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SEISMIC ANISOTROPY IN THE UPPER MANTLE

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SUMMARY

From the study of ultramafic rocks it is clear that there is a strong tendency toward oliving orientation in which the b crystallographic axes show a distinct concentration normal to a schistosity or banding. Olivine aand c axes tend to lie in a girdle normal to this b axis concentration. Laboratory measurements of the elasticity of dunite with this fabric show behavior similar to transversely isotropic media for compressional waves.

Evidence is sufficiently strong from both laboratory studies of elasticity and petrofabric studies to suggest that many ultramafic rocks behave macroscopically as transversely isotropic elastic solids. On the strength of prevailing theories regarding the composition and mechanical behavior of the upper mantle, these results suggest an upper mantle which is transversely isotropic to seismic wave propagation. The existence of laminar convection in the upper mantle may provide a mechanism to produce sub-parallel orientation of olivine. Where mantle flow is predominantly sheet-like over large regions such as beneath the oceans, a normal vertical axis transverse isotropy is suggested. In these regions there is no directional dependence of compressional wave refraction arrivals. However, where this pattern is disrupted by rising convection currents or transcurrent faulting, appreciable deviations from this configuration should occur. If seismic observations prove to substantiate the transversely isotropic behavior of the upper mantle, observable seismic anisotropy will be a powerful tool in determining the mantle composition, stress state, and existence and pattern of convection currents, as well as the type of mechanical behavior associated with convection.

INTRODUCTION

OOL The elastic properties of rocks are usually presented in terms of isotropic elasticity, in which the elastic responses such as seismic wave velocities do not vary with direction. Under the simplifying assumption of isotropy only two independent constants are required to completely describe elastic behavior. However, recent laboratory measurements show that most ultramafic and metamorphic rocks are not adequately described by isotropic models but require anisotropic elastic descriptions (Birch, 1960, 1961; Christensen, 1965, 1966a). Of prime importance was the discovery by Birch

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Compressional wave ve	locities an	d anisotrop	oies in ultram	afic rocks			
	2 kbar			10 kbar			Reference
	Vp, highest	km/sec lowest	diff. % of mean	Vp, highest	km/sec lowest	diff. % of mean	
Harzburgite	1.91	7.70	2.7	8.05	7.82	2.9	Birch, (1960)
Dunite	7.68	7.46	2.9	7.87	7.63	3.1	Birch (1960)
(Webster, N.C.) Peridotite 1	7.85	7.45	5.2	8.31	8.04	3.3	Christensen (1966b)
(Hawaii) Peridotite 2	7.88	7.69	2.4	8.53	8.20	3.9	Christensen (1966b)
(Hawall) Dunite (altered)	6.62	6.18	6.9	6.93	6.62	4.6	Birch (1960)
(webster, N.C.) Peridotite 0029	7.38	7.00	5.3	7.84	7.46	5.0	Kanamori and Mizutani (1965)
(Japan) Dunite	7.46	6.98	6.6	7.57	7.19	5.1	Birch (1960)
(1ransvaar) Dunite	7.65	7.12	7.2	7.93	7.49	5.7	Christensen (1966b)
(Addle, N.C.) Dunite	8.35	7.61	9.3	8.51	7.91	7.3	Birch (1960)
(Addle, N.C.) Dunite	8.49	7.70	9.8	8.69	8.00	8.3	Birch (1960)
(Balsani Gap, N.C.) Dunite	8.96	8.22	8.6	9.09	8.35	8.5	Christensen (1966b)
(wasıı.) Dunite (Man. 7aaland)	8.25	7.48	9.8	8.43	7.66	9.6	Birch (1960)
(wew zearand) Dunite (Wash.)	8.85	7.92	11.1	8.95	8.07	10.3	Birch (1960)
PL.	C						

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TABLE I

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Fig.1. Compressional wave velocities (km/sec) for propagation parallel to the crystallographic axes of olivine. (Data from Verma, 1960.)

(1960) that dunites are extremely anisotropic to compressional waves. (Although, strictly speaking, the terms compressional and shear waves in the usual sense are not appropriate to an anisotropic medium, the terms are useful and retained here to indicate the high and low velocity waves respectively.) Compressional wave velocities and associated anisotropies at high pressure of olivine-rich rocks for which velocities have been measured in three or more directions are given in Table I. Birch (1961) successfully correlated the anisotropy for one specimen, the Twin Sisters Dunite, with a preferred orientation of olivine crystals. The anisotropy of one olivine single crystal was determined by Verma (1960) using laboratory measurements of elastic wave velocities. Verma's reported compressional wave velocities in a single crystal of magnesium-rich olivine for propagation parallel to the a, b, and c axes are shown in Fig.1. Since olivine is generally considered to be one of the major constituents of the earth's upper mantle it is apparent that portions of the earth's interior may be elastically anisotropic and, if present, anisotropy provides another parameter for the identification of rocks beneath the earth's surface.

Theoretical treatments of the effects of anisotropy on seismic wave propagation are readily available in the geophysical literature. Recently several workers have presented theory pertaining to anisotropy in the upper mantle. Backus (1965) considers in detail the effects of anisotropy on P_n and S_n velocity as a function of azimuth. He assumes that the region just below the Mohorovičić discontinuity has the most general form of linear elastic behavior, i.e., behavior analogous to the elasticity of a triclinic crystal. Thus for this model, 21 elastic parameters are necessary to completely describe the elasticity of the earth's upper mantle. Anderson (1961, 1962) and other workers consider wave propagation in the simpler transversely isotropic medium. Transversely isotropic materials are characterized by an axis of symmetry normal to which all longitudinal or compressional waves travel at the same velocity. Transverse or shear waves propagating normal to the symmetry axis have velocities which depend only on the polarization

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TABLE II			-Lilas -issues along	
Wave type	Propagation direction (x ₃	Direction of	wave velocity ¹	1
Longitudinal	Kon (Hommige W // Give	Xo	[coo/0] ⁵	18
Transverse	x, X,	y, (or xa)		(2)
Longitudinal	у Х ₁ (ог х2)	x ₁ (or x ₉)	$[c_{11}/p]^{\frac{1}{2}}$) (9)
Transverse	x_1 (or x_2)	x ³	[c44/p]1	(4)
Transverse	$x_1 (or x_2)$	$x_2 (or x_1)$	$[\frac{1}{2}(c_{11} - c_{12})/p]^{\frac{1}{2}}$	(2)
Quasi-longitudinal	$\frac{1}{45^{\circ}}$ from x ₃	not x_1 , x_2 ,	$\{([(c_{13} + c_{44})^2 + (c_{11} - c_{33})^2]^{\frac{1}{2}} + (c_{13} + c_{33})^2 \}^{\frac{1}{2}} \}$	(9)
(high velocity)	axis	or x ₃	$\frac{1}{2}(c_{11} + c_{33} + 2c_{44})) / 2p \}$	
¹ Relationships betwe	en non-zero coefficients: c ₄₄ c ₁₁ c ₆₆	$= c_{55}$ $= c_{22}$ $= \frac{1}{2} (c_{11} - c_{12})$		
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direction. Waves propagating other than normal or parallel to the symmetry axis are not strictly longitudinal or transverse in nature. Five independent elastic constants are sufficient to completely describe a transversely isotropic elastic solid.

Theory indicates that in the long wavelength limit a sequence of isotropic layers acts as a transversely isotropic medium (Backus, 1962). This phenomenon has particular application in the study of surface wave dispersion. Helbig (1966) recently presented an extensive development of seismic ray theory in a tangentially isotropic earth model (the spherical analog of transverse isotropy with vertical symmetry axis).

Most of these and other treatments are motivated by a desire to calculate the seismic effects of various forms of anisotropy and then to detect such effects in existing seismic data. Although the manifestations of anisotropy are usually not unique, it is generally felt that this approach should provide a basis by which to determine the type and degree of anisotropy existing in the earth's interior. To date, this general approach has yielded inconclusive results although the theoretical solutions are valuable. In the present paper a direct look is taken at the elastic properties and fabrics of ultramafic rocks in an attempt to define the nature of anisotropy existing in the upper mantle.

Petrofabric analyses of olivine orientation show several common patterns of alignment: (1) strong concentrations of all three olivine axes; (2) concentrations of a axes normal to a girdle containing b and c axes; (3) concentrations of c axes normal to a girdle of a and b axes; (4) concentrations of b axes normal to a girdle containing a and c axes.

Experimental measurements of elastic wave velocities in dunite and theoretical considerations of the elasticity of olivine single crystals show that fabrics with single maxima lying normal to girdles containing the other two axes behave as transversely isotropic solids. Because the latter pattern appears to be particularly common in ultramafic rocks emphasis is placed upon the relationship of this fabric to seismic anisotropy in the upper mantle.

ELASTICITY OF TRANSVERSELY ISOTROPIC MEDIA

In cartesian notation the relationship between stress (T_{ij}) and strain (S_{ij}) tensors is given by the generalized Hooke's law for linear elasticity.

$T_{ij} = C_{ijkl}S_{kl}$

The summation convention is taken over repeated indices. Elements of the fourth rank tensor C_{ijkl} are designated elastic stiffness coefficients or merely elastic constants. Due to the symmetry properties of the stress and strain tensors and the necessity for a positive definite strain energy function, $C_{ijkl} = C_{jikl} = C_{ijlk} = C_{klij}$, and the maximum number of independent elements of the 81 stiffness coefficients is reduced to 21. Thus a 21 element medium represents the most general anisotropic medium. Examples are crystals in the triclinic system.

Elastic constants are related to the velocities of elastic waves in a medium through the equations of small motion. In the absence of body forces these are, for i = 1, 2, 3:

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(1)

$$\frac{\partial T_{ij}}{\partial x_j} = \rho \frac{\partial^2 u_i}{\partial t^2} \tag{2}$$

where u_i is the particle displacement vector in cartesian coordinate direction x_i and ρ is the density. Since:

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

eq.2 may be written:

$$C_{ijkl} \stackrel{1}{\geq} \left\{ \frac{\partial^2 u_k}{\partial x_j \partial x_l} + \frac{\partial^2 u_l}{\partial x_j \partial x_k} \right\} = \rho \frac{\partial^2 u_i}{\partial t^2}$$

If the displacement in the medium is produced by a plane harmonic wave (i.e., an infinite medium approximation) which is traveling in the direction of the wave vector k_i at a phase velocity c and with an angular frequency ω , then:

$$u_{i} = A_{i} e^{i(\omega t - k_{j} x_{j})},$$

where A_i is an amplitude factor and u_i represents the displacement field. Substituting this expression into eq.3 and carrying out the indicated differentiation yields:

$$-\rho\omega^2 u_i = -\frac{1}{2}C_{ijkl} \left\{ k_j k_l u_k + k_j k_k u_l \right\}$$
(4)

Since $C_{ijkl} = C_{ijlk}$ and j, k and l are dummy summation indices on the right side of eq.4, $C_{ijkl}k_jk_lu_k = C_{ijkl}k_jk_ku_l$ and eq.4 becomes:

$$\rho\omega^2 u_i = C_{ijkl} k_j k_l u_k \tag{5}$$

The phase velocity of the wave has a magnitude $c = \omega/k$ where $k^2 = k_i k_i$. Dividing through both sides of eq.5 by k^2 gives:

$$\rho c^2 u_i = C_{ijkl} v_j v_l u_k \tag{6}$$

where $\nu_j = k_j/k$, i.e., ν_j is a unit vector in the direction of propagation of the wave characterized by the wave vector k_j .

Eq.6 comprises the eigenvalue problem which determines the characteristic velocities (eigenvalues) and particle motion (eigenvectors) of the system. The phase velocity c of the propagating plane waves are related directly to the coefficients of the elastic tensor C_{ijkl} and the density ρ . In general the three eigenvalues of the operator $(1/\rho)C_{ijkl}$ $\nu_j \nu_l$ give the phase velocities of three distinct waves and the associated eigenvectors give the directions of particle motion. The directions of particle motion will not in general be perpendicular to or parallel to the wave vector. The mode of propagation is thus neither longitudinal nor transverse.

For most cases it is impossible short of numerical solution of eq.6 to relate a given velocity directly to one or more stiffness coefficients. However, for materials possessing certain symmetries, it is possible to write direct relations enabling the determination of some or all of the elastic coefficients via the measurement of elastic wave velocities in one or more directions.

One of the simplest forms of anisotropy is exhibited by hexagonal crystals and is frequently designated transverse isotropy. In the following discussion the symmetry axis for this type of elastic behavior corresponds

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(3)

to the x_3 axis. For waves traveling parallel to the x_3 axis only two distinct modes of propagation exist having particle motion parallel to and perpendicular to the symmetry axis. The direction of the wave vector is given by $\nu_j = (0,0,1)$. A longitudinal wave has particle motion in the x_3 direction, $u_i = (0,0,u_3)$ and eq.6 becomes:

$$\rho c^2 u_3 = C_{3333} u_3 \tag{7}$$

from which $c^2 = C_{3333}/\rho$. Similarly for transverse waves with particle motion in the x_1 direction, $u_i = (u_1, 0, 0)$ and eq.6 may be written:

$$\rho c^2 u_1 = C_{1313} u_1 \tag{8}$$

or $c^2 = C_{1313}/\rho$. Particle motion in the x_2 direction yields $c^2 = C_{2323}/\rho$ and hence $C_{1313} = C_{2323}$. Two elastic constants are thus determined by velocity measurements along the symmetry axis.

Transmission perpendicular to the x_3 axis must be independent of azimuth about this axis. Considering the case $v_j = (1,0,0)$, i.e., propagation in the x_1 direction, eq.6 simplifies to:

$$\rho c^2 u_i = C_{i1k1} u_k \tag{9}$$

 $u_i = (u_{1,0,0})$ for longitudinal wave propagation, resulting in $c^2 = C_{1111}/\rho$. Since longitudinal wave propagation along the x_2 axis must have the same velocity, $C_{1111} = C_{2222}$. Transverse waves polarized in the x_3 direction but transmitted in the x_1 direction give $c^2 = C_{3131}/\rho$ which is identical to the velocity of vertically traveling shear waves. Transverse waves propagating in the x_1 direction but polarized in the x_2 direction give $c^2 = C_{2121}/\rho$. It can be further shown by manipulation of coordinate transformation equations (Love, 1944) that $C_{2121} = \frac{1}{2} (C_{1111} - C_{1122})$. From the above relationships four independent constants may be deter-

From the above relationships four independent constants may be determined from velocity measurements parallel to and perpendicular to the symmetry axis. A convenient way to measure the fifth constant is to select a propagation direction 45° from the x_3 axis. The particle motion polarization directions will in general no longer be in the direction of or perpendicular to the wave vector. A solution using the highest velocity wave, sometimes termed quasi-longitudinal, may be given in the form:

$$C_{1133} = \left\{ \left[2\rho c^2 - C_{2323} - \frac{1}{2} \left(C_{1111} + C_{3333} \right) \right]^2 - \frac{1}{4} \left(C_{1111} - C_{3333} \right)^2 \right\}^{\frac{1}{2}} - C_{2323}$$
(10)

which is easily derived from the results of Hearmon (1961, p.72). \bigcirc

All these results are commonly presented in a simplified index notation which reduces the number of permutations of the indices. This change of notation is obtainable from $C_{ijkl} = c_{qr}$, where:

$$q = \begin{cases} \frac{i+j}{2}, & i=j\\ 9-i-j, & i\neq j \end{cases} \quad \text{and} \quad r = \begin{cases} \frac{k+l}{2}, & k=l\\ 9-k-l, & k\neq l \end{cases}$$

Table II summarizes the relationships between velocities and elastic constants for transversely isotropic media using the simplified notation. Similar results can be obtained in principle for other forms of anisotropy.

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EVIDENCE FOR TRANSVERSE ISOTROPY IN ULTRAMAFICS

We are faced with the fundamental problem of determination of the type of anisotropy by means of velocity measurements. From eq.6 it can be seen that knowledge of the velocities (eigenvalues) alone is insufficient in itself to determine the elements of the tensor C_{ijkl} since the particle motion vector is unknown. However, given knowledge of the particle motion u_i

TABLE III

Compressional wave velocities (km/sec) in the Addie. N.C., dunite (after Christensen, 1966b)

Propagation direction	Pressure(kbar)							
	0.1	0.5	1.0	2.0	4.0	6.0	8.0	10.0
A	6.9	6.86	6.90	7.12	7.23	7.34	7.41	7.49
В	6.9	7.08	7.20	7.33	7.51	7.55	7.60	7.66
С	6.9	7.11	7.28	7.38	7.50	7.59	7.65	7.70
D	7.0	7.33	7.43	7.50	7.62	7.71	7.80	7.88
Е	7.1	7.35	7.43	7.53	7.63	7.74	7.81	7.88
F	7.1	7.36	7.42	7.56	7.75	7.81	7.87	7.93
G	7.1	7.44	7.54	7.65	7.77	7.81	7.87	7.93



Fig.2. Orientation diagrams for 120 grains of olivine in Addie dunite (after Christensen, 1966b). (A) *b* axes, contours at 6%, 4%, 2%, and 1% per 1% area; (B) *a* axes, contours at 6%, 4%, 2%, and 1% per 1% area; contours at 4%, 2%, and 1% per 1% area. (C) *c* axes, contours at 4%, 2%, and 1% per 1% area. Directions *A* through *G* refer to propagation directions in Table III.

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Fig.3. Compressional wave velocities in Addie dunite at 10 kbar corrected for serpentine.

associated with each wave vector v_j and wave velocity c, linear equations containing 21 independent unknown C_{ijkl} 's can be constructed from eq.6. Thus given 21 appropriate measurements, either in 7 distinct directions with three velocities per direction or up to 21 different directions, for which the equations are linearly independent, the 21 independent elastic constants could be calculated. The rank of the matrix operator for the case in which these 21 equations are not independent will be a measure of the departure from general anisotropy for the material under consideration, i.e., the degree to which the material possesses symmetry elements. For example, the rank of the 21 by 21 matrix for the case of transversely isotropic material would be five.

Since measurement of the velocities is relatively easy but experimental determination of the associated vibration directions is difficult, we do not usually have sufficient data to uniquely determine the anisotropy of a specimen. Hence the "model fitting" approach is actually used. With this approach an anisotropic model is selected which best fits the observed data on the basis of calculations made from the model. Thus when an axis of symmetry is observed in compressional wave velocity measurements to the accuracy of observed data, the assumption of transverse isotropy is justified, particularly in the absence of this type of symmetry in the velocity surfaces for all other common groups.

An indication of the nature of anisotropy in the upper mantle is thus given by recent laboratory measurements of the elasticity of olivine-rich rocks by Christensen (1966b). A dunite specimen from Addie, N.C., was found to have elastic properties similar to transverse isotropy for compressional wave propagation. Compressional wave velocities for seven directions of propagation in this specimen are given in Table III. A petrofabric analysis of the specimen shows a strong concentration of olivine a and caxes in the plane normal to the b axis maxima. The angular relationships between the directions of measured velocity in Table III and the olivine orientation are shown in Fig.2. This orientation pattern is responsible for low compressional wave velocities for directions parallel to maximum concentrations of b axes and relatively high velocities normal to the maximum concentrations of b axes, which are in agreement with Verma's (1960) data for single crystal olivine (Fig.1). The direction of lowest velocity, propagation direction A, is normal to a weak banding in the specimen. Because the

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olivine a and c axes have a nearly random distribution normal to the b axes maximum, velocities for propagation directions parallel to the plane of the banding (D, E, F, and G, Table III) are approximately equivalent.

In the Addie dunite all velocities are lower than velocities in relatively fresh dunite due to the presence of approximately 15% randomly oriented serpentine. Approximate velocities at 10 kbar and 25° C estimated for serpentine-free rock are given in Fig.3. The velocities were obtained by assuming a velocity of 5.1 km/sec at 10 kbar for serpentine (Christensen, 1966b). A slight lowering of these velocities, due to temperature considerations, and the presence of a small amount of pyroxene, would produce velocities varying from 7.8 to 8.3 km/sec. These velocities are generally comparable with $P_{\rm n}$ velocities observed in the Western Hemisphere (Pakiser and Steinhart, 1964).

ULTRAMAFIC FABRICS AND TRANSVERSE ISOTROPY

Petrofabric analyses of ultramafic rocks generally show strong concentrations of olivine axes. Preferred olivine orientation may be the result of one or a combination of three different mechanisms: (1) rotation of inequant grains in a flowing crystal mush; (2) plastic flow; and (3) recrystallization. For some olivine bearing rocks such as basalt there is strong evidence supporting preferred orientation of olivine by fluid flow (Brothers, 1959). For many ultrabasics, however, there is considerable doubt as to which process is primarily responsible for preferred olivine orientation. Since many ultramafics are located in orogenic belts it is highly probable that their present fabric is the product of an original fabric modified in varying degrees by later deformation.

The fabrics of many olivine-rich rocks have been summarized by Turner (1942), Ladurner (1954) and Brothers (1959). The studies show quite clearly that fabrics of many olivine bearing rocks display several consistent features. Of fundamental importance is the tendency of olivine (010) planes to parallel planes of foliation or banding in ultramafics. Thus these rocks generally show strong concentrations of olivine *b* axes normal to planar structures.

Tilley (1947) finds a preferred orientation of olivine (010) planes in a mylonitized dunite from the St. Paul's rocks. This orientation pattern, characterized by olivine b axes normal to shear planes, offers strong evidence that olivine (010) alignment can originate in the solid state from dynamic forces. Other examples of the parallelism between olivine (010)planes and foliation in rocks which have undergone solid deformation are described by Andreatta (1934) for tectonites in northern Italy and Ernst (1935) for olivine schists from Norway. Both authors report strong concentrations of olivine b axes normal to the schistosity and girdles of a and c axes parallel to the schistosity. The importance of (010) of olivine as a glide plane and the orientation of this glide plane parallel to the principal S surface in olivine tectonites have been cited by Turner (1942), Chuboda and Frechen (1950), Brothers (1959) and Hess (1964). This mechanism of orientation was proposed by Hess (1964) to explain observed variations with azimuth of compressional wave velocities in the vicinity of the Mendocino and Molokai fracture zones.

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Experimental studies of deformation of olivine at 5 kbar confining pressure show that the slip systems in olivine change as a function of temperature and strain rate. Raleigh and Carter (1966) report that the predominant slip system in olivine at high temperatures and low rates of strain is T(slip plane) = (010) and t(slip direction) = [100]. Analyses of the orientations of kink bands and translation glide planes in experimentally deformed olivine by Raleigh (1967) suggest that $\{110\}$, (010), and (100) are possible slip planes in olivine. Slip planes at 5 kbar and 700°C are parallel to {110} the slip direction being parallel to the olivine c axis. At 1,000°C and 5 kbar, Raleigh (1967) reports a second slip system, T = (010) and $t = \lceil 100 \rceil$. Raleigh (1968) concludes that at temperatures less than 1,000°C active slip systems in olivine are: (1) {110} , [001]; (2) (100), [001]; and (3) (100), [010]. At 1,000°C slip systems with $T = \{110\}, t = [001]$ and $T = \{0kl\}, t = [100]$ were determined. Raleigh (1968) finds the latter system predominant at low strain rates. The experiments were too few in number to show whether a field of temperature and strain rate exists where any one of the $\{0kl\}$ planes, such as (010), is favored (C.B. Raleigh, personal communication, 1967).

The implications of preferred orientation of minerals in rocks have been debated for more than a century. Most authors agree that the ultimate pattern of preferred orientation (associated with flow) is geometrically related to the stress system. The classic concept that crystals rotate toward an ultimate stable orientation with their active glide planes aligned has been criticized by Turner and Weiss (1963, pp.360, 409, 426). Turner and Weiss (1963) conclude that processes connected with recrystallization are probably much more important than direct componental movement in the development of mineral orientation. Because of this, the concept of preferred orientation of olivine by (010) gliding must be viewed with some caution. Nevertheless petrofabric evidence indicates that (010) of olivine is aligned in a variety of ultrabasic rocks; the orientation mechanism may be something other than slip.

Preferred orientation of olivine also may originate under conditions of laminar flow in a high viscosity fluid medium, whereas quiescent gravitative settling results in a random orientation of olivine. Huang and Merritt (1952) report a strong preferred orientation of olivine in flowbanded troctolites from Oklahoma. Olivine a and c axes parallel the plane of banding and olivine b axes show a strong maximum normal to the banding. Non-banded troctolites from the same area have no preferred orientation. This random orientation is attributed to concentration of olivine by gravitative settling. Turner (1942) also concludes that gravitative settling of olivine does not produce a preferred orientation. Turner (1942) further attributes a strong concentration of olivine b axes normal to banding which contains a and c axes in some Hebridean peridotites, to laminar flow with interstitial lubrication of the olivine crystals. Orientation diagrams for olivine from basaltic dikes, volcanic necks, and surface flows reported by Brothers (1959) show patterns which are similar to the troctolites and peridotites. Flow planes in the basaltic rocks, which are defined by feldspar lath orientation, are parallel to olivine a and c girdles and perpendicular to b axis maxima. Brothers (1959) concludes that the controlling factor in alignment of olivine grains during flow is crystal form. He emphasizes the importance of large side-pinacoid (010) which is commonly characteristic of olivine. This pinacoid tends to be parallel to planes of laminar flow and

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thereby parallels the foliation or banding of the olivine-rich rocks. The resulting alignment of olivine produces strong concentrations of b axes which lie normal to girdles containing a and c axes in the plane of the foliation or banding.

Challis (1965) presents orientation data for a harzburgite, a harzburgite dunite, and a dunite from a large ultramafic body in the South Island of New Zealand. The olivine crystals in these rocks have a strong dimensional orientation. They tend to align parallel to the broad (010) face in the plane of layering. Thus petrofabric analyses show strong b axis concentrations normal to the plane of layering and fissility of the rocks. The a and c crystallographic axes of the harzburgitic dunite and dunite form girdles in the plane of layering, whereas the harzburgite has relatively strong concentrations of olivine a and c axes parallel to the layering. Challis (1965) concludes that the orientation of olivine in these rocks originated from crystal settling possibly accompanied by some flow, such as would be produced by convection currents.

Forbes (1963) reports directional olivine fabrics for dunite, enstatiteolivine peridotite, and titanaugite-olivine inclusions from basalts of the Hut Point area, Ross Island, Antarctica. The inclusions show well defined girdles of olivine a and c axes and maxima of olivine b axes. Clinopyroxene exsolution lamellae in the orthopyroxene of the dunite and enstatite-olivine peridotite inclusions suggest initial crystallization under high confining pressures. Because of this, Forbes considers these inclusions to be noncognate xenoliths and therefore possibly relicts from the upper mantle.

Many of these examples have been cited by Brothers (1959) to show that the common pattern of alignment in olivine-rich rocks is a concentration of olivine b axes normal to a girdle containing a and c axes. Brothers (1959, p.583) concludes that:

"It seems likely that two entirely distinct processes of alignment, fluid flow and solid deformation, are capable of producing closely similar patterns of orientation in olivine rocks. The strong affinity shown by these highly developed fabrics in the two different settings may be due to the fact that the commonly present large side-pinacoid (010) tends to lie in planes of laminar flow foliation in the fluid environment, while the same face acts as the glide plane which is oriented parallel to the principal *S* surface foliation during deformation and flexure gliding in olivine tectonites."

As shown in the preceding section, ultramafic rocks with this common fabric, regardless of their mode of origin, tend to behave as transversely isotropic solids to seismic wave propagation. Relatively low compressional wave velocities are expected for propagation normal to the planar elements of these rocks. Another pattern of olivine alignment which would produce transverse isotropy has been reported by Raleigh (1965) for the Cypress Island peridotite body in Washington. Fabric diagrams show the common pattern of olivine alignment to be strong concentrations of a axes and girdles of b and c axes. Single crystal measurements in olivine (Fig.1) suggest that these specimens are transversely isotropic, the symmetry axis being a direction of relatively high rather than low compressional wave velocity. Raleigh (1965) considers the fabric of this body to have originated from penetrative deformation accompanied by plastic flow or recrystallization.

A third type of transverse isotropy results from ultramafics with an olivine c axis maximum and girdles of olivine a and b axes. This fabric,

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which has been described by Huang and Merritt (1952) and Brothers (1959), would be manifested by only slight anisotropy since the c crystallographic axis is an axis of intermediate velocity for olivine. The single crystal measurements suggest that the symmetry axis would be a direction of low compressional wave velocity.

DISCUSSION

Reported fabric analyses show that olivine-rich rocks are characterized by a variety of fabrics which have apparently developed from several mechanisms. Before it is possible to properly evaluate the relative roles of fluid flow, slip, and recrystallization in producing these patterns of orientation in the mantle, it will be necessary to obtain more laboratory data on the behavior of olivine aggregates under mantle conditions. The slip system $\{0kl\}$, [100], termed pencil glide, observed by Raleigh (1968) provides interesting speculation as to one possible model of anisotropy in the upper mantle. If this type of glide is directly responsible for preferred olivine orientation, and convection of the laminar variety as envisaged by Orowan (1964) is the driving force behind the slip, then we would expect to find an upper mantle characterized by concentrations of a olivine axes and girdles of b and c axes. This orientation pattern would produce transverse isotropy with a high compressional wave velocity parallel to the symmetry axis, which would in turn presumably parallel flow directions in the upper mantle. In regions where convection produces horizontal flow, a strong dependence of P_n velocity on azimuth would be apparent. If flow directions are uniform over large domains, regions of rock moving vertically under the influence of convection should show little variation in P_n velocities.

Petrographic evidence to date suggests that the common pattern of alignment in olivine-rich rocks is girdles of a and c axes, paralleling schistosity or banding and normal to b axis concentrations. Because of this, we tentatively accept this fabric as the most probable for producing seismic anisotropy in the upper mantle. Since orientation of these planar structures would be expected parallel to the laminar creep, and should in fact be related to the mechanism of creep, transverse isotropy with a vertical symmetry axis would develop within zones of horizontal movement in a convecting olivine-rich upper mantle. The highest compressional wave velocities are found for propagation directions normal to the symmetry axis for this model. Seismic refraction studies should show little or no azimuthal variation of P_n velocity for these regions of normal mantle (e.g., eq.9). Regions of maximum anisotropy which correspond to zones of maximum shear concentration are likely to be of small vertical extent, increasing the difficulty of detection by seismological investigations. Regions of vertically moving mantle material, as well as transcurrent fracture zones associated with horizontal shear would produce perturbations on the normal condition of transverse isotropy with a vertical axis of symmetry. The material would still be transversely isotropic, but due to tilting of the olivine (010) planes, the axis of symmetry would be inclined to the vertical. Refraction data of Raitt and Shor, as given by Hess (1964), taken near the Molokai and Mendocino fracture zones, might then be explained as a 'tilted' transversely isotropic mantle.

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Transverse isotropic solids are relatively simple geometrically because of their axial symmetry. In some regions of the earth's mantle transverse isotropy may be modified by local stress conditions to a lower symmetry. If stress within the mantle produces a subparallel orientation of olivine a and c axes as well as b axes, the resulting symmetry becomes analogous to orthorhombic crystals. This fabric has been reported for dunite from Dun Mountain, New Zealand (Battey, 1960), harzburgite from Red Hills, New Zealand (Challis, 1965), and peridotite nodules from Austria (Ladurner, 1954). Since only five elastic parameters are needed to describe a transversely isotropic solid and orthorhombic crystals require nine constants, the recognition and correlation of stress and flow conditions which produce the latter type of anisotropy would be slightly more complicated.

Seismology provides potentially the most direct evidence on anisotropy of the upper mantle. It is suggested that some cases of regional variation of P_n velocities are related to tilting of the transverse isotropic symmetry axis. To date the examination of seismic body waves, surface waves, and the earth's free oscillations has failed to yield conclusive evidence regarding the presence of transverse isotropy in the upper mantle. Transversely isotropic regions with vertical symmetry axes are difficult to distinguish from isotropic regions. The effects of anisotropy on body waves for a layered spherical earth model, as given by Helbig (1966), produce only slight modifications of the travel-time curves. Transversely isotropic layers should show up as differences in the arrival times of SV and SH waves which have propagated through the layer, e.g., Table II, eq.4 and 5. Examination of surface wave dispersion and free oscillations as an additional technique may also indicate the presence of one or more transversely isotropic layers. These methods give hope that we may be able to detect with certainty from seismological observations, the presence of anisotropic regions as well as be able to determine the type and degree of anisotropy.

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