THE PETROLOGIC NATURE OF THE LOWER OCEANIC CRUST AND UPPER MANTLE*

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ABSTRACT. The compositions of the lower oceanic crust and upper mantle are investigated using data from high pressure experiments of compressional and shear wave velocities in rocks. Four compositional models for the lower oceanic crust are considered: 1) partially serpentinized peridotite, 2) gabbro, 3) metabasalt and metagabbro and 4) an ophiolite model consisting of metamorphosed sheeted dikes overlying late differentiates and cumulate gabbros. Comparisons of compressional wave velocities (V_p) from dredged oceanic rocks with layer 3 refraction velocities show that peridotites 30 to 40% serpentinized, unaltered gabbro, metagabbro and metabasalt all have velocities similar to observed lower crustal velocities. Thus compressional wave velocity measurements alone will not distinguish between the various crustal models. Although only a limited amount of refraction data on shear wave velocities (V_s) are available, it appears that lower crustal Poisson's ratios, calculated from V_p and V_s, are significantly lower than measured values in partially serpentinized peridotite and unaltered gabbro. In support of models 3 and 4 it is shown that Poisson's ratios of metabasalt and metagabbro, on the other hand, agree well with seismic data from the upper portion layer 3. The low Poisson's ratios reported for the lower crust of Iceland ($\sim$ 0.27) suggest that metabasalt and metagabbro are abundant constituents of layer 3. The 7.4 km/sec layer, often found between layer 3 and oceanic upper mantle in the Pacific Ocean, is interpreted as most likely being composed of peridotite, 10 to 20% serpentinized, or feldspathic

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peridotite. Compressional and shear wave velocities in eclogite and peridotite at appropriate pressures are similar to oceanic upper mantle velocities. An upper mantle of peridotite or dunite composition is favored, however, in regions where strong upper mantle anisotropy is observed.

1. INTRODUCTION

During the past few years several papers have been directly concerned with the petrologic nature of the oceanic crust and upper mantle. These papers have attracted much scientific attention because of the current interests in plate tectonics and the geological processes operating at ridge crests. Even though abundant geological and geophysical information is available on the crust and upper mantle, the relationship of this information to an understanding of composition is vague. Many rocks have been dredged from oceanic regions which offer clues to the petrologic nature of the lower levels of the crust and the upper mantle. However, it is impossible from geological criteria to accurately assess whether or not various rock types are abundant at different depth intervals. Similarly, ophiolite suites, which are believed by many to be on land exposures of oceanic crust, present complications because they are often dismembered and when complete differ significantly from one another in thickness, petrology and internal structure.

Much geophysical information on the crust and upper mantle, including heat flow, gravity and magnetic data, is also abstract and requires deciphering in order to interpret the physical significance of the measurements. Since the most direct information on the nature of the rocks beneath the oceans comes from seismology, it is appropriate to concentrate on seismic velocities of the lower oceanic crust and upper mantle. In the following discussion models of the mineralogical composition of the lower oceanic crust and upper mantle will be evaluated with the aid of experimental data on velocities in rocks.

2. SEISMIC STRUCTURE

Seismologists now recognize several layers within the oceanic crust. Average oceanic crustal structure [1] is often referred to in terms of a three layer crust in which the uppermost layer (layer 1) consists of a thin veneer of unconsolidated to semiconsolidated sediments, usually less than 1 km thick. Layer 2, often referred to as basement, is generally between 1.0 and 2.5 km in thickness and is believed to consist of basalt which is metamorphosed at its lower levels. Layer 3, immediately overlying the mantle, is quite variable in thickness (usually between 3 and 6 km) and at present is of unknown composition. Although many recent seismic studies have found a three layered crust, it now has become

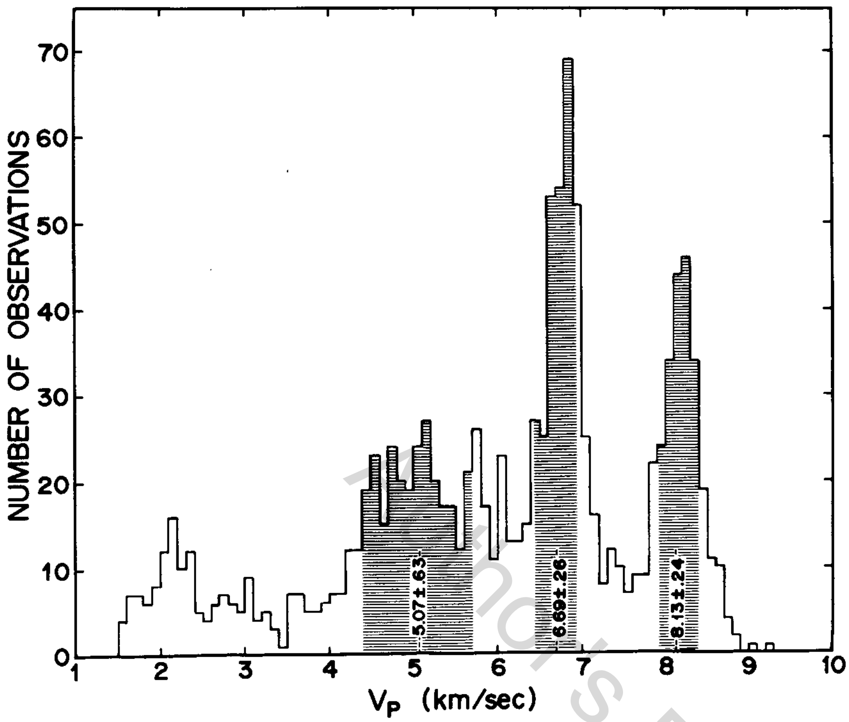

Fig. 1. Crustal and upper mantle compressional wave velocities.

increasingly apparent that in many regions crustal structure is much more complicated than this simple model. Examples include crust under ridge crests [2,3] and the high velocity basal crustal layer common in some oceanic regions [4].

In Fig. 1 crustal and upper mantle compressional wave velocities are shown in histogram form for 415 sites located in main oceanic basins. In addition, the average velocities of Raitt [1] are shown for layers 2 and 3 and the upper mantle. As can be seen from the diagram, the subdivisions of Raitt still hold, however many observed velocities fall outside the reported standard deviations. Thus even though it may be appropriate to envision the oceanic crust as containing three more or less well defined layers, such a simple model must be treated cautiously.

Much less information is available on shear velocities in the oceanic crust and the available data to 1970 have been summarized by Christensen [5]. In general for lower crustal velocities between 6.60 and 7.00 km/sec, shear wave velocities vary from 3.61 to 3.89 km/sec and calculated Poisson's ratios are between 0.25 and 0.29. It will be shown later that these values are extremely

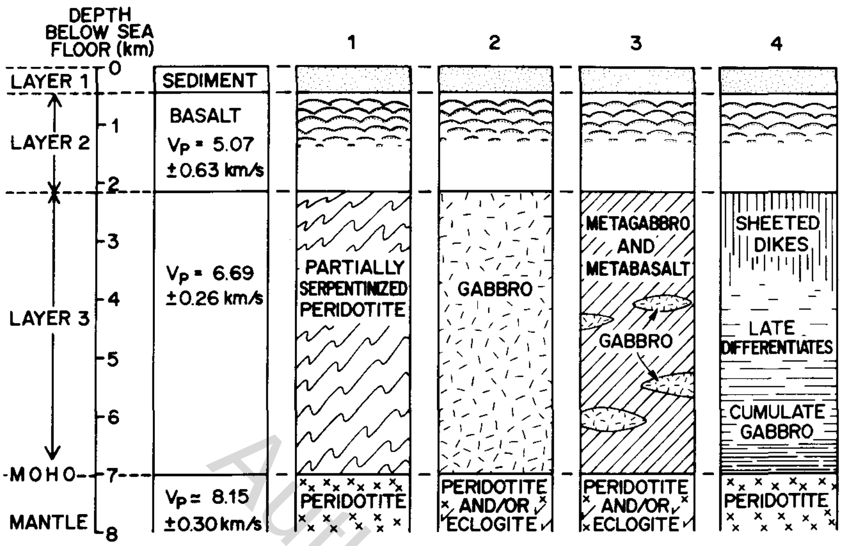

Fig. 2. Petrologic models for the lower crust and upper mantle.

important in interpreting composition from laboratory measurements of seismic velocities.

3. PETROLOGIC MODELS OF THE LOWER OCEANIC CRUST

Although the composition of the oceanic crust has been of considerable interest for the past decade, surprisingly few models have been seriously considered as viable representations of the petrologic nature of the crust. These are illustrated in Fig. 2 along with the average seismic structure of Raitt [1]. It should be emphasized that all four models are probably correct at least locally. Also it seems probable that all of these models are greatly oversimplified. However, the relative abundance of the rocks given in these simple sections is still a matter of speculation and a subject which can be clarified by comparisons of seismic refraction velocities with laboratory measurements.

Through the success of the Deep Sea Drilling Project, the upper portion of layer 2 has been found to consist of basalt at several localities. The laboratory measured velocities in these basalts agree well with refraction velocities of layer 2 [6]; because of this it is probable that basalt is the abundant rock type below the sea floor sediments. It also appears that the lower portion of layer 2 has undergone metamorphic recrystallization [7], since the magnetic anomalies of the oceanic crust probably originate in only the upper half kilometer of layer 2.

The serpentinite lower crustal model (model 1, Fig. 3), originally proposed by Hess [8], assumes that the lower oceanic crust is generated under oceanic ridges by hydration of mantle peridotite. This model is attractive in several ways; serpentinite is simple to generate at ridge crests from an upper mantle composed of peridotite and as emphasized by Hess [8] serpentinite is easily disposed of at subduction zones by dehydration. Nevertheless this model has been strongly criticized by proponents of a mafic lower crust, three different models of which are shown in Fig. 3.

Model 2, which assumes that the lower crust consists of gabbro, has been proposed in several papers [1,9,10,11]. A slight variation of this model has hornblende gabbro as an abundant lower crustal rock, if sufficient water is present during the crystallization of basic magma within the lower crust [12].

As has been suggested as an alternative to the serpentinite and gabbro models, [12,13,14], metabasalts and metagabbros may be abundant constituents of the lower crust. For this model (model 3, Fig. 2) gabbros are assumed to occur within the lower crust as dikes and sills which have intruded the metamorphics. It is usually assumed that the metamorphism (greenschist to amphibolite facies) originates at ridge crests where high thermal gradients prevail, and the metabasalts and metagabbros are transported laterally by sea floor spreading.

Model 4 of Fig. 2 is based on rocks from ophiolites, believed by many to represent oceanic crust [15,16,17]. The hard rock portion of these sequences usually begin from the top with pillow basalts overlying sheeted dikes. The sheeted dikes, which are usually equated with the upper portion of layer 3, are vertical or near vertical and often metamorphosed to greenschist and amphibolite facies grade. Beneath the sheeted dikes are cumulate gabbros often containing abundant hornblende. Diorites, granophyres and trondhjemites, representing late stage products of differentiation, are common between the sheeted dikes and the gabbros. The lower portion of the ophiolite column (interpreted to represent mantle) consists of an uppermost ultramafic cumulate phase, containing abundant dunite and harzburgite, which overlies ultramafic tectonite composed of harzburgite.

4. LOWER CRUSTAL COMPOSITION

Since the dominant physical variable within the lower crust and upper mantle is pressure, experimental studies of seismic velocities in rocks at high pressure are the most significant for the analysis of seismic refraction velocities. Pressures within the lower oceanic crust and immediately beneath the Mohorovicic discontinuity are usually between 1 and 3 kbars. Compressional wave velo-

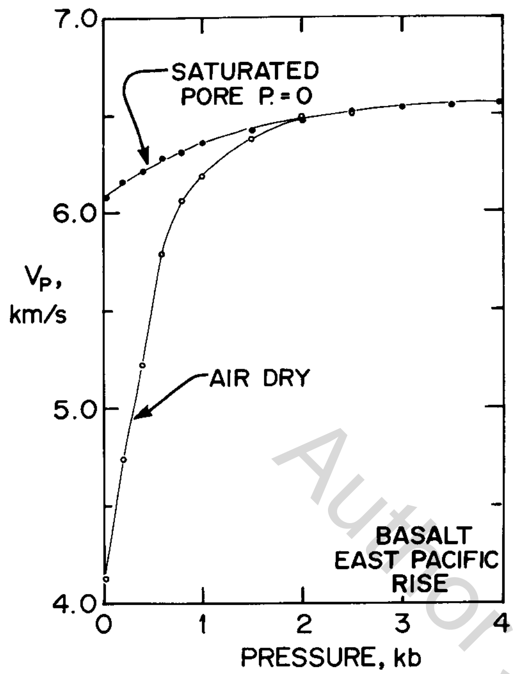

Fig. 3. Compressional wave velocities for saturated and air-dry basalt.

cities for a sample of oceanic basalt to 4 kbars, illustrated in Fig. 3, show two important features of rock velocities. First, velocities increase rapidly over the initial few kilobars increase in pressure, a finding ascribed to closure of grain boundary cracks [18]. At higher pressures grain boundary porosity is essentially eliminated, and the velocities are primarily related to the elastic properties of the minerals within the rocks. Second, it is significant that low pressure compressional wave velocities are higher if the rock pore spaces are water saturated. Since for most rocks the effect of pore water on velocities is usually minimal above 1 to 2 kbars, water saturation is an important variable only in velocity measurements of possible oceanic crustal rocks and has little importance in the interpretation of mantle velocities.

Since the classic works of Birch [18,19], in which compressional wave velocities were reported to 10 kbars for a wide variety of igneous and metamorphic rocks, several papers have presented data on velocities in rocks which are pertinent to a discussion of crustal and upper mantle composition. An extensive listing will not be at-

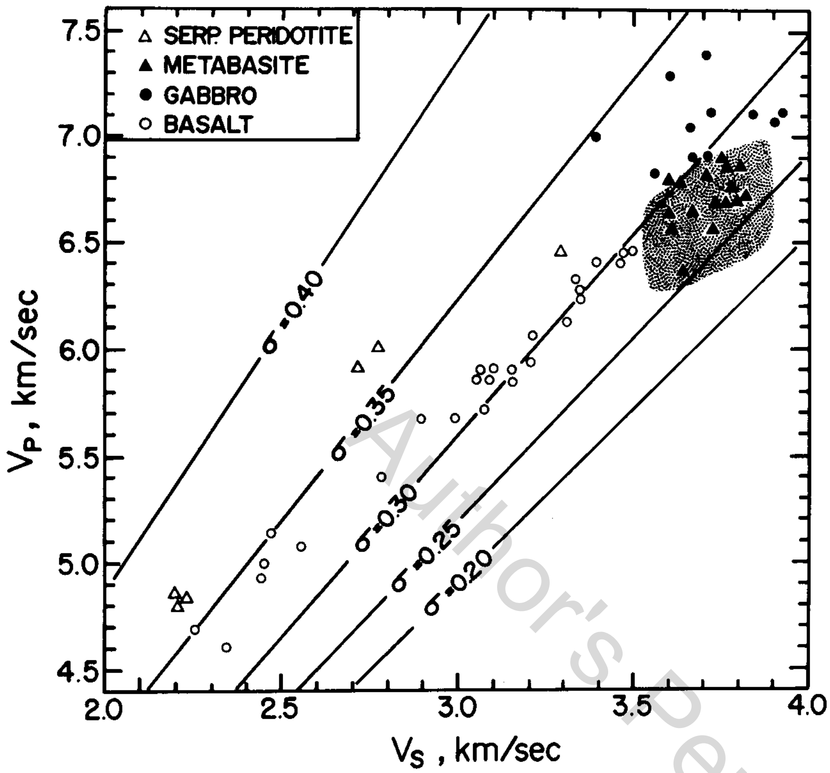

Fig. 4. The range of observed refraction velocities for layer 3 (stippled area) and rock velocities at 1 kbar.

tempted here; however, in addition to Birch's papers, much use will be made of the studies of Simmons [20], Christensen [5,12,21,22], Christensen and Shaw [23], and Christensen and Ramananantoandro [24]. Many of these papers also include data on shear wave velocities at elevated pressures, which provide important constraints on crustal and upper mantle composition when combined with compressional wave velocities.

Compressional wave velocities reported for layer 3 are similar to laboratory measurements of velocities in gabbro [12,18,21], amphibolite [12,18,21] and greenstone [22]. In addition, lower crustal velocities in the range of 6.7 to 6.9 km/sec agree with laboratory measurements in partially serpentinized peridotite containing between 30 and 40% serpentine [5,12]. Thus if only oceanic compressional wave velocity refraction data are compared with rock velocities, all of the models illustrated in Fig. 3 are probable.

Recently it has been shown that the Poisson's ratios (σ) of partially serpentinized peridotites calculated from compressional (V_p) and shear (V_s) wave velocities from the relation

$$2\sigma = 1 - \frac{1}{(V_p/V_s)^2 - 1},$$

are usually much higher than values calculated from lower oceanic crustal refraction data [5]. This is illustrated in Fig. 4, in which velocities are plotted at 1 kbar for a variety of water saturated rocks from the ocean floors. Also shown are lines of constant Poisson's ratio and the range of lower crustal refraction data for which both compressional and shear wave velocities have been reported [5]. Of importance is the observation that Poisson's ratios for oceanic gabbros are generally much higher than observed values for layer 3, whereas laboratory measurements of σ for metabasalts and metagabbros agree well with seismic refraction measurements. Thus models 1 and 2 of Fig. 3 are unlikely to be abundant within the oceanic crust. It should be emphasized that refraction theory assumes that layer velocities are for waves traveling near the upper boundary of the layer. Thus the conclusion that the upper portion of layer 3 is metamorphic agrees with models 3 and 4, since the sheeted dikes of model 4 are usually metamorphosed.

At present it is impossible to distinguish between models 3 and 4 from seismic refraction data; however the velocity distributions within layer 3 of the two models should differ significantly. The late differentiates of model 4, which occur beneath the sheeted dikes, have very low velocities [18] and, if abundant, should form a low velocity region within layer 3. Also Poisson's ratio in the lower regions of layer 3 should be high if cumulate gabbros are abundant.

Crustal studies by seismic refraction techniques in Iceland provide abundant data on crustal values of Poisson's ratios for the crust of this region. Pálmason [3] reports average lower compressional and shear velocities of 6.35 km/sec and 3.53 km/sec, respectively, with Poisson's ratios near 0.27. The low velocities, which are also common in the upper mantle, are most likely related to the high temperature gradient in the region. Poisson's ratio, on the other hand, shows little change with temperature; thus from Fig. 4 it appears that metabasalt and metagabbro are abundant within the lower crust of Iceland.

A high velocity basal crustal layer with compressional wave velocities averaging 7.4 km/sec and a thickness of about 3 km has been found in several locations in the Pacific Ocean basin [4]. At present no shear velocity data have been published for this layer, so one can only speculate as to its nature using compressional wave velocity measurements. The velocities for this layer are in general much higher than those observed for amphibolite and gabbro. Nevertheless, appropriate velocities have been reported for specific directions in anisotropic varieties of these rocks [21]. The most probable composition for this layer, not to be confused with "anomalous mantle" under ridge crests, is that of peridotite 10 to 20% serpentinized or feldspathic peridotite, both of which have appropriate velocities. Either of these compositions is consistent with model 3 of Fig. 3. Feldspathic peridotite does not occur in sufficient amounts within ophiolites to form a 3 km thick basal crustal layer. Thus a serpentinized peridotite origin for the 7.4 km/sec layer is the most favored for model 4.

5. UPPER MANTLE COMPOSITION

Compressional wave velocities in the oceanic upper mantle are generally between 7.8 and 8.6 km/sec, with a mean of approximately 8.2 km/sec (Fig. 1). The velocities severely limit permissible mineralogies, such that the most likely upper mantle rocks are peridotite and eclogite. The relative abundances of these two rock types, however, are still highly debated.

Recently Hart and Press [25] reported lithospheric S_n velocities ranging from 4.58 to 4.71 km/sec. Based on calculated velocities for various upper mantle petrologic models [26], they concluded that the upper mantle is composed of an eclogite-peridotite mix, because shear velocities of 4.71 km/sec are higher than that of peridotite. This, however, does not agree with laboratory measurements of shear wave velocities in fresh peridotites and dunites [24,27], which show that at pressures of 6 to 10 kbars unaltered peridotites have shear velocities between 4.6 and 4.8 km/sec. Similar shear velocities have been reported for eclogites [27]. Thus, in contrast with lower crustal studies, shear velocities are of

TABLE 1. Compressional wave velocities (km/sec) and anisotropies at 2 kbars

Rock	Highest Velocity	Lowest Velocity	Difference, % of mean	Reference
Dunite (North Carolina)	8.35	7.61	9.3	[18]
Dunite (Washington)	8.85	7.92	11.1	[18]
Dunite (New Zealand)	8.25	7.48	9.8	[18]
Dunite (Washington)	8.96	8.22	8.6	[28]
Dunite (Washington)	8.62	7.81	9.9	[24]
Dunite (Washington)	9.00	7.70	15.6	[24]
Eclogite (Colorado)	8.34	8.23	1.3	[29]
Eclogite (Colorado)	8.04	7.96	1.0	[29]
Eclogite (Japan)	8.54	8.40	1.8	[29]
Eclogite (Japan)	8.12	7.88	3.0	[29]

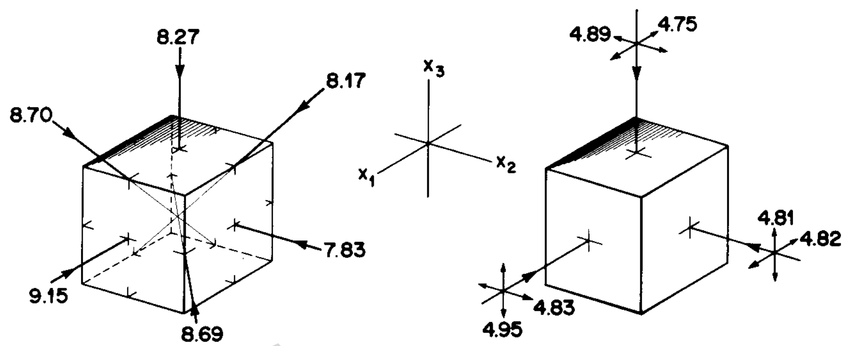

Fig. 5. Seismic velocities for an anisotropic dunite [24].

little value in deciphering upper mantle composition.

The elastic properties of rocks are usually considered to be isotropic, in which the elastic responses such as seismic wave velocities do not vary with direction. Under this simplifying assumption of isotropy, only two independent constants are required to completely describe elastic behavior. However, several recent investigations have shown that most ultramafic rocks are not adequately described by isotropic models, but require anisotropic elastic descriptions.

Compressional wave velocities and associated anisotropies at high pressure for several ultramafics and eclogites are given in Table 1. As was originally shown by Birch [18,19], the strong variation of compressional wave velocity with propagation direction in ultramafic rocks is related to preferred olivine orientation. Single crystal olivine is highly anisotropic with a maximum compressional wave velocity of 9.9 km/sec for propagation parallel to the a crystallographic axis and a minimum velocity of 7.7 km/sec for propagation parallel to the b axis. More recent studies of seismic anisotropy [24,28,29] have shown that the degree of preferred mineral orientation controls the magnitude of the anisotropy. Also, studies of shear wave propagation in olivine bearing ultramafic rocks have found that shear wave velocities within rocks with strong fabrics vary with displacement direction as well as propagation direction [24,30]. These relationships and the magnitude of anisotropy for a specimen of dunite with strong olivine orientation are illustrated in Fig. 5.

Detailed seismic refraction studies of the upper mantle in the northeast Pacific [31,32,33] have clearly shown that compressional wave velocities vary significantly with azimuth, the highest velocities being normal and the lowest parallel to ridge crests. The magnitude of the anisotropies are usually between 0.3 and 1.0 km/sec, in agreement with many laboratory measurements in olivine-rich ultramafics.

It is significant that eclogites, in general, do not show the strong anisotropy characteristic of many ultramafics [18,27,34]. Thus the observed anisotropies in the Pacific are most likely accounted for by dunite and peridotite with preferred olivine orientation. Upper mantle seismic velocities in other oceanic regions, however, which do show anisotropy may very well be accounted for by an eclogite model.

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