# Seismic Anisotropy in the Oceanic Upper Mantle: Evidence From the Bay of Islands Ophiolite Complex

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Olivine fabrics in 17 field-oriented ultramafics and mafics from three widely-spaced traverses in the Bay of Islands Ophiolite Complex, Newfoundland, display a remarkably uniform symmetry in which the olivine a crystallographic axes are aligned subprependicular to the sheeted dikes and the b and c axes lie within the plane of the sheeted dikes. The ultramafics studied consist entirely of tectonites; any olivine formed at the ridge crest by cumulus processes has since been re-oriented by translation gliding and/or syntectonic recrystallization. Deformation has extended from the ultramafics into the overlying gabbro, which suggests that in many oceanic regions the deepest levels of layer 3 consist of gabbroic tectonites. Compressional wave velocities computed from these petrofabrics display 5-6% anisotropy in the plane of the Mohorovičić discontinuity, with  $V_p$  fast parallel to the direction of spreading inferred from dike orientations. Since this pattern is identical to that observed for the oceanic upper mantle, it is concluded that the Bay of Islands Complex is a segment of oceanic crust and upper mantle. Shear wave velocity contours calculated from the same fabrics indicate that the upper mantle is nearly isotropic in terms of the maximum shear wave velocity,  $V_{s_{max}}$ , but that the difference in velocity,  $\Delta V_s$ , between shear waves of orthogonal polarization traveling in the same direction may be sufficiently large parallel to the intersection of the Mohorovičić discontinuity and the sheeted dikes to allow detection of two distinct shear wave arrivals.

#### INTRODUCTION

Nearly 70 years ago, Anton Mohorovičić found evidence in the Balkans of a sharp velocity discontinuity a few tens of kilometers below the earth's surface. In the course of later seismological studies, this discontinuity was shown to mark a fundamental boundary separating the earth's crust and upper mantle.

During the past decade, studies of upper mantle velocity structure have experienced renewed interest due, in part, to the discovery by Hess [1964] of seismic anisotropy in the oceanic upper mantle. Hess' original observation was based on  $P_n$  velocities measured by Raitt [1963] and Shor and Pollard [1964] in the Mendocino and Maui areas of the northeast Pacific. Since then, detailed studies have shown that such seismic anisotropy is common and probably related to sea floor spreading processes [Shor et al., 1973; Bibee and Shor, 1976]. Of particular significance are the studies of Raitt et al. [1969] off northern California and Baja California, Morris et al. [1969] near the Hawaiian arch, Keen and Barrett [1971] off Vancouver Island, British Columbia, and Snydsman et al. [1975] in the Cocos plate. All of these refraction surveys demonstrated a similar anisotropy pattern in which the maximum  $P_n$  velocities are parallel or nearly parallel to the spreading direction. The maximum detected anisotropy varied from 0.3 km/s off Baja California to 0.7 km/s off the coast of British Columbia.

The discovery of seismic anisotropy was stimulated by the observation of *Birch* [1960, 1961] that compressional wave velocities vary with propagation direction in many probable upper mantle rocks, due, presumably, to the preferred orientation of olivine and compressional wave velocity measurements

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in single crystal olivine by Verma [1960] of 9.87, 7.73, and 8.65 km/s in the a, b, and c crystallographic directions, respectively. Detailed studies of petrofabrics and velocity measurements at elevated pressures [Christensen, 1965, 1966] have subsequently confirmed that seismic anisotropy is related to preferred mineral orientation in ultramafic rocks. Maximum velocities were found to coincide with propagation parallel to concentrations of olivine a crystallographic axes and minimum velocities with propagation parallel to b axes. More recent laboratory studies have both confirmed these earlier results and provided more detailed information on shear as well as compressional wave propagation in ultramafic rocks [Christensen, 1971; Kumazawa et al., 1971; Christensen and Ramananatoandro, 1971; Babuska, 1972].

If the oceanic mantle is strongly anisotropic due to the preferred orientation of olivine, an investigation of seismic anisotropy in ultramafics from ophiolites should provide a critical test of the hypothesis that ophiolites represent obducted fragments of oceanic lithosphere. Ideally, such a test should be conducted in an ophiolite in which well-developed sheeted dikes and relatively unfaulted lithologic boundaries of known attitude provide a structural reference frame within which samples can be oriented both with respect to each other and to the direction of spreading. Portions of the Bay of Islands ophiolite complex in western Newfoundland appear to meet these criteria. Within a large portion of the North Arm Massif (Figure 1), the boundary between the ultramafics and overlying gabbros (i.e., the Mohorovičić discontinuity) presently strikes approximately N45°E and dips 60°NW. Although there is some variability, the sheeted dikes on the average strike N45°W and dip about 70° to the southwest (Figure 2). Thus to be consistent with oceanic seismic refraction measurements, the maximum velocity within the ultramafics should be close to horizontal and NE-SW if, as is com-



Fig. 1. Location of samples used for petrofabric studies from the North Arm Massif and Table Mountain, Bay of Islands Ophiolite Complex, Newfoundland (map after *Williams* [1971]).

monly assumed, the sheeted dikes were originally parallel to the ridge crest.

With the objectives of measuring seismic anisotropy and, if detected, relating this anisotropy to the spreading direction, field-oriented samples were collected along two traverses in the North Arm Massif from the basal olivine gabbros and the underlying ultramafics (Figure 1). In addition, a small number of samples was collected for comparison along a traverse on Table Mountain, a smaller massif to the north which because of erosion lacks sheeted dikes but has a well-exposed gabbro ultramafic contact. Both field and thin section examinations of the ultramafics from both massifs reveal a highly variable and pervasive serpentinization. This serpentinization, common in many ophiolites, has been shown to often form during or after obduction onto continental margins [e.g., *Christensen*, 1972; Wenner and Taylor, 1973; Margaritz and Taylor, 1974] and to produce a drastic lowering of velocities in ultramafic rocks [Birch, 1961; Christensen, 1966]. The effect of serpentinization on velocity combined with the variability in abundance of serpentinization within the lower portion of the complex complicate the detailed study of anisotropy by conventional ultrasonic methods. However, velocities and hence anisotropy can be obtained rigorously if sufficient relict mineral grains are present to reconstruct the original petrofabric by universal stage techniques and if the elastic constants of the constituent minerals are well known. Since it is estimated that pyroxene constituted no more than 15% of the original mantle rocks and at some levels considerably less, it may be assumed that any seismic anisotropy within the complex is primarily related to preferred olivine orientation. Since the elastic constants of



Fig. 2. Equal area, lower hemisphere projection of normals to 48 sheeted dikes from North Arm Mtn. Contours 2%, 4% and 6% per 1% area.

olivine as well as their pressure derivatives have been measured to a high accuracy [e.g., Verma, 1960; Kumazawa and Anderson, 1969], it is possible to calculate anisotropy in dunites and peridotites in detail. In the following section, petrofabric diagrams are given for seventeen ultramafic and gabbroic rocks from the North Arm Massif and Table Mountain and seismic velocities are calculated for the ultramafics as a function of direction from the fabric data. Based on this study, it can be demonstrated that the seismic anisotropy of the Bay of Islands Ophiolite Complex agrees remarkably well in magnitude and direction with that observed in the upper mantle from seismic refraction studies. Besides strengthening the hypothesis that the Bay of Islands ophiolites represent fragments of oceanic lithosphere, the results provide new insight into the exact nature of olivine orientation within the upper mantle and the relationship of preferred olivine orientation to upper mantle flow.



Fig. 3. Equal area, lower hemisphere projections of [100], [010], and [001] axes of olivine plotted as Kamb diagrams for samples 116, 111, 109, 3, 108, 107, 103, 104C, and 102A from the southwest traverse across the North Arm Massif; samples 137, 134A, 131, and 129B from the northeast traverse; and samples 157, 161, 164, and 162 from Table Mountain. Samples 116 and 137 are gabbroic tectonites, and 157 is a plagioclase peridotite; the remaining samples are ultramafic tectonites. N = 100 for each sample; projection contoured in  $2\sigma$  intervals with the lowest contour =  $4\sigma$ ;  $\sigma = 2.75$ ;  $E = 3\sigma$ ; counting area A = 0.083.



Fig. 3. (continued)

**OLIVINE FABRICS AND SEISMIC ANISOTROPY** 

Since seismic refraction studies provide anisotropy information only within two dimensions, a certain ambiguity is inherent in relating refraction velocities to olivine fabric. Observed upper mantle anisotropy patterns can be produced by several significantly different olivine fabrics [*Christensen and Crosson*, 1968]. For example, an upper mantle containing olivine with strong concentrations of all three crystallographic axes will be similar in elastic properties to crystals with orthorhombic symmetry. The maximum compressional wave velocity in this case will be in a direction parallel to the olivine a axes concentration and the minimum velocity will correspond to the olivine baxes concentration.

A much simpler type of anisotropy, which is common in

many ultramafic rocks, originates from preferred olivine orientation patterns which contain a strong concentration of one crystallographic axis and girdles of the other two axes. Rocks with this fabric are transversely isotropic and only five elastic parameters are required to completely describe their velocity surfaces compared to nine for orthorhombic symmetry and twenty-one for the general case of a triclinic solid. Transversely isotropic materials are characterized by an axis of symmetry normal to which compressional waves travel at the same velocity for all directions. This axis is a direction of either maximum or minimum compressional wave velocity; shear waves propagating normal to the symmetry axis have velocities which depend only on the polarization direction. It has been shown that the upper mantle velocity data of Raitt [1963] and Shor and Pollard [1964] taken near the Mendocino and Molokai fracture zones can be adequately explained by either



the orthorhombic case or the transversely isotropic case with a nearly horizontal symmetry axis [Crosson and Christensen, 1969]. If the upper mantle is transversely isotropic and the symmetry axis corresponds to a strong olivine b axes concentration (Type I anisotropy of Crosson and Christensen [1969]), then the symmetry axis must be nearly horizontal and normal to the spreading direction, since crystallographic b is the slow direction in olivine. If, however, the symmetry axis is parallel to a strong concentration of olivine a axes (type II anisotropy of Crosson and Christensen, [1969]) the spreading direction should coincide with the symmetry axis.

The petrofabric patterns of olivine within the eleven ultramafics studied from the North Arm Massif, shown as K amb plots in Figure 3, display a well-developed orthorhombic symmetry which is remarkably consistent from sample to sample. The crystallographic a axes form distinct maxima which are aligned NE-SW and generally dip 0°-15° to the northeast, while the b and c axes are concentrated in a NW-SE vertical plane perpendicular to a. Within this plane, the c axes form vertical maxima while the b axes occasionally form weak girdles about a, but more commonly form pronounced maxima which dip 0°-40° to the SE, with the dip being most pronounced in samples 104C, 102A, and 131. It is significant that the a axes maxima tend to lie perpendicular to the plane of the sheeted dikes and subparallel to the plane of the Mohorovičić discontinuity (i.e., the contact between the ultramafics and the overlying gabbros, which strikes NE-SW and dips to the NW) while the b and c axes lie within the plane of the sheeted dikes. Since this fabric is relatively constant in symmetry and orientation throughout two widely separated traverses, it can only be concluded that it is representative of the entire massif. Although the samples from Table Mountain cannot be oriented as rigorously as those from the North Arm Massif, their fabrics are clearly consistent with that outlined above despite significant rotation between the two bodies: the a axes are again concentrated in strong maxima lying in the plane of the Mohorovičić discontinuity, while the b and c axes are aligned perpendicular to a, either in distinct maxima or diffuse girdles.

The ultramafics of many ophiolites have been subdivided into an upper cumulate section, which is considered genetically related to overlying cumulate gabbros [*Thayer*, 1969], and a lower tectonite section [e.g., *Greenbaum*, 1972]. It is evident from the fabrics presented in Figure 3, however, that the ultramafics of the North Arm Massif and Table Mountain consist entirely of tectonites. If any of the olivine was originally formed by cumulus processes at the ridge crest, it has since been reoriented to produce a fabric similar to that of the underlying ultramafics. Somewhat unexpectedly, the olivine fabric shown in Figure 3 for the gabbros immediately overlying the ultramafics is identical to that in the tectonites. This

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suggests that tectonization has extended beyond the ultramafics into the overlying gabbros and that the deepest levels of layer 3 may locally consist of gabbroic tectonites. A similar pre-emplacement deformation has been reported by *Avé Lallemant* [1976] in the gabbros of the Canyon Mountain Ophiolite of eastern Oregon.

### CALCULATED VELOCITIES

Beginning with the work of Verma [1960], the elastic constants and hence the velocities for different propagation directions in single crystal olivine have been well established. Once the elastic constants and their pressure derivatives are known, it is relatively straightforward to calculate velocities at upper mantle pressures for different propagation directions in olivine aggregates with known petrofabrics. Calculations of this type were first performed by Kumazawa [1964] for hypothetical olivine aggregates having simple petrofabrics. More recently, detailed calculations of anisotropy from fabric diagrams have shown excellent agreement with velocities measured in the laboratory [Klima and Babuška, 1968; Crosson and Lin, 1971; Baker and Carter, 1972; Carter et al., 1972].

Using the technique described by *Crosson and Lin* [1971], the elastic constants of olivine and their pressure derivatives at ambient temperature [*Kumazawa and Anderson*, 1969], the petrofabric orientation data for each grain, the density of olivine, the pressure appropriate to each sample and the direction cosines for the directions in which velocities are to be calculated, we have determined the compressional wave velocity as a function of direction for each of the ultramafic samples shown in Figure 3. The data are presented in velocity contour form for each sample in Figure 4 and averaged for the North Arm Massif and Table Mountain ultramafics in Figures 5 and 6, respectively. Since the solution of the Cristoffel equation for any given wave normal gives three velocities which correspond, in general, to one quasi-compressional and two quasishear waves [e.g., Musgrave, 1970], it is also possible to calculate the shear wave velocity as a function of vibration direction for any propagation direction. Since the velocity of transverse waves in any anisotropic medium is strongly dependent upon vibration direction, the rocks discussed here will display two orthogonally polarized shear waves traveling at different velocities for most directions of propagation. The velocities of these two waves,  $V_{s_{max}}$  and  $V_{s_{min}}$ , are also shown as a function of propagation direction in Figures 5 and 6, together with the difference in velocity,  $\Delta V_s$ , between these two modes and the resultant maximum and minimum values of Poisson's ratio,  $\sigma(V_{s_{\max}})$  and  $\sigma(V_{s_{\min}})$ . Superimposed on both figures are our best estimates of the average attitudes of the sheeted dikes and the Mohorovičić discontinuity.

Perhaps the most striking feature of the composite contour



Fig. 4. Equal area, lower hemisphere projection of compressional wave velocity contours calculated for ultramafic samples shown in Figure 3. Contour interval is 0.1 km/s.

diagrams shown in Figures 5 and 6 is the well-developed compressional wave anisotropy pattern in the North Arm and Table Mountain ultramafics and the remarkable agreement between this pattern and theoretical predictions. In the North Arm Massif, the compressional wave velocities are high normal to the sheeted dikes because this direction is nearly parallel to the concentration of olivine a axes. Since the olivine band c crystallographic axes are concentrated within the plane of the sheeted dikes, the compressional wave velocities in this plane are low and display only 1% anisotropy. The most significant velocities for comparison with refraction data, however, are for propagation directions parallel to the Mohorovičić discontinuity; within this plane, the compressional wave anisotropy is 5% of the mean velocity, with the maximum velocity (8.7 km/s) subperpendicular to the sheeted dikes and the minimum velocity (8.2 km/s) subparallel. Although the samples from Table Mountain cannot be oriented with respect to the sheeted dikes, it is nonetheless clear from Figure 6 that the anisotropy in the plane of the Mohorovičić discontinuity is even more prounounced ( $\sim 6\%$ ) on Table Mountain than on the North Arm Massif.

From an analysis of anisotropy data in several localities Bibee and Shor [1976] conclude that on the average the high velocity direction in the upper mantle coincides with the spreading direction. In Figure 5 the direction of maximum compressional wave velocity is offset from the estimated direction of sea floor spreading (the normal to the sheeted dikes) by  $10^{\circ}-15^{\circ}$ . This could simply be due to an error in estimating the average attitude of the sheeted dikes, however, similar differences have been reported from seismic refraction experiments. For example, Keen and Barrett [1971] found the direction of



maximum velocity off the coast of British Columbia to be  $17^{\circ}$  from the presumed direction of spreading while *Morris et al.* [1969] observed a difference of  $10^{\circ}$  near the Hawaiian Islands. Similarly, the data of *Raitt et al.* [1969] show a difference of  $18^{\circ}$  in the Quartet area and  $9^{\circ}$  in the Flora area. One possible explanation for those observations is that the direction of maximum compressional wave velocity may reflect local changes in the direction of spreading [Keen and Barrett, 1971].

The mean compressional wave velocity in the plane of the Mohorovičić discontinuity in Figures 5 and 6 is 8.5 km/s whereas the mean  $P_n$  velocity observed at sea is 8.1 km/s [*Christensen and Salisbury*, 1975]. Recent measurements in our





Fig. 5. Average of equal area, lower hemisphere projections of compressional wave velocity  $V_p$  shown in Figure 4 for the North Arm Massif. Also shown are composite projections for the maximum shear wave velocity  $V_{s_{max}}$ ; the minimum shear wave velocity  $V_{s_{max}}$ ; the shear wave dispersion  $\Delta V_s$ , in km/s; the Poisson's ratio based on  $V_{s_{max}}$ . Each projection based on data from 12 samples (1200 measurements). Velocity projections contoured in 0.1 km/s intervals. Dashed lines represent the attitude of the sheeted dikes, and solid great circles represent the attitude of the boundary between the gabbros and ultramafics.

laboratory of the effect of temperature on velocities in dunite indicate that increasing temperature will lower compressional wave velocities by about 0.1 km/s per 100°C. An increase in temperature of 200°C plus the addition of 10% pyroxene will bring the calculated velocities [*Christensen*, 1966] into excellent agreement with observed upper mantle velocities and at the same time have little effect on anisotropy.

If the North Arm Massif and Table Mountain ultramafics represent segments of oceanic upper mantle, it follows from Figures 5 and 6 that the upper mantle is nearly isotropic for the faster of the two shear waves. Since the oceanic upper mantle is strongly anisotropic in terms of  $V_p$ , however, it follows from the relation,

$$\sigma = \frac{1}{2} \left[ 1 - \frac{1}{(V_p/V_s)^2 - 1} \right]$$

that values of Poisson's ratio,  $\sigma$ , based on  $V_p$  and  $V_{s_{max}}$  will be strongly direction dependent, with the maximum values observed parallel to the direction of spreading. The actual shear wave recorded will, of course, depend on the directional response of the seismometer. It is also interesting to note that the dispersion,  $\Delta V_s$ , of shear waves of different polarization traveling in the same direction is also direction dependent, with the maximum dispersion being developed parallel to the intersection of the plane of the sheeted dikes and the Mohorovičić discontinuity. Because of the scarcity of shear wave data for the oceanic upper mantle, it has not been possible to test for the relations predicted above involving  $V_s$ . It seems likely, however, that these relations might be evaluated by a relatively simple OBS experiment designed to study variations in  $V_s$  with direction and polarization at a site of known compressional wave anisotropy.

#### IMPLICATIONS AND CONCLUSIONS

Ever since its recognition in the 1960's, the compressional wave anisotropy of the oceanic upper mantle has been considered one of the most distinctive seismic features of the oceanic lithosphere. Although such anisotropy has been recognized previously in ultramafic samples from ophiolites [e.g., Avé Lallemant, 1976; George, 1978; Peselnick and Nicolas, 1978], it has not been possible in the past to demonstrate a regional anisotropy pattern from a suite of samples or to orient this pattern with respect to the spreading direction by means of structural features in the ophiolites such as sheeted dikes.

As anticipated by *Hess* [1964], the compressional wave seismic anisotropy of the oceanic upper mantle is due almost exclusively to the preferred orientation of olivine. From the cases observed here, it is clear that the olivine fabric at many sites displays an orthorhombic symmetry with the olivine a axes aligned subparallel to the direction of spreading and the b and c axes concentrated in a vertical plane parallel to the spreading axis. A weak tendency in a number of samples from



Fig. 6. Average of equal area, lower hemisphere projections of compressional wave velocity  $V_p$  shown in Figure 4 for Table Mountain. Also shown are composite projections for the maximum shear wave velocity,  $V_{s_{max}}$ ; the minimum shear wave velocity,  $V_{s_{min}}$ ; the shear wave dispersion  $\Delta V_s$ , in km/s; the Poisson's ratio based on  $V_{s_{max}}$ ,  $\sigma(V_{s_{max}})$ ; and the Poisson's ratio based on  $V_{s_{min}}$ ,  $\sigma(V_{s_{min}})$ . Each projection based on data from three samples (300 measurements). Velocity projections contoured in 0.1 km/s intervals. Solid great circles represent the attitude of the boundary between the gabbros and ultramafics.



Fig. 7. Deviations from a mean upper mantle velocity of 8.159 km/s as a function of azimuth for velocities measured NE of Hawaii [*Morris et al.*, 1969]. Curve represents compressional wave anisotropy pattern for the North Arm Massif.

the Bay of Islands Complex suggests, however, that at a num ber of sites, the anisotropy may be due to a related form of axial symmetry in which the olivine a axes lie subparallel to the spreading direction, as before, but the b and c axes form girdles. This latter fabric produces transverse isotropy within the complex (type II of *Crosson and Christensen* [1969]) in which the fast direction corresponds to the maximum concentration of olivine a axes and velocities in the plane normal to this maximum are relatively low and vary only slightly with propagation direction (e.g., see Figure 4, samples 111, 131, and 162).

The excellent agreement between data from the Bay of Islands ophiolite and observed upper mantle anisotropy is illustrated in Figure 7, in which the deviation from a mean  $P_n$ velocity of 8.159 km/s is plotted as a function of azimuth for 1147 vertically refracted mantle arrivals from the Hilo and Show expeditions northeast of the Hawaiian Islands [Morris et al., 1969]. In their original presentation of their data, Morris et al. included a solution using the  $2\phi$  terms of the *Backus* [1965] anisotropy function. In Figure 7, this solution has been replaced by the observed compressional wave anisotropy pattern for the North Arm Massif by setting the azimuth of the sheeted dikes equal to 180°, or parallel to the spreading axis. Since the two anisotropy patterns are indistinguishable in both magnitude and orientation, the conclusion is inescapable that the ultramatics from the North Arm Massif represent oceanic upper mantle.

Finally, it should be noted that the seismic velocity structure of a traverse through a mafic section of the Bay of Islands Ophiolite obtained from velocities measured in the laboratory under appropriate conditions of hydrostatic confining pressure and water saturation is similar to that of normal oceanic crust [Salisbury and Christensen, 1978]. With the recognition of an ultramafic anisotropy pattern identical in magnitude and direction to that observed at sea in oriented samples from the same complex, it is clear that this ophiolite, and presumably many more, are segments of ocean lithosphere emplaced on land.

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