Diabase	0.4	6.36	3.52	1.81	0.28	0.68	0.35
$\rho = 2.85 \text{ g/cm}^3$	0.6	6.39	3.54	1.81	0.28	0.69	0.36
$\phi = 0.4$	1.0	6.43	3.56	1.81	0.28	0.70	0.36
	2.0	6.48	3.58	1.81	0.28	0.71	0.37
	4.0	6.53	3.60	1.81	0.28	0.72	0.37
	6.0	6.56	3.61	1.82	0.28	0.73	0.37

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 497.13 m	0.2	6.27	3.64	1.72	0.25	0.62	0.38
Diabase	0.4	6.32	3.65	1.73	0.25	0.63	0.38
$\rho = 2.84 \text{ g/cm}^3$	0.6	6.35	3.66	1.74	0.25	0.64	0.38
$\phi = 0.7\%$	0.8	6.37	3.67	1.74	0.25	0.65	0.38
	1.0	6.39	3.67	1.74	0.25	0.65	0.38
	2.0	6.42	3.69	1.74	0.25	0.66	0.39
	4.0	6.45	3.70	1.74	0.25	0.67	0.39
	6.0	6.46	3.70	1.74	0.26	0.67	0.39
CY-4 518.12 m	0.2	6.60	3.68	1.79	0.27	0.73	0.39
Diabase	0.4	6.64	3.71	1.79	0.27	0.74	0.40
$\rho = 2.88 \text{ g/cm}^3$	0.6	6.68	3.73	1.79	0.27	0.75	0.40
$\phi = 0.4\%$	0.8	6.70	3.74	1.79	0.27	0.76	0.40
	1.0	6.71	3.75	1.79	0.27	0.76	0.41
	2.0	6.76	3.76	1.80	0.28	0.78	0.41
	4.0	6.79	3.76	1.80	0.28	0.79	0.41
	6.0	6.80	3.77	1.81	0.28	0.80	0.41
CY-4 579.32 m	0.2	6.35	3.49	1.82	0.28	0.70	0.35
Diabase	0.4	6.42	3.53	1.82	0.28	0.71	0.36
$\rho = 2.89 \text{ g/cm}^3$	0.6	6.45	3.55	1.82	0.28	0.72	0.37
$\phi = 0.6\%$	0.8	6.48	3.57	1.82	0.28	0.72	0.37
	1.0	6.50	3.58	1.82	0.28	0.73	0.37
	2.0	6.57	3.62	1.82	0.28	0.75	0.38
	4.0	6.64	3.66	1.82	0.28	0.76	0.39
	6.0	6.68	3.68	1.81	0.28	0.77	0.40
CY-4 603.07 m	0.2	6.34	3.62	1.75	0.26	0.64	0.37
Diabase	0.4	6.41	3.65	1.76	0.26	0.66	0.38
$\rho = 2.83 \text{ g/cm}^3$	0.6	6.45	3.66	1.76	0.26	0.67	0.38
$\phi = 0.6\%$	0.8	6.47	3.67	1.76	0.26	0.68	0.38
	1.0	6.49	3.68	1.76	0.26	0.68	0.38
	2.0	6.52	3.70	1.76	0.26	0.69	0.39
	4.0	6.54	3.71	1.76	0.26	0.70	0.39
	6.0	6.55	3.71	1.76	0.26	0.70	0.39
CY-4 640.30 m	0.2	6.58	3.76	1.75	0.26	0.69	0.40
Gabbro	0.4	6.65	3.80	1.75	0.26	0.71	0.41
$\rho = 2.82 \text{ g/cm}^3$	0.6	6.69	3.83	1.75	0.26	0.71	0.41
$\phi = 0.0\%$	0.8	6.72	3.85	1.75	0.26	0.72	0.42
	1.0	6.74	3.86	1.75	0.26	0.72	0.42
	2.0	6.78	3.89	1.74	0.25	0.73	0.43
	4.0	6.81	3.90	1.75	0.26	0.74	0.43
	6.0	6.82	3.90	1.75	0.26	0.75	0.43
CY-4 680.10 m 0.2	0.2	6.68	3.72	1.80	0.28	0.80	0.42
Hornblende Gabbro	0.4	6.76	3.77	1.80	0.28	0.82	0.43
$\rho = 3.04 \text{ g/cm}^3$	0.6	6.81	3.80	1.79	0.27	0.83	0.44
$\phi = 0.3\%$	0.8	6.85	3.82	1.79	0.27	0.83	0.44
	1.0	6.87	3.84	1.79	0.27	0.84	0.45
	2.0	6.93	3.92	1.77	0.26	0.84	0.47
	4.0	6.97	4.00	1.74	0.25	0.83	0.49
	6.0	6.99	4.04	1.73	0.25	0.83	0.50

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 720.18 m	0.2	6.77	3.79	1.79	0.27	0.77	0.41
Hornblende Gabbro	0.4	6.84	3.81	1.80	0.28	0.79	0.42
$\rho = 2.88 \text{ g/cm}^3$	0.6	6.88	3.82	1.80	0.28	0.80	0.42
$\phi = 0.1\%$	0.8	6.90	3.83	1.80	0.28	0.81	0.42
	1.0	6.91	3.84	1.80	0.28	0.81	0.42
	2.0	6.94	3.86	1.80	0.28	0.82	0.43
	4.0	6.96	3.88	1.79	0.27	0.82	0.43
	6.0	6.97	3.89	1.79	0.27	0.82	0.44
CY-4 739.93 m	0.2	6.95	3.89	1.79	0.27	0.83	0.45
Hornblende Gabbro	0.4	6.98	3.93	1.77	0.27	0.83	0.46
$\rho = 2.97 \text{ g/cm}^3$	0.6	6.99	3.95	1.77	0.26	0.83	0.46
$\phi = 0.2\%$	0.8	7.00	3.97	1.76	0.26	0.83	0.47
	1.0	7.01	3.97	1.76	0.26	0.83	0.47
	2.0	7.03	3.99	1.76	0.26	0.84	0.47
	4.0	7.05	4.01	1.76	0.26	0.84	0.48
	6.0	7.06	4.02	1.76	0.26	0.85	0.48
CY-4 759.90 m	0.2	6.79	3.86	1.76	0.26	0.78	0.44
Altered Hb. Gabbro	0.4	6.83	3.88	1.76	0.26	0.79	0.45
$\rho = 2.97 \text{ g/cm}^3$	0.6	6.84	3.89	1.76	0.26	0.79	0.45
$\phi = 0.2\%$	0.8	6.85	3.90	1.76	0.26	0.79	0.45
	1.0	6.86	3.91	1.76	0.26	0.80	0.45
	2.0	6.89	3.93	1.75	0.26	0.80	0.46
	4.0	6.93	3.94	1.76	0.26	0.82	0.46
	6.0	6.95	3.95	1.76	0.26	0.82	0.47
CY-4 780.03 m	0.2	6.54	3.68	1.78	0.27	0.71	0.39
Altered Gabbro	0.4	6.58	3.70	1.78	0.27	0.72	0.39
$\rho = 2.88 \text{ g/cm}^3$	0.6	6.60	3.71	1.78	0.27	0.73	0.40
$\phi = 0.1\%$	0.8	6.62	3.72	1.78	0.27	0.73	0.40
	1.0	6.63	3.73	1.78	0.27	0.73	0.40
	2.0	6.67	3.75	1.78	0.27	0.74	0.41
	4.0	6.70	3.79	1.77	0.26	0.75	0.42
	6.0	6.72	3.81	1.76	0.26	0.75	0.42
CY-4 800.05 m	0.2	6.34	3.44	1.84	0.29	0.69	0.34
Altered Gabbro	0.4	6.38	3.48	1.83	0.29	0.70	0.34
$\rho = 2.83 \text{ g/cm}^3$	0.6	6.40	3.50	1.83	0.29	0.70	0.35
$\phi = 0.6\%$	0.8	6.42	3.52	1.83	0.29	0.70	0.35
	1.0	6.43	3.53	1.82	0.28	0.70	0.35
	2.0	6.48	3.57	1.82	0.28	0.71	0.36
	4.0	6.54	3.60	1.82	0.28	0.72	0.37
	6.0	6.57	3.62	1.82	0.28	0.73	0.37
CY-4 840.85 m	0.2	6.63	3.79	1.75	0.26	0.72	0.42
Gabbro	0.4	6.67	3.82	1.75	0.26	0.73	0.43
$\rho = 2.92 \text{ g/cm}^3$	0.6	6.69	3.84	1.74	0.26	0.74	0.43
$\phi = 0.2\%$	0.8	6.71	3.85	1.74	0.25	0.74	0.43
	1.0	6.72	3.86	1.74	0.25	0.74	0.44
	2.0	6.76	3.89	1.74	0.25	0.75	0.44
	4.0	6.79	3.91	1.74	0.25	0.76	0.45
	6.0	6.81	3.92	1.74	0.25	0.76	0.45

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 880.12 m	0.2	6.63	3.88	1.71	0.24	0.72	0.45
Gabbro	0.4	6.69	3.91	1.71	0.24	0.74	0.46
$\rho = 3.02 \text{ g/cm}^3$	0.6	6.73	3.92	1.72	0.24	0.75	0.47
$\phi = 0.2\%$	0.8	6.76	3.94	1.72	0.24	0.76	0.47
	1.0	6.78	3.95	1.72	0.24	0.76	0.47
	2.0	6.86	3.97	1.73	0.25	0.79	0.48
	4.0	6.94	3.99	1.74	0.25	0.82	0.48
	6.0	6.99	4.00	1.75	0.26	0.84	0.49
CY-4 919.96 m	0.2	7.25	3.94	1.84	0.29	0.96	0.47
Gabbro	0.4	7.29	3.95	1.85	0.29	0.97	0.47
$\rho = 3.01 \text{ g/cm}^3$	0.6	7.32	3.96	1.85	0.29	0.98	0.47
$\phi = 0.1\%$	0.8	7.34	3.97	1.85	0.29	0.99	0.47
	1.0	7.35	3.98	1.85	0.29	0.99	0.48
	2.0	7.40	4.00	1.85	0.29	1.01	0.48
	4.0	7.45	4.02	1.85	0.29	1.03	0.49
	6.0	7.47	4.02	1.86	0.30	1.04	0.49
CY-4 960.78 m	0.2	7.00	3.78	1.85	0.29	0.88	0.42
Gabbro	0.4	7.12	3.83	1.86	0.30	0.92	0.43
$\rho = 2.94 \text{ g/cm}^3$	0.6	7.18	3.85	1.86	0.30	0.94	0.44
$\phi = 0.1\%$	0.8	7.22	3.87	1.87	0.30	0.95	0.44
	1.0	7.24	3.87	1.87	0.30	0.95	0.44
	2.0	7.28	3.89	1.87	0.30	0.97	0.45
	4.0	7.31	3.91	1.87	0.30	0.98	0.45
	6.0	7.32	3.91	1.87	0.30	0.98	0.45
CY-4 980.03 m	0.2	6.91	3.80	1.82	0.28	0.87	0.44
Diabase	0.4	6.96	3.82	1.82	0.28	0.88	0.44
$\rho = 3.05 \text{ g/cm}^3$	0.6	6.99	3.83	1.83	0.29	0.89	0.45
$\phi = 0.1\%$	0.8	7.02	3.84	1.83	0.29	0.90	0.45
	1.0	7.03	3.84	1.83	0.29	0.91	0.45
	2.0	7.08	3.86	1.84	0.29	0.92	0.45
	4.0	7.09	3.87	1.83	0.29	0.93	0.46
	6.0	7.09	3.87	1.83	0.29	0.93	0.46
CY-4 1000.06 m	0.2	7.09	3.86	1.84	0.29	0.91	0.44
Gabbro	0.4	7.13	3.87	1.84	0.29	0.92	0.45
$\rho = 2.98 \text{ g/cm}^3$	0.6	7.14	3.88	1.84	0.29	0.92	0.45
$\phi = 0.0\%$	0.8	7.16	3.89	1.84	0.29	0.93	0.45
	1.0	7.16	3.89	1.84	0.29	0.93	0.45
	2.0	7.19	3.91	1.84	0.29	0.94	0.46
	4.0	7.22	3.92	1.84	0.29	0.95	0.46
	6.0	7.23	3.93	1.84	0.29	0.95	0.46
CY-4 1019.96 m	0.2	6.86	3.44	1.99	0.33	0.91	0.35
Gabbro	0.4	6.98	3.48	2.01	0.33	0.95	0.35
$\rho = 2.91 \text{ g/cm}^3$	0.6	7.02	3.51	2.00	0.33	0.96	0.36
$\phi = 0.2$	1.0	7.05	3.54	1.99	0.33	0.96	0.36
	2.0	7.07	3.57	1.98	0.33	0.96	0.37
	4.0	7.08	3.59	1.97	0.33	0.96	0.38
	6.0	7.09	3.60	1.97	0.33	0.97	0.38

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 1039.87 m	0.2	7.12	3.86	1.84	0.29	0.91	0.44
Gabbro	0.4	7.21	3.88	1.86	0.30	0.94	0.45
$\rho = 2.96 \text{ g/cm}^3$	0.6	7.26	3.90	1.86	0.30	0.96	0.45
$\phi = 0.1$	1.0	7.32	3.92	1.87	0.30	0.98	0.46
	2.0	7.36	3.95	1.87	0.30	0.99	0.46
	4.0	7.40	3.96	1.87	0.30	1.00	0.47
	6.0	7.41	3.97	1.87	0.30	1.01	0.47
CY-4 1079.85 m	0.2	6.85	3.80	1.80	0.28	0.84	0.44
Diabase	0.4	6.91	3.82	1.81	0.28	0.86	0.44
$\rho = 3.03 \text{ g/cm}^3$	0.6	6.95	3.83	1.82	0.28	0.87	0.44
$\phi = 0.1\%$	0.8	6.97	3.84	1.82	0.28	0.88	0.45
	1.0	6.99	3.84	1.82	0.28	0.89	0.45
	2.0	7.03	3.85	1.82	0.29	0.90	0.45
	4.0	7.07	3.86	1.83	0.29	0.92	0.45
	6.0	7.09	3.86	1.83	0.29	0.93	0.46
CY-4 1100.00 m	0.2	6.85	3.84	1.78	0.27	0.83	0.45
Gabbro	0.4	6.92	3.87	1.79	0.27	0.85	0.45
$\rho = 3.03 \text{ g/cm}^3$	0.6	6.96	3.88	1.79	0.27	0.86	0.46
$\phi = 0.2\%$	0.8	6.99	3.90	1.79	0.27	0.87	0.46
	1.0	7.01	3.90	1.80	0.28	0.87	0.46
	2.0	7.06	3.92	1.80	0.28	0.89	0.47
	4.0	7.09	3.94	1.80	0.28	0.90	0.47
	6.0	7.11	3.95	1.80	0.28	0.91	0.48
CY-4 1119.95 m	0.2	6.81	3.82	1.78	0.27	0.82	0.44
Diabase	0.4	6.87	3.84	1.79	0.27	0.84	0.45
$\rho = 3.03 \text{ g/cm}^3$	0.6	6.91	3.86	1.79	0.27	0.85	0.45
$\phi = 0.1\%$	0.8	6.93	3.87	1.79	0.27	0.85	0.45
	1.0	6.95	3.87	1.79	0.27	0.86	0.45
	2.0	7.01	3.89	1.80	0.28	0.88	0.46
	4.0	7.07	3.90	1.81	0.28	0.90	0.46
	6.0	7.11	3.90	1.82	0.28	0.92	0.46
CY-4 1160.12 m	0.2	6.92	3.68	1.88	0.30	0.91	0.41
Gabbro	0.4	6.98	3.78	1.85	0.29	0.90	0.44
$\rho = 3.04 \text{ g/cm}^3$	0.6	7.01	3.83	1.83	0.29	0.90	0.45
$\phi = 0.2\%$	0.8	7.04	3.87	1.82	0.28	0.90	0.46
	1.0	7.06	3.89	1.82	0.28	0.91	0.46
	2.0	7.13	3.92	1.82	0.28	0.92	0.47
	4.0	7.17	3.94	1.82	0.28	0.94	0.47
	6.0	7.18	3.95	1.82	0.28	0.94	0.48
CY-4 1180.00 m	0.2	7.03	3.70	1.90	0.31	0.93	0.41
Gabbro	0.4	7.09	3.78	1.87	0.30	0.93	0.43
$\rho = 2.98 \text{ g/cm}^3$	0.6	7.13	3.82	1.86	0.30	0.93	0.44
$\phi = 0.2\%$	0.8	7.15	3.84	1.86	0.30	0.94	0.44
	1.0	7.17	3.86	1.86	0.30	0.94	0.44
	2.0	7.23	3.88	1.86	0.30	0.96	0.45
	4.0	7.27	3.89	1.87	0.30	0.98	0.45
	6.0	7.30	3.90	1.87	0.30	0.99	0.46

TABLE I: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 1200.00 m	0.2	6.88	4.04	1.70	0.24	0.78	0.50
Gabbro	0.4	6.95	4.08	1.71	0.24	0.80	0.51
$\rho = 3.04 \text{ g/cm}^3$	0.6	7.00	4.10	1.71	0.24	0.81	0.51
$\phi = 0.1\%$	0.8	7.03	4.12	1.71	0.24	0.82	0.52
	1.0	7.05	4.13	1.71	0.24	0.82	0.52
	2.0	7.10	4.16	1.71	0.24	0.84	0.53
	4.0	7.15	4.17	1.72	0.24	0.86	0.53
	6.0	7.18	4.17	1.72	0.25	0.87	0.53
CY-4 1220.05 m	0.2	6.95	3.92	1.77	0.27	0.83	0.46
Gabbro	0.4	7.05	3.97	1.77	0.27	0.85	0.47
$\rho = 2.97 \text{ g/cm}^3$	0.6	7.10	4.01	1.77	0.27	0.86	0.48
$\phi = 0.2\%$	0.8	7.13	4.03	1.77	0.27	0.87	0.48
	1.0	7.15	4.04	1.77	0.26	0.87	0.49
	2.0	7.20	4.08	1.77	0.26	0.88	0.50
	4.0	7.25	4.11	1.77	0.26	0.90	0.50
	6.0	7.27	4.12	1.77	0.26	0.91	0.51
CY-4 1240.02 m	0.2	6.91	3.86	1.79	0.27	0.84	0.45
Diabase	0.4	7.00	3.88	1.80	0.28	0.87	0.45
$\rho = 3.02 \text{ g/cm}^3$	0.6	7.05	3.89	1.81	0.28	0.89	0.46
$\phi = 0.2\%$	0.8	7.08	3.90	1.82	0.28	0.90	0.46
	1.0	7.10	3.90	1.82	0.28	0.91	0.46
	2.0	7.14	3.92	1.82	0.28	0.92	0.46
	4.0	7.18	3.93	1.83	0.29	0.94	0.47
	6.0	7.19	3.93	1.83	0.29	0.95	0.47
CY-4 1260.00 m	0.2	6.91	3.69	1.87	0.30	0.89	0.41
Gabbro	0.4	7.01	3.77	1.86	0.30	0.90	0.43
$\rho = 2.99 \text{ g/cm}^3$	0.6	7.07	3.82	1.85	0.29	0.91	0.44
$\phi = 0.2\%$	0.8	7.11	3.84	1.85	0.29	0.93	0.44
	1.0	7.15	3.86	1.85	0.29	0.93	0.44
	2.0	7.23	3.88	1.86	0.30	0.96	0.45
	4.0	7.31	3.90	1.88	0.30	1.00	0.46
	6.0	7.36	3.91	1.88	0.30	1.02	0.46
CY-4 1280.00 m	0.2	6.83	3.90	1.75	0.26	0.78	0.45
Gabbro	0.4	6.89	3.92	1.76	0.26	0.80	0.46
$\rho = 2.96 \text{ g/cm}^3$	0.6	6.92	3.94	1.76	0.26	0.81	0.46
$\phi = 0.1\%$	0.8	6.95	3.95	1.76	0.26	0.82	0.46
	1.0	6.96	3.95	1.76	0.26	0.82	0.46
	2.0	7.02	3.96	1.77	0.26	0.84	0.47
	4.0	7.07	3.97	1.78	0.27	0.86	0.47
	6.0	7.10	3.97	1.79	0.27	0.88	0.47
CY-4 1320.00 m	0.2	6.70	3.72	1.80	0.28	0.77	0.40
Hornblende Gabbro	0.4	6.77	3.75	1.80	0.28	0.79	0.41
$\rho = 2.91 \text{ g/cm}^3$	0.6	6.81	3.77	1.81	0.28	0.80	0.41
$\phi = 0.2\%$	0.8	6.84	3.78	1.81	0.28	0.80	0.42
	1.0	6.87	3.79	1.81	0.28	0.82	0.42
	2.0	6.94	3.81	1.82	0.28	0.84	0.42
	4.0	7.00	3.82	1.83	0.29	0.87	0.43
	6.0	7.03	3.82	1.84	0.29	0.88	0.43

TABLE I: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 1340.01 m	0.2	7.42	4.03	1.84	0.29	1.06	0.51
Gabbro	0.4	7.46	4.10	1.82	0.28	1.05	0.53
$\rho = 3.16 \text{ g/cm}^3$	0.6	7.48	4.14	1.81	0.28	1.05	0.54
$\phi = 0.1\%$	0.8	7.49	4.17	1.80	0.28	1.05	0.55
	1.0	7.50	4.18	1.79	0.27	1.04	0.55
	2.0	7.53	4.21	1.79	0.27	1.05	0.56
	4.0	7.59	4.23	1.79	0.27	1.07	0.57
	6.0	7.62	4.24	1.80	0.28	1.09	0.57
CY-4 1380.23 m	0.2	7.21	3.84	1.88	0.30	0.98	0.45
Gabbro	0.4	7.29	3.90	1.87	0.30	1.00	0.46
$\rho = 3.03 \text{ g/cm}^3$	0.6	7.33	3.93	1.86	0.30	1.00	0.47
$\phi = 0.2\%$	0.8	7.36	3.95	1.86	0.30	1.01	0.47
	1.0	7.38	3.97	1.86	0.30	1.01	0.48
	2.0	7.45	4.01	1.86	0.30	1.03	0.49
	4.0	7.59	4.23	1.79	0.27	1.07	0.57
	6.0	7.62	4.24	1.80	0.28	1.09	0.57
CY-4 1400.08 m	0.2	7.08	3.70	1.91	0.31	0.95	0.41
Gabbro	0.4	7.20	3.79	1.90	0.31	0.97	0.43
$\rho = 2.97 \text{ g/cm}^3$	0.6	7.26	3.84	1.89	0.31	0.98	0.44
$\phi = 0.2\%$	0.8	7.30	3.87	1.89	0.30	0.99	0.45
	1.0	7.33	3.89	1.88	0.30	1.00	0.45
	2.0	7.38	3.92	1.88	0.30	1.02	0.46
	4.0	7.43	3.94	1.89	0.31	1.03	0.46
	6.0	7.45	3.94	1.89	0.31	1.04	0.47
CY-4 1420.08 m	0.2	6.80	3.79	1.80	0.28	0.79	0.42
Gabbro	0.4	6.90	3.86	1.79	0.27	0.80	0.43
$\rho = 2.90 \text{ g/cm}^3$	0.6	6.95	3.90	1.78	0.27	0.81	0.44
$\phi = 0.2\%$	0.8	6.98	3.92	1.78	0.27	0.82	0.45
	1.0	7.00	3.93	1.78	0.27	0.83	0.45
	2.0	7.04	3.95	1.79	0.27	0.84	0.45
	4.0	7.08	3.96	1.79	0.27	0.85	0.46
	6.0	7.10	3.96	1.79	0.27	0.86	0.46
CY-4 1440.14 m	0.2	7.10	3.79	1.87	0.30	0.89	0.41
Gabbro	0.4	7.23	3.92	1.84	0.29	0.91	0.44
$\rho = 2.86 \text{ g/cm}^3$	0.6	7.28	3.98	1.83	0.29	0.92	0.45
$\phi = 0.2\%$	0.8	7.32	4.00	1.83	0.29	0.92	0.46
	1.0	7.33	4.02	1.83	0.29	0.93	0.46
	2.0	7.38	4.04	1.83	0.29	0.94	0.47
	4.0	7.43	4.06	1.83	0.29	0.96	0.47
	6.0	7.45	4.07	1.83	0.29	0.97	0.48
CY-4 1459.68 m	0.2	7.28	4.09	1.78	0.27	0.95	0.52
Gabbro	0.4	7.39	4.12	1.79	0.27	0.99	0.52
$\rho = 3.08 \text{ g/cm}^3$	0.6	7.46	4.14	1.80	0.28	1.01	0.53
$\phi = 0.2\%$	0.8	7.50	4.16	1.80	0.28	1.02	0.53
	1.0	7.53	4.17	1.81	0.28	1.03	0.54
	2.0	7.61	4.20	1.81	0.28	1.06	0.55
	4.0	7.69	4.24	1.82	0.28	1.09	0.56
	6.0	7.73	4.25	1.82	0.28	1.11	0.56

TABLE I: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 1520.12 m	0.2	6.79	3.71	1.83	0.29	0.81	0.40
Gabbro	0.4	6.87	3.79	1.81	0.28	0.82	0.42
$\rho = 2.93 \text{ g/cm}^3$	0.6	6.91	3.83	1.80	0.28	0.83	0.43
$\phi = 0.2\%$	0.8	6.94	3.86	1.80	0.28	0.83	0.44
	1.0	6.96	3.87	1.80	0.28	0.83	0.44
	2.0	7.01	3.90	1.80	0.28	0.85	0.45
	4.0	7.05	3.92	1.80	0.28	0.86	0.45
	6.0	7.07	3.93	1.80	0.28	0.87	0.46
CY-4 1540.25 m	0.2	7.22	3.94	1.83	0.29	0.99	0.49
Gabbro	0.4	7.36	4.03	1.83	0.29	1.02	0.51
$\rho = 3.15 \text{ g/cm}^3$	0.6	7.44	4.09	1.82	0.28	1.04	0.53
$\phi = 0.2\%$	0.8	7.49	4.12	1.82	0.28	1.05	0.53
	1.0	7.52	4.14	1.82	0.28	1.06	0.54
	2.0	7.59	4.17	1.82	0.28	1.08	0.55
	4.0	7.64	4.20	1.82	0.28	1.10	0.56
	6.0	7.68	4.21	1.82	0.29	1.12	0.56
CY-4 1559.39 m	0.2	6.88	3.71	1.85	0.29	0.86	0.41
Gabbro	0.4	7.04	3.91	1.80	0.28	0.87	0.46
$\rho = 2.98 \text{ g/cm}^3$	0.6	7.12	4.00	1.78	0.27	0.87	0.48
$\phi = 0.3\%$	0.8	7.16	4.03	1.77	0.27	0.88	0.48
	1.0	7.18	4.05	1.77	0.27	0.89	0.49
	2.0	7.24	4.07	1.78	0.27	0.91	0.49
	4.0	7.30	4.08	1.79	0.27	0.93	0.50
	6.0	7.33	4.09	1.79	0.27	0.94	0.50
CY-4 1579.65 m	0.2	6.64	3.65	1.82	0.28	0.77	0.39
Gabbro	0.4	6.93	3.76	1.84	0.29	0.85	0.41
$\rho = 2.93 \text{ g/cm}^3$	0.6	7.04	3.82	1.84	0.29	0.88	0.43
$\phi = 0.2\%$	0.8	7.09	3.86	1.84	0.29	0.89	0.44
	1.0	7.12	3.89	1.83	0.29	0.90	0.44
	2.0	7.18	3.93	1.83	0.29	0.91	0.45
	4.0	7.24	3.95	1.83	0.29	0.93	0.46
	6.0	7.27	3.96	1.84	0.29	0.94	0.46
CY-4 1600.54 m	0.2	6.82	3.72	1.84	0.29	0.85	0.42
Gabbro	0.4	6.98	3.84	1.82	0.28	0.88	0.45
$\rho = 3.02 \text{ g/cm}^3$	0.6	7.05	3.91	1.80	0.28	0.89	0.46
$\phi = 0.2\%$	0.8	7.09	3.95	1.79	0.27	0.89	0.47
	1.0	7.11	3.97	1.79	0.27	0.89	0.48
	2.0	7.18	4.01	1.79	0.27	0.91	0.49
	4.0	7.24	4.03	1.80	0.28	0.94	0.49
	6.0	7.27	4.03	1.80	0.28	0.95	0.49
CY-4 1640.04 m	0.2	7.04	3.95	1.78	0.27	0.86	0.46
Gabbro	0.4	7.10	3.98	1.78	0.27	0.87	0.47
$\rho = 2.98 \text{ g/cm}^3$	0.6	7.14	4.01	1.78	0.27	0.88	0.48
$\phi = 0.1\%$	0.8	7.16	4.02	1.78	0.27	0.89	0.48
	1.0	7.18	4.03	1.78	0.27	0.89	0.48
	2.0	7.23	4.05	1.78	0.27	0.90	0.49
	4.0	7.27	4.07	1.79	0.27	0.92	0.50
	6.0	7.29	4.08	1.79	0.27	0.93	0.50

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 1659.98 m	0.2	6.86	3.80	1.81	0.28	0.83	0.43
Gabbro	0.4	6.92	3.85	1.80	0.28	0.84	0.44
$\rho = 2.96 \text{ g/cm}^3$	0.6	6.96	3.88	1.79	0.27	0.84	0.45
$\phi = 0.2\%$	0.8	6.98	3.90	1.79	0.27	0.84	0.45
	1.0	7.00	3.92	1.79	0.27	0.85	0.46
	2.0	7.06	3.99	1.77	0.27	0.85	0.47
	4.0	7.13	4.06	1.76	0.26	0.86	0.49
	6.0	7.17	4.10	1.75	0.26	0.87	0.50
CY-4 1680.06 m	0.2	7.15	3.82	1.87	0.30	0.93	0.43
Gabbro	0.4	7.24	3.85	1.88	0.30	0.96	0.44
$\rho = 2.95 \text{ g/cm}^3$	0.6	7.29	3.87	1.88	0.30	0.98	0.44
$\phi = 0.1\%$	0.8	7.32	3.88	1.88	0.30	0.99	0.44
	1.0	7.33	3.90	1.88	0.30	0.99	0.45
	2.0	7.38	3.93	1.88	0.30	1.00	0.46
	4.0	7.42	3.97	1.87	0.30	1.01	0.47
	6.0	7.44	3.99	1.86	0.30	1.01	0.47
CY-4 1699.90 m	0.2	6.74	3.86	1.75	0.26	0.76	0.44
Gabbro	0.4	6.94	3.97	1.75	0.26	0.81	0.47
$\rho = 2.98 \text{ g/cm}^3$	0.6	7.04	4.02	1.75	0.26	0.83	0.48
$\phi = 0.2\%$	0.8	7.09	4.05	1.75	0.26	0.85	0.49
	1.0	7.12	4.06	1.75	0.26	0.85	0.49
	2.0	7.16	4.09	1.75	0.26	0.87	0.50
	4.0	7.19	4.11	1.75	0.26	0.87	0.51
	6.0	7.21	4.12	1.75	0.26	0.88	0.51
CY-4 1720.12 m	0.2	6.74	3.95	1.71	0.24	0.72	0.46
Gabbro	0.4	6.98	4.03	1.73	0.25	0.79	0.47
$\rho = 2.92 \text{ g/cm}^3$	0.6	7.07	4.07	1.74	0.25	0.82	0.48
$\phi = 0.2\%$	0.8	7.11	4.09	1.74	0.25	0.83	0.49
	1.0	7.13	4.10	1.74	0.25	0.83	0.49
	2.0	7.16	4.13	1.74	0.25	0.84	0.50
	4.0	7.19	4.15	1.73	0.25	0.84	0.51
	6.0	7.20	4.16	1.73	0.25	0.85	0.51
CY-4 1740.02 m	0.2	7.06	4.10	1.72	0.25	0.85	0.52
Gabbro	0.4	7.18	4.14	1.73	0.25	0.89	0.53
$\rho = 3.09 \text{ g/cm}^3$	0.6	7.24	4.16	1.74	0.25	0.91	0.54
$\phi = 0.1\%$	0.8	7.28	4.18	1.74	0.25	0.92	0.54
	1.0	7.30	4.19	1.74	0.25	0.92	0.54
	2.0	7.36	4.23	1.74	0.25	0.94	0.55
	4.0	7.41	4.26	1.74	0.25	0.95	0.56
	6.0	7.43	4.27	1.74	0.25	0.96	0.57
CY-4 1759.86 m	0.2	7.60	4.15	1.83	0.29	1.08	0.54
Olivine Websterite	0.4	7.67	4.17	1.84	0.29	1.11	0.54
$\rho = 3.11 \text{ g/cm}^3$	0.6	7.71	4.18	1.84	0.29	1.12	0.55
$\phi = 0.1\%$	0.8	7.73	4.19	1.85	0.29	1.13	0.55
	1.0	7.75	4.20	1.85	0.29	1.14	0.55
	2.0	7.80	4.20	1.86	0.30	1.16	0.55
	4.0	7.84	4.20	1.87	0.30	1.18	0.55
	6.0	7.86	4.20	1.87	0.30	1.20	0.55

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 1779.76 m	0.2	7.75	4.12	1.88	0.30	1.16	0.53
Websterite	0.4	7.79	4.18	1.87	0.30	1.17	0.54
$\rho = 3.11 \text{ g/cm}^3$	0.6	7.81	4.21	1.86	0.30	1.16	0.55
$\phi = 0.2\%$	0.8	7.83	4.24	1.85	0.29	1.16	0.56
	1.0	7.85	4.26	1.84	0.29	1.16	0.56
	2.0	7.90	4.30	1.84	0.29	1.17	0.58
	4.0	7.96	4.32	1.84	0.29	1.20	0.58
	6.0	7.99	4.33	1.85	0.29	1.21	0.58
CY-4 1799.99 m	0.2	7.22	3.88	1.86	0.30	0.97	0.45
Websterite	0.4	7.41	3.95	1.88	0.30	1.03	0.47
$\rho = 3.02 \text{ g/cm}^3$	0.6	7.49	4.00	1.87	0.30	1.05	0.48
$\phi = 0.2\%$	0.8	7.53	4.03	1.87	0.30	1.06	0.49
	1.0	7.55	4.04	1.87	0.30	1.06	0.49
	2.0	7.60	4.08	1.86	0.30	1.08	0.50
	4.0	7.65	4.09	1.87	0.30	1.10	0.51
	6.0	7.67	4.10	1.87	0.30	1.11	0.51
CY-4 1820.03 m	0.2	7.43	4.16	1.79	0.27	0.99	0.53
Websterite	0.4	7.50	4.23	1.77	0.27	0.99	0.55
$\rho = 3.07 \text{ g/cm}^3$	0.6	7.53	4.27	1.76	0.26	0.99	0.56
$\phi = 0.2\%$	0.8	7.55	4.28	1.76	0.26	1.00	0.56
	1.0	7.56	4.29	1.76	0.26	1.00	0.57
	2.0	7.61	4.30	1.77	0.27	1.02	0.57
	4.0	7.68	4.31	1.78	0.27	1.05	0.57
	6.0	7.72	4.31	1.79	0.27	1.08	0.57
CY-4 1839.96 m	0.2	6.88	4.08	1.68	0.23	0.79	0.52
Olivine Websterite	0.4	7.21	4.12	1.75	0.26	0.92	0.53
$\rho = 3.14 \text{ g/cm}^3$	0.6	7.36	4.15	1.78	0.27	0.98	0.54
$\phi = 0.2\%$	0.8	7.44	4.17	1.78	0.27	1.01	0.55
	1.0	7.48	4.18	1.79	0.27	1.02	0.55
	2.0	7.56	4.24	1.78	0.27	1.04	0.56
	4.0	7.62	4.29	1.78	0.27	1.06	0.58
	6.0	7.66	4.33	1.77	0.27	1.06	0.59
CY-4 1880.05 m	0.2	7.46	4.09	1.82	0.29	1.07	0.54
Olivine Websterite	0.4	7.62	4.19	1.82	0.28	1.11	0.57
$\rho = 3.21 \text{ g/cm}^3$	0.6	7.68	4.25	1.81	0.28	1.12	0.58
$\phi = 0.1\%$	0.8	7.72	4.29	1.80	0.28	1.13	0.59
	1.0	7.74	4.31	1.80	0.28	1.13	0.60
	2.0	7.81	4.35	1.79	0.27	1.15	0.61
	4.0	7.87	4.38	1.80	0.28	1.17	0.62
	6.0	7.90	4.39	1.80	0.28	1.18	0.62
CY-4 1899.94 m	0.2	7.29	4.10	1.78	0.27	0.97	0.53
Plagioclase Websterite	0.4	7.41	4.23	1.75	0.26	0.99	0.57
$\rho = 3.17 \text{ g/cm}^3$	0.6	7.49	4.29	1.75	0.26	1.00	0.58
$\phi = 0.1\%$	0.8	7.54	4.32	1.75	0.26	1.02	0.59
	1.0	7.57	4.33	1.75	0.26	1.03	0.60
	2.0	7.64	4.36	1.75	0.26	1.05	0.60
	4.0	7.67	4.37	1.75	0.26	1.06	0.61
	6.0	7.68	4.38	1.75	0.26	1.07	0.61

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 1919.98 m	0.2	7.32	4.11	1.78	0.27	0.99	0.54
Olivine Websterite	0.4	7.39	4.20	1.76	0.26	1.00	0.57
$\rho = 3.21 \text{ g/cm}^3$	0.6	7.44	4.24	1.75	0.26	1.01	0.58
$\phi = 0.1\%$	0.8	7.48	4.26	1.76	0.26	1.02	0.58
	1.0	7.52	4.27	1.76	0.26	1.03	0.59
	2.0	7.62	4.30	1.77	0.27	1.07	0.60
	4.0	7.67	4.33	1.77	0.27	1.09	0.60
	6.0	7.67	4.34	1.77	0.26	1.09	0.61
CY-4 1939.88 m	0.2	7.49	4.17	1.80	0.28	1.04	0.55
Websterite	0.4	7.68	4.27	1.80	0.28	1.10	0.58
$\rho = 3.16 \text{ g/cm}^3$	0.6	7.77	4.32	1.80	0.28	1.12	0.59
$\phi = 0.2\%$	0.8	7.80	4.36	1.79	0.27	1.13	0.60
	1.0	7.83	4.38	1.79	0.27	1.13	0.61
	2.0	7.87	4.43	1.78	0.27	1.14	0.62
	4.0	7.92	4.45	1.78	0.27	1.15	0.63
	6.0	7.94	4.47	1.78	0.27	1.16	0.63
CY-4 1960.08 m	0.2	7.55	4.20	1.80	0.28	1.05	0.55
Plagioclase Websterite	0.4	7.63	4.26	1.79	0.27	1.07	0.57
$\rho = 3.13 \text{ g/cm}^3$	0.6	7.68	4.29	1.79	0.27	1.08	0.58
$\phi = 0.1\%$	0.8	7.71	4.30	1.79	0.27	1.09	0.58
	1.0	7.73	4.31	1.79	0.27	1.10	0.58
	2.0	7.77	4.33	1.80	0.28	1.11	0.59
	4.0	7.80	4.35	1.79	0.27	1.12	0.59
	6.0	7.81	4.36	1.79	0.27	1.13	0.60
CY-4 2000.00 m	0.2	7.78	4.19	1.86	0.30	1.17	0.55
Olivine Websterite	0.4	7.88	4.25	1.86	0.30	1.20	0.57
$\rho = 3.14 \text{ g/cm}^3$	0.6	7.93	4.28	1.85	0.29	1.21	0.58
$\phi = 0.2\%$	0.8	7.97	4.30	1.85	0.29	1.22	0.58
	1.0	7.99	4.32	1.85	0.29	1.23	0.59
	2.0	8.06	4.37	1.84	0.29	1.24	0.60
	4.0	8.11	4.41	1.84	0.29	1.26	0.61
	6.0	8.14	4.44	1.83	0.29	1.26	0.62
CY-4 2039.81 m	0.2	7.71	4.30	1.80	0.28	1.10	0.58
Olivine Websterite	0.4	7.82	4.33	1.81	0.28	1.14	0.59
$\rho = 3.15 \text{ g/cm}^3$	0.6	7.87	4.35	1.81	0.28	1.16	0.60
$\phi = 0.1\%$	0.8	7.91	4.36	1.81	0.28	1.17	0.60
	1.0	7.93	4.37	1.81	0.28	1.18	0.60
	2.0	7.98	4.40	1.82	0.28	1.20	0.61
	4.0	8.03	4.41	1.82	0.28	1.22	0.61
	6.0	8.06	4.42	1.82	0.29	1.23	0.62
CY-4 2079.89 m	0.2	7.61	4.12	1.85	0.29	1.11	0.53
Websterite	0.4	7.73	4.22	1.83	0.29	1.14	0.56
$\rho = 3.14 \text{ g/cm}^3$	0.6	7.79	4.26	1.83	0.29	1.15	0.57
$\phi = 0.2\%$	0.8	7.82	4.28	1.83	0.29	1.16	0.58
	1.0	7.84	4.30	1.83	0.29	1.16	0.58
	2.0	7.89	4.33	1.82	0.28	1.17	0.59
	4.0	7.93	4.36	1.82	0.28	1.18	0.60
	6.0	7.95	4.38	1.81	0.28	1.19	0.61

TABLE 1: (cont.)

Sample	P (kb)	Vp (km/s)	Vs (km/s)	Vp/Vs	$\sigma$	K (Mb)	$\mu$ (Mb)
CY-4 2119.86 m	0.2	7.62	4.23	1.80	0.28	1.11	0.58
Olivine Websterite	0.4	7.82	4.32	1.81	0.28	1.18	0.61
$\rho = 3.24 \text{ g/cm}^3$	0.6	7.92	4.38	1.81	0.28	1.20	0.62
$\phi = 0.1\%$	0.8	7.97	4.41	1.81	0.28	1.22	0.63
	1.0	8.00	4.43	1.81	0.28	1.23	0.64
	2.0	8.10	4.48	1.81	0.28	1.26	0.65
	4.0	8.20	4.53	1.81	0.28	1.30	0.67
	6.0	8.25	4.55	1.81	0.28	1.32	0.67
CY-4 2159.83 m	0.2	7.53	4.02	1.87	0.30	1.10	0.51
Olivine Websterite	0.4	7.59	4.08	1.86	0.30	1.11	0.52
$\rho = 3.13 \text{ g/cm}^3$	0.6	7.62	4.12	1.85	0.29	1.11	0.53
$\phi = 0.2\%$	0.8	7.64	4.15	1.84	0.29	1.11	0.54
	1.0	7.66	4.17	1.84	0.29	1.11	0.55
	2.0	7.71	4.22	1.83	0.29	1.12	0.56
	4.0	7.75	4.25	1.82	0.29	1.13	0.57
	6.0	7.78	4.27	1.82	0.28	1.14	0.57

$\rho$  = density;  $\phi$  = porosity.

TABLE 2. Compressional Wave Velocities (Vp) and Anisotropies at 2 kb Confining Pressure

Rock	Vp (horiz.) km/sec	Vp (vert.) km/sec	Anisotropy
Gabbro, 1140m	6.84	7.12	4.0%
Websterite, 1893m	7.71	7.58	1.7%
Websterite, 1910m	7.78	7.60	2.3%

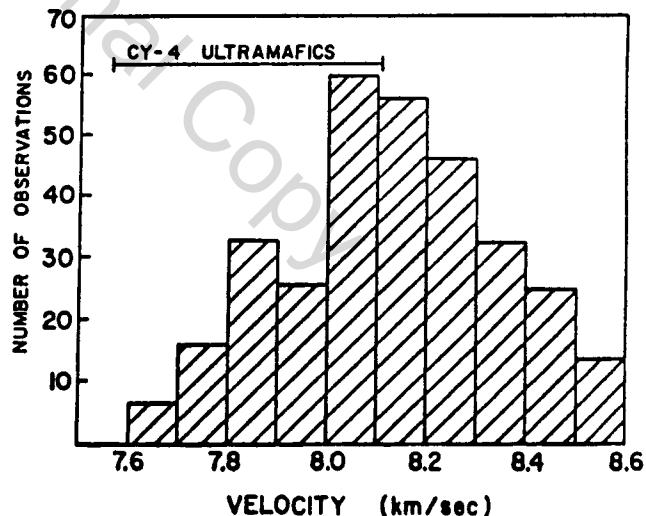


Figure 3: Comparison of CY-4 ultramafic rock velocities with histogram of Pacific upper mantle velocities (data from Christensen, 1982).

increase from 3.2 km/sec to 3.8 km/sec over the same interval. The gradients reflect both decreasing porosity and changes in secondary mineralogy caused by increasing metamorphic grade with increasing depth. Average porosities of dike rocks from the top of the drill hole are 3% whereas near the base of the sheeted dike section, porosities are generally less than 1% (Table 1). The uppermost dikes are primarily plagioclase-pyroxene rocks with less than 10% secondary minerals. With increasing depth, chlorite, laumontite, actinolite, epidote and hornblende become abundant in thin section. Note that compressional wave velocities for samples near the base of the sheeted dike section exceed the 6.69 km/sec average Layer 3 velocity of Raitt (1963).

The second interval of seismic interest extends from 630 m to 950 m. This zone consists of high level gabbro commonly containing amphibole. In addition, some dikes occur in the upper 100 m of this zone. With increasing depth, velocities first increase then decrease to 6.5 km/sec and 3.6 km/sec for  $V_p$  and  $V_s$ , respectively, at approximately 800 m. The velocity reversals originate from alteration of plagioclase and partial replacement of pyroxene by fibrous amphibole caused by deuterian alteration of the gabbro. Also within this region are dikes and sills of plagiogranite which have low velocities and densities (Christensen, 1977). No velocities were measured for the Troodos plagiogranite since only a small volume was encountered in the drill hole.

The third zone, extending from depths of 950 m to 1750 m, consists of relatively fresh pyroxene gabbros containing minor amphibole, olivine and serpentine. The gabbros within this region have remarkably uniform velocities with compressional and shear wave velocities averaging 7.2 km/sec and 4.0 km/sec, respectively. The velocities reported in Table 1 and shown in Figures 1 and 2 are for horizontal wave propagation. Petrographic examination of thin sections over this depth interval shows significant plagioclase orientation which produces some anisotropy. Plagioclase is oriented with (010) normals near vertical, which would produce fast compressional wave velocities for vertical wave propagation (Ryzhova, 1964). The velocity measurements presented in Table 2 for a gabbro sampled at 1140 m show that the resulting anisotropy is approximately 4%.

The lowest zone, extending from a core depth of 1750 m to the bottom of the hole, consists of ultramafic rocks. Lithologies are predominantly websterite and olivine websterite cut by diabase dikes. Although the rocks in this interval are quite fresh, serpentine is locally present. The 7.7 to 7.8 km/sec compressional wave velocities in this section are lower than many reported oceanic Pn velocities, but clearly fall within the range of observed upper mantle velocities (Figure 3). The sharp transition from gabbro to pyroxenite produces a major refractor for compressional waves. The shear wave velocity discontinuity, however, is not as abrupt (Figures 1

and 2). In addition, anisotropy in the ultramafic section is low (Table 2) compared to anisotropies observed in ultramafic rocks believed to have originated from the oceanic upper mantle (Christensen, 1984).

## SUMMARY AND CONCLUSIONS

The velocity structure of the Troodos ophiolite as determined from laboratory studies is similar in many ways to that of normal oceanic crust. Rock velocities from the upper 700 m of the drill hole show strong positive gradients similar to those in oceanic crustal Layer 2. Near the base of the sheeted dikes an abrupt change of the velocity gradient could be interpreted as the boundary between Layers 2 and 3. Compressional wave velocities in the gabbroic section average approximately 7.0 km/sec, in reasonable agreement with logging data from the hole ( $6.7 \pm 0.3$  km/s; Salisbury and Christensen, 1985) and with the many reported refraction velocities for Oceanic Layer 3. The major discontinuity at 1750 m depth, which separates overlying gabbros from ultramafic rocks, is similar to the oceanic Mohorovicic discontinuity, as defined by seismic studies. The petrologic Moho, which separates cumulate ultramafic rocks from underlying ultramafic tectonites, was not sampled by drilling and presumably lies deeper in the section.

There are, however, important differences between the structure of the CY-4 section and normal oceanic crust. These differences may be common in oceanic crust formed in an arc environment. Of major significance is the thickness of the gabbroic section commonly equated with Oceanic Layer 3. Average in situ Layer 3 thicknesses range between 4 and 5 km (Raitt, 1963; Christensen and Salisbury, 1975), whereas the apparent thickness of Layer 3 in drill hole CY-4 is only 1 km. The measured velocities in the underlying ultramafic section are clearly too high to be equated with Oceanic Layer 3, even if one assumes the presence of a high velocity basal Layer 3B as proposed by Sutton et al. (1971), but later questioned by Lewis and Snydsman (1977). Finally, the pyroxenite section from CY-4 does not show the strong azimuthal anisotropy commonly observed in the oceanic upper mantle. Since recovery textures become increasingly abundant toward the base of the hole, strongly anisotropic ultramafic tectonics may well exist deeper in the section.

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## REFERENCES

- Birch, F.
- 1960: The velocity of compressional waves in rocks to 10 kilobars, Part 1; *Journal of Geophysical Research*, v. 65, no. 4, p. 1083-1102.
- Birch, F.
- 1961: The velocity of compressional waves in rocks to 10 kilobars, 2; *Journal of Geophysical Research*, v. 66, p. 2199-2224.
- Christensen, N.I.
- 1977: The geophysical significance of oceanic plagiogranite; *Earth and Planetary Science Letters*, v. 36, p. 297-300.
- Christensen, N.I.
- 1978: Ophiolites, seismic velocities and oceanic crustal structure; *Tectonophysics*, v. 47, p. 131-157.
- Christensen, N.I.
- 1982: Seismic velocities; in *Handbook of Physical Properties of Rocks*, ed. R.S. Carmichael; CDC Press, Inc., Boca Raton, v. 11, p. 1-228.
- Christensen, N.I.
- 1984: The magnitude, symmetry and origin of upper mantle anisotropy based on fabric analyses of ultramafic tectonites; *Geophysics Journal of the Royal Astronomical Society*, v. 76, p. 89-111.
- Christensen, N.I. and Lundquist, S.M.
- 1982: Pyroxene orientation within the upper mantle; *Geological Society of America, Bulletin*, v. 93, p. 279-388.
- Christensen, N.I. and Salisbury, M.H.
- 1975: Structure and constitution of the lower oceanic crust; *Reviews of Geophysics and Space Physics*, v. 13, no. 1, p. 57-86.
- Christensen, N.I. and Salisbury, M.H.
- 1979: Seismic anisotropy in the oceanic upper mantle: evidence from the Bay of Islands ophiolite complex; *Journal of Geophysical Research*, v. 84, p. 4601-4610.
- Christensen, N.I. and Salisbury, M.H.
- 1982: Lateral heterogeneity in the seismic structure of the oceanic crust; *Geophysical Journal of the Royal Astronomical Society*, v. 68, p. 675-688.
- Christensen, N.I. and Smewing, J.D.
- 1981: Geology and seismic structure of the northern section of the Oman ophiolite; *Journal of Geophysical Research*, v. 86, no. B4, p. 2545-2555.
- Coleman, R.G.
- 1971: Plate tectonic emplacement of upper mantle peridotites along continental edges; *Journal of Geophysical Research*, v. 76, p. 1212-1222.
- Dewey, J.F. and Bird, J.M.
- 1971: Origin and emplacement of the ophiolite suite: Appalachian Ophiolites in Newfoundland; *Journal of Geophysical Research*, v. 76, p. 3179-3206.
- Kroenke, L.W., Manghnani, M.H., Rai, C.S., Fryer, P. and Ramananandro, R.
- 1976: Elastic composition of oceanic lower crust and upper mantle; in *The Geophysics of the Pacific Ocean Basin and its Margin*, ed. G.H. Sutton, M.H. Manghnani and R. Moberly; Woollard Volume - Geophysical Monograph, American Geophysical Union, v. 19, p. 407-421.
- Lewis, B.T.R. and Snydsman, W.E.
- 1977: Evidence for a low velocity layer at the base of the oceanic crust; *Nature*, v. 266, p. 340-345.
- Miyashiro, A.
- 1973: The Troodos Ophiolitic complex was probably formed in an island arc; *Earth and Planetary Science Letters*, v. 19, no. 2, p. 218-224.
- Moores, E.M. and F.J. Vine
- 1971: The Troodos Massif, Cyprus, and other ophiolites as oceanic crust: evaluation and implications; in *A Discussion on the Petrology of Igneous and Metamorphic Rocks from the Ocean Floor*; Philosophical Transactions of the Royal Society of London, Series A., v. 268, p. 443-466.
- Peterson, J.J., Fox, P.J. and Schreiber, E.
- 1974: Newfoundland ophiolites and the geology of the oceanic layer; *Nature*, v. 247, p. 194-196.
- Raitt, R.W.
- 1963: The crustal rocks; in *The Sea, Ideas and Observations on Progress in the Study of the Seas, The Earth beneath the Sea*, ed. M.N. Hill; John Wiley, New York, v. 3, p. 85-102.
- Robinson, P.T., Nelson, W.G., O'Hearn, T. and Schmincke, H.U.
- 1983: Volcanic glass compositions of the Troodos Ophiolite, Cyprus; *Geology*, v. 11, p. 400-404.
- Ryzhova, T.V.
- 1964: Elastic properties of plagioclase, *Izvestia Geophysical Series*, v. 7, p. 1049-1051.
- Salisbury, M.H. and Christensen, N.I.
- 1978: The seismic velocity structure of a traverse through the Bay of Islands ophiolite complex, Newfoundland: an exposure of oceanic crust and upper mantle; *Journal of Geophysical Research*, v. 83, no. 2, p. 805-817.
- Salisbury, M.H. and Christensen, N.I.
- 1985: Velocity structure of the Troodos ophiolite from borehole logs; *American Geophysical Union, Transactions*, v. 66, p. 1122.
- Shor, G.G., Jr., Menard, H.W. and Raitt, R.W.
- 1971: Structure of the Pacific basin; in *The Sea*, ed. A.E. Maxwell; John Wiley, New York, v. 4, p. 327.
- Sutton, G.H., Maynard, G.L. and Hussong, D.M.
- 1971: Widespread occurrence of a high-velocity basal layer in the Pacific crust found with repetitive sources and sonobuoys; in *The Structure and Physical Properties of the Earth's Crust*, ed. J.G. Heacock; Geophysical Monograph Series, American Geophysical Union, Washington, D.C., v. 14, p. 193-209.