AZIMUTHAL ANISOTROPY OF SURFACE WAVES AND THE POSSIBLE TYPE OF THE SEISMIC ANISOTROPY DUE TO PREFERRED ORIENTATION OF OLIVINE IN THE UPPERMOST MANTLE BENEATH THE PACIFIC OCEAN

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The group velocities of surface waves in the period range 22-89 s were measured to retrieve the anisotropy pattern of the surface wave velocities in the Eastern Pacific Ocean. WWSSN long period records at KIP, Hawaii, from ridge events in the Gulf of California, the East Pacific rise, and the Easter Island Cordillera were used to cover propagation directions N60°E-N140°E. These station and epicenters are in very favorable positions to minimize the effects of the lateral heterogeneity owing to ocean floor ages. The fast direction of the Rayleigh wave group velocity is normal to ridge, showing 3-5% azimuthal anisotropy. The Love wave group velocity shows little azimuthal anisotropy.

A model of a possible type of preferred orientation of constituent olivine beneath the Pacific Ocean is proposed, based on the elastic constants and the petrofabrics of dunite from Hidaka, Hokkaido, Japan, and that of olivine nodules in the ophiolite complex from the Bay of Islands and Oman. In this model, *a*-axis is concentrated along a particular direction and *b*- and *c*-axes form a girdle. Elastic constants of the model are $C_{11}=2.44$, $C_{22}=C_{33}=2.05$, $C_{12}=C_{13}=0.72$, $C_{23}=0.67$, $C_{44}=0.69$, and $C_{55}=C_{66}=0.75$ (10^{12} dyn·cm), where X_1 -axis, or the direction of the *a*-axis concentration, is normal to ridge and X_3 -axis is vertical.

If we assume that the type of the preferred orientation is an age-independent property of suboceanic lithosphere, this model can explain the overall features of the large-scale anisotropy in the Pacific Ocean: the azimuthal anisotropy of surface wave velocities as described above; the SH-SV anisotropy of surface waves of about 0.15 km/s; the P_n anisotropy of 7.9 km/s to 8.6 km/s; the high S_n velocity of about 4.8 km/s; and the ScS polarization anisotropy.

1. Introduction

Since the first recognition of large-scale anisotropy by HESS (1964), there has been much firm seismological evidence for the large-scale anisotropy. Following

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HESS (1964), the P_n anisotropy was reported by MORRIS *et al.* (1969), RAITT *et al.* (1969), KEEN and BARRETT (1971), OKADA *et al.* (1978), and SHIMAMURA *et al.* (1983). The surface wave anisotropy including so-called SH-SV anisotropy and the azimuthal variation of propagation velocity were widely recognized by McEVILLY (1964), KAMINUMA (1966), FORSYTH (1975), SCHLUE and KNOPOFF (1977), YU and MITCHELL (1979), and MITCHELL and YU (1980). Recently, we have also had evidence from free oscillations (ANDERSON and DZIEWONSKI, 1982). Petrofabric observations of outcrop nodules presumed to have been in the uppermost mantle showed clear anisotropy as investigated by KASAHARA (1968), PESELNICK *et al.* (1974), CHRISTENSEN and SALISBURY (1979) and CHRISTENSEN and SMEWING (1981).

The large-scale anisotropy is believed to be exclusively due to the preferred orientation of crystallographic axes of constituent olivine in the uppermost mantle. This large-scale anisotropy should be directly connected with the formation and the geodynamic processes of plates. Therefore, it is of great importance to resolve the variety of seismological observations of the large-scale anisotropy in terms of the preferred orientation of the constituent olivine. Several hypotheses have been suggested for the type of the preferred orientation (HESS, 1964; FRANCIS, 1969; CRAMPIN and BAMFORD, 1977; KAWASAKI, 1982). However, some observational facts seem to be inconsistent with the nature of the models based on single crystal olivine (SCO) or a mixture (MIX) of the SCO and isotropic or transversely isotropic materials. In particular, FORSYTH's (1975) observation of the little (less than 1%) anisotropy of Love waves was difficult to explain by any of the previously proposed hypotheses. These disparities have been worrying seismologists interested in the large-scale anisotropy in the past decade.

One of our purposes is to retrieve the azimuthal anisotropy pattern of surface waves in the Eastern Pacific Ocean, the eastern part of the Pacific plate, which seems to have been the most controversial among observations on the large-scale anisotropy. The second purpose is to trace the variety of the observations back to the possible form of the constituent olivine in the uppermost mantle beneath the Pacific Ocean.

2. Data and the Method

We found 36 events from sorting EDF tapes (USGS) for ridge events of magnitudes 5.8–7.0 for the period range 1963–1978 and the latitude range $N35^{\circ}$ – $S40^{\circ}$ along the eastern boundary of the Pacific plate: the Gulf of California, the East Pacific rise, and the Easter Island Cordillera. Scanning WWSSN long period records at KIP, Hawaii, we excluded 22 events because of lack of records and small amplitude surface wave traces compared with long period microseisms which are continuously large at KIP. Long period records of the remaining 14 events were digitized.

The group velocities were calculated by the use of the multi-filter technique

of DZIEWONSKI *et al.* (1969) with the proper Hanning window, the beginning and the end of which were the arrival times of surface waves of group velocities 3.5 km/s and 4.2 km/s for Rayleigh waves, and 4.0 km/s and 4.8 km/s for Love waves, respectively. In some cases, the window was extended further, based on our judgement of the duration of the fundamental mode Rayleigh and Love waves. Other details of the method used in this paper are the same as described in YOSHIDA (1978). We adopted only group velocities obtained with single point "99", which denotes the maximum of the log normalized amplitude of the instantaneous amplitude spectra (see DZIEWONSKI *et al.*, 1969 or YOSHIDA, 1978) and averaged out 3 group velocities in the adjacent periods. Origin times and epicenters determined by the USGS were used. Even if the origin times and the epicenters had errors of 15 s or 50 km, respectively, they possibly yield errors of about 0.04 km/s ($\sim 1\%$) to the group velocity estimations. Because the errors of the USGS hypocenters are considered to be not so large, the errors have no effects on the conclusions in the later sections.

Corrections for anelasticity and sphericity of the earth are about 1% of surface wave velocities and cannot be neglected when inverting them into the velocity structure of the earth's interior. However, these corrections are not made to the observed group velocities in the present study because these corrections are independent of a length and an azimuth of a propagation path of the surface waves analyzed and are not necessary for our purpose of seeing anisotropy patterns of the surface wave group velocities in the Pacific Ocean.

It was pointed out (e.g., THATCHER and BRUNE, 1969) that the higher mode contamination possibly yields serious error to the group velocity estimation for the Love waves in the period range of several tens of seconds for the oceanic structure having a distinct low velocity zone (LVZ). However, if we consider the earth model such as the PREM (DZIEWONSKI and ANDERSON, 1981) with a less distinct LVZ, relative excitations of the higher mode surface waves are likely to be small (FORSYTH, 1975). For this reason, we neglected the higher mode contamination of the Love waves.

Figure 1 displays epicenters (Table 1) and azimuthal coverage of propagation paths of the surface waves for which dispersion curves (Tables 2 and 3) were finally obtained with satisfactory quality. Isochrons of ocean floor age are simply trending north-south (PITMAN *et al.*, 1974) in this area. Since the propagation paths contain ocean floors of various ages in nearly the same ratios in this setting of the station KIP and the epicenters, the effects of lateral heterogeneity due to the age of the ocean floor are minimized. The azimuthal coverage could not be extended further because of abrupt change of the trend of the isochrons outside the area.

2.1 The azimuthal anisotropy of surface waves

Figures 2 and 3 are azimuthal variations of average group velocities of Rayleigh (Table 2) and Love waves (Table 3) for three period ranges indicated. For periods shorter than 30 s, the group velocity scattered widely and was not used to reveal

Table 1. List of ridge events along the Gulf of California, the East Pacific rise, and the Easter Island Cordillera, for which satisfactory dispersion curves at KIP, Hawaii, were obtained.

No.	Date			Origin time			Lat.(°)	Long.(°)	Depth (km)	M_s	m_b	$\Delta(^{\circ})$	$\phi(^{\circ})$
	Yr	M	D	h	min	s							
1	1964	10	12	21	55	33.2	31.30S	110.80W	25	6.0		69.5	138.0
2	1965	12	06	11	34	51.9	19.00N	107.10W	20	5.9		47.6	83.4
3	1966	08	07	17	36	26.7	31.80N	114.50W	16	6.3		40.0	65.6
4	1968	08	09	03	08	04.2	22.40S	113.00W	33	5.4	5.8	62.0	132.2
5	1969	04	22	06	31	57.5	26.77S	114.13W	33	5.6	6.2	64.3	136.6
6	1971	02	09	14	00	41.8	34.40N	118.40W	08	6.2	6.5	37.0	60.8
7	1973	09	21	07	13	34.0	04.39S	102.00W	33	6.1	6.0	60.6	108.4
8	1974	05	10	08	12	05.0	04.37S	102.11W	33	6.1	6.0	60.5	108.4
9	1974	05	31	14	04	59.9	27.23N	111.24W	33	5.3	6.3	42.8	72.6
10	1975	09	11	21	59	57.2	06.99N	104.28W	33	5.8	6.2	53.8	97.2
11	1979	01	26	10	04	32.0	17.41N	100.88W	41	5.8	6.6	53.7	83.6

Δ is an epicentral distance. ϕ is an azimuthal direction of the epicenter measured clockwise from the north.

Fig. 1. Lambert equal area projection of the Pacific Ocean. Origin of the projection is at KIP. This shows azimuthal coverage of propagation paths, for which satisfactory dispersion curves were obtained. Numerals are event No. in Table 1.

the anisotropy pattern. The scatter may be attributed partly to inaccuracy of the group velocity estimation due to the long period microseisms, partly to lateral heterogeneity in very shallow structure including depths of the ocean floor, and partly

Table 2. Observed group velocities of Rayleigh waves.

Period (s)	Event No.									
	1	3	4	5	6	7	8	9	10	11
22.8	3.62	3.66	3.70	3.65	3.73	3.78	3.92	3.62		4.18
24.3	3.60	3.78	3.66	3.64	3.74	3.70	3.99	3.63		4.16
25.9	3.64	3.88	3.68	3.61	3.78	3.66	4.02	3.66		4.14
27.7	3.70	3.98	3.74	3.67	3.82	3.71	4.06	3.75		4.14
29.5	3.75	4.08	3.81	3.72	3.86	3.76	4.09	3.84		4.11
31.5	3.83	4.07	3.89	3.81	3.92	3.87	4.06	3.91		4.09
33.6	3.91	4.05	3.97	3.90	3.98	3.98	4.02	3.98		4.08
35.9	3.93	4.05	3.98	3.99	4.01	4.06	4.03	4.04	4.10	4.08
38.3	3.92	4.05	3.97	3.98	3.99	4.06	4.02	4.05	4.09	4.04
40.9	3.92	4.05	3.96	3.98	3.98	4.05	4.00	4.04	4.06	4.02
43.6	3.90	4.03	3.95	3.96	4.02	4.04	3.98	4.02	4.03	4.00
46.6	3.89	4.02	3.95	3.93	4.04	4.03	3.97	4.01	4.01	3.95
49.7	3.88	4.00	3.98	3.91	4.00	4.01	3.96	3.99	3.97	3.88
53.0	3.88	3.98	3.95	3.88	3.99	3.99	3.95	3.96	3.97	3.85
56.6	3.86	3.95	3.92	3.85	3.97	3.97	3.94	3.92	3.98	3.84
60.4	3.86	3.92	3.90	3.83	3.88	3.95	3.92	3.90	3.96	3.86
64.4	3.85	3.90	3.86	3.82	3.78	3.93	3.91	3.89	3.94	3.86
68.8	3.82	3.89	3.82	3.80	3.74	3.91	3.89	3.90	3.90	3.80
73.4	3.80	3.88	3.82	3.78	3.71	3.90	3.88	3.92	3.84	3.74
78.3	3.77	3.85	3.81	3.77	3.67	3.89	3.87	3.91	3.76	
83.6	3.73	3.81	3.78	3.73	3.64	3.89	3.86	3.89	3.70	
89.2	3.69	3.74	3.76	3.68	3.63	3.88	3.84	3.83	3.65	

Unit: km/s

Table 3. Observed group velocities of Love waves.

Period (s)	Event No.						
	2	4	5	7	9	10	11
35.9	4.42	4.40	4.39	4.34	4.42	4.36	4.35
38.3	4.40	4.42	4.40	4.34	4.42	4.40	4.38
40.9	4.40	4.42	4.40	4.35	4.43	4.43	4.40
43.6	4.39	4.43	4.40	4.37	4.44	4.45	4.41
46.6	4.40	4.43	4.41	4.39	4.45	4.46	4.43
49.7	4.43	4.44	4.41	4.41	4.45	4.46	4.44
53.0	4.46	4.44	4.42	4.42	4.44	4.44	4.44
56.6	4.48	4.44	4.42	4.43	4.42	4.42	4.42
60.4	4.50	4.44	4.42	4.43	4.41	4.42	4.41
64.4	4.51	4.44	4.42	4.42	4.40	4.41	4.39
68.8	4.50	4.44	4.42	4.42	4.40	4.40	4.39
73.4	4.49	4.44	4.42	4.42	4.40	4.39	4.39
78.3	4.49	4.44	4.42	4.41	4.40	4.38	4.41
83.6	4.49	4.43	4.42	4.40	4.41		4.42
89.2	4.50	4.42	4.41	4.40	4.42		

Unit: km/s

Fig. 2. Azimuthal distribution of Rayleigh wave group velocities averaged over the period range indicated. Solid lines are sinusoids which are anisotropy pattern of QSV-wave velocity of the possible model for the preferred orientation of the constituent olivine proposed in the later section of this paper. Absolute value of the sinusoids are arbitrary.

to higher mode contamination. For the period range longer than 30 s, there seems to be no effect of the very shallow structure, such as water depths and thicknesses of oceanic crust, on the anisotropy pattern. For periods longer than 70 s, the data scatter again. This may be due to poorly dispersed wave train because of short path lengths (50° – 70°).

Figure 2 indicates that the Rayleigh waves are fastest parallel to the trend ($N80^{\circ}E$) of the fracture zones in the Eastern Pacific Ocean. The amount of anisotropy is 0.1–0.15 km/s. According to MITCHELL and YU (1980), the Rayleigh wave group velocities at a period of 40 s are 4.001 km/s and 4.077 km/s in the regions of ocean floor ages of 20–50 m.y. and 50–100 m.y., respectively. The difference between them is 0.076 km/s. Thus, the observed amount of the anisotropy of 0.1–0.15 km/s seems to be too large to account for by lateral heterogeneity, as far as we are within a scope of plate-thickening hypothesis as derived by YOSHII (1975). If we interpret the anisotropy pattern by the $\sin(2\theta)$ term following the result of FORSYTH (1975) in this area, it has the anisotropy of 3–5%.

Figure 3 shows little anisotropy of the Love waves. The Love waves are the slowest parallel to the fracture zones. The present authors think that we have confirmed Forsyth's discovery by Figs. 2 and 3. Note that the definition of the amount of the anisotropy in this paper is as $2 \times (V_{\max} - V_{\min}) / (V_{\max} + V_{\min})$, which is twice as many as FORSYTH's (1975) definition.

Fig. 3. Azimuthal distribution of Love wave group velocities averaged over the period range indicated. Solid lines are the same as those in Fig. 2 except for QSH-wave velocity.

If we consider the SCO for the reference model of the possible from of constituent olivine and we assume a -axis normal to ridge, the azimuthal anisotropy of quasi body waves (CRAMPIN, 1976), the QSV and the QSH, amounts to 0.4–0.5 km/s (KASAHARA *et al.*, 1968), respectively. The observed anisotropy of the Rayleigh waves is about one-third of that required by the anisotropy pattern of the QSV of the SCO model. On the other hand, the QSH waves have the same group velocity every 90° in planes of symmetry of the SCO. Thus, the SCO requires that the anisotropy patterns of the QSH and, consequently, the Love waves should be represented by $\sin(4\theta)$ term. In this constraint, the azimuthal anisotropy of the Love waves of $\sim 1\%$ means a change of group velocity of 0.04–0.05 km/s every 45° of azimuth. Although we do not give statistical discussion to the amount of the observed azimuthal anisotropy of the Love waves because of small azimuthal coverage, it can be said from Fig. 3 that a group velocity change with the azimuth change of 45° is 0.05 km/s at the most and the anisotropy of the Love waves should be 1% or less.

The observed anisotropy for the Love waves is small, which is contradictory to the SCO model. As far as we are concerned with the SCO or the MIX, we cannot resolve the disparity between large P_n anisotropy and the small anisotropy of the Love waves. On the other hand, the observations are well-interpreted (Figs. 2 and 3) by sinusoids which are the anisotropy pattern of velocities of the QSV and QSH waves of the possible model HDM proposed in the later section for the preferred orientation of the constituent olivine. Absolute values of the QSV-

Fig. 4. Dispersion curves which show abnormal behavior. Bars indicate a range of point "99", meaning of which is given in the text and in YOSHIDA (1978), and dots are group velocities averaged over five adjacent periods.

and QSH-wave velocities specifying the sinusoids are arbitrary.

In this paper, a simple comparison is being made between azimuthal anisotropy patterns of the surface wave observations and the quasi body waves, the QSH and the QSV. In an exact sense, the anisotropy pattern of the observations must be compared with that of theoretical generalized surface waves. However, if we consider a lithosphere of a thickness of about several tens of kilometers consisting of the oriented olivine with a crust of 5 km thickness, the nature of surface wave dispersion in the periods around 40–50 s should be controlled principally by the statistical orientation of the constituent olivine. The anisotropy patterns of group velocities of the Rayleigh and the Love waves must be nearly equal to those of group velocities of the quasi body waves, the QSV and the QSH, respectively, to the first order approximation. This is the reason for the simple comparison. Strict comparison will be made in the next paper.

Dispersion curves averaged over azimuths show a general trend similar to those in the Pacific Ocean of ages 50–80 m.y. of YOSHIDA (1978).

Some dispersion curves showed abnormal behavior as illustrated in Fig. 4. We excluded such dispersion curves in the analysis and included one additional event (No. 11 in Table 1). The reason for such abnormal behavior mainly of the Love waves may be ScS contamination which arrives at KIP with apparent velocities 4.1–4.5 km/s at epicentral distances 40°–45°.

2.2 A model of the possible form of constituent olivine

As reviewed earlier in this paper, we have had much firm evidence for the large-scale anisotropy. A good example is SHIMAMURA *et al.*'s (1983) long-shot experiments in the Northwest Pacific Ocean. However, even their results do not contain details as to represent the azimuthal variation of the P_n velocity. The accent of their paper is the amount of the large P_n anisotropy, ranging from 7.9 km/s to 8.6 km/s. Despite a lot of evidence, most of it is unfortunately not ap-

Fig. 5. Examples of equal area projection of P-wave velocities (km/s) of peridotites from Oman (a), Table Mountain of the Bay of Islands (b), and North Arm Mountain of the Bay of Islands (c). Reproduced from CHRISTENSEN and SMEWING (1981).

plicable to the quantitative inversion for the form of upper mantle materials incorporated with the anisotropy. As we are in the model refinement stage of the anisotropy study, it seems to be a better policy to start from actual olivine rocks, for which the elastic constants and petrofabrics are well investigated. Thereafter, we modify the anisotropy parameters to fit the observation and to integrate various kinds of anisotropy observations into a single anisotropy model, which involves the specific preferred orientation of constituent olivine crystals in the uppermost mantle.

Alpine type dunite from Hidaka (KASAHARA *et al.*, 1968), olivine nodules from Ichinomegata (YOSHINO, 1971), the Bay of Islands (CHRISTENSEN and SALISBURY, 1979) and Oman (CHRISTENSEN and SMEWING, 1981) display a distinct trend of an axial symmetry in which a -axis is highly concentrated and b - and c -axes form a girdle about the a -axis. The propagation velocity of the faster among two orthogonally polarized S waves within the rocks for the above cases is comparatively uniform in directions of the girdle perpendicular to the a -axis. These facts seem to be the key to resolve the disparity between the large P_n anisotropy and the little azimuthal anisotropy of the Love wave group velocity.

Figure 5 shows typical examples of the equal area projection of the P-wave velocities summarized by CHRISTENSEN and SMEWING (1981). Numerals are the P-wave velocities (km/s) of peridotites from Oman (a), Table Mountain of the Bay of Islands (b), and North Arm Mountain of the Bay of Islands (c).

Keeping the basic framework of the axial symmetry about the a -axis normal to ridge, we attempted a trial and error approach to find a model of the elastic anisotropy in the uppermost mantle which can successfully explain overall features of the patterns of large-scale anisotropy beneath the Pacific Ocean. In a trial and error approach, we proceeded as follows. C_{11} , $C_{22}(=C_{33})$, C_{44} , and $C_{55}(=C_{66})$ were constrained such that $V_{P_{\max}}(=\sqrt{C_{11}/\rho})$ and $V_{P_{\min}}(=\sqrt{C_{22}/\rho})$ were in the ranges of 8.55–8.6 km/s and 7.85–7.90 km/s, respectively, and that $V_{SV_{\max}}(=\sqrt{C_{55}/\rho})$, $V_{SV_{\min}}(=\sqrt{C_{44}/\rho})$, and $\Delta V_{SV}(=V_{SV_{\max}}-V_{SV_{\min}})$ were in the ranges of

4.55–4.60 km/s, 4.75–4.80 km/s, and 0.2–0.3 km/s, respectively. Incremented by 0.01×10^{12} dyn·cm, many sets of C_{ij} were generated within the ranges. For every set, $C_{12}(=C_{23})$ was incremented by 0.01×10^{12} dyn·cm and azimuthal variation of the QSH in the horizontal plane was calculated by the formula of KASAHARA *et al.* (1968). When we found a set of C_{ij} in which azimuthal anisotropy of the QSH is less than 0.03 km/s, we accepted the set of C_{ij} as a final one. Thus, we obtained a model, which we would like to call HDM (Hidaka Dunite Model) in the following, because the dunite from Hidaka first motivated the present authors to undertake this study.

Elastic constants of the HDM are in Table 4, together with those of the SCO and the dunite of Hidaka (KASAHARA *et al.*, 1968). Notation of C_{ij} is the same as LOVE (1944). X_1 -axis (the a -axis) is normal to and X_2 -axis is parallel to the ridge. X_3 -axis is vertical. Figure 6 illustrates azimuthal variation of velocities of the quasi body waves within the horizontal X_1 – X_2 plane of the HDM.

If we take into account pressure and temperature derivatives of olivine (KUMAZAWA and ANDERSON, 1969) and the pressure and temperature condition at the uppermost mantle, the elastic constants may have an uncertainty of 5×10^{10} dyn/cm², which is small compared with the order of the amount of the anisotropy pattern and was neglected in this study.

Various kinds of anisotropic observations have been presented so far as regional studies. However, we here assume that the type of preferred orientation of the constituent olivine is age-independent and universal property within the oceanic lithosphere. Then, although agreements are not strict, the anisotropy patterns predicted by the HDM basically agree with the following independent discoveries related to the large-scale anisotropy beneath the Pacific Ocean (also tabulated in Table 5).

2.2.1 P_n anisotropy of 7.9–8.6 km/s

The amount of the P_n anisotropy scatters from 3% to 8% (HESS, 1964; MORRIS *et al.*, 1969; RAITT *et al.*, 1969; KEEN and BARRETT, 1971; SNYDSMAN *et al.*, 1975; SHIMAMURA *et al.*, 1983). Reviewing the original data illustrated in these papers, the present authors think that resolution is better in the papers of MORRIS *et al.* (1969) and SHIMAMURA *et al.* (1983), which commonly show a large anisotropy of 7.9–8.6 km/s. We refer to 7.9–8.6 km/s hereafter as the amount of the P_n anisotropy.

2.2.2 High S_n velocity of ~ 4.8 km/s

SHIMAMURA *et al.* (1977) and KASAHARA *et al.* (1983) found fast S_n velocity of about 4.8 km/s in the Northwestern and the Eastern Pacific Ocean. In the same direction P_n velocity was not so large (8.0–8.2 km/s). This can be interpreted only by the large-scale anisotropy.

2.2.3 Azimuthal anisotropy of surface waves

Several percent of the azimuthal anisotropy of the Rayleigh waves and little anisotropy of the Love waves were first found by FORSYTH (1975) and confirmed in the previous section of this paper.

Table 4. Elastic constants of single crystal olivine (SCO in the text), Hidaka dunite, and the model for the constituent olivine in the uppermost mantle beneath the Pacific Ocean, proposed in this paper.

C_{11}	C_{22}	C_{33}	C_{12}	C_{23}	C_{13}	C_{44}	C_{55}	C_{66}	Density	Material	Reference
3.237	1.976	2.351	0.664	0.756	0.716	0.6468	0.7805	0.7904	3.31	single crystal olivine	KUMAZAWA and ANDERSON (1969)
2.55	2.06	2.11	0.64	0.68	0.68	0.68	0.78	0.76	3.30	Hidaka dunite	KASAHARA <i>et al.</i> (1968)
2.44	2.05	2.05	0.72	0.67	0.72	0.69	0.75	0.75	3.30	HDM	this study

Unit: 10^{12} dyn·cm for C_{ij} and g/cm³ for density

Table 5. Observations related to the large-scale anisotropy in the uppermost mantle and those predicted by the model HDM proposed in this paper.

Type of observation	Predicted by the model proposed	Observation	Reference
P_n anisotropy	7.88–8.60 km/s	7.9–8.6 km/s	MORRIS <i>et al.</i> (1969), SHIMAMURA <i>et al.</i> (1983)
High S_n velocity	4.78 km/s	~4.8 km/s	SHIMAMURA <i>et al.</i> (1977), Kasahara <i>et al.</i> (personal communication)
Azimuthal anisotropy			
for Rayleigh waves	4.2%	~2%	FORSYTH (1975)
for Love waves	0.4%	≤1%	FORSYTH (1975)
SH-SV anisotropy	0.11 km/s	~0.15 km/s	FORSYTH (1975), SCHLUE and KNOPOFF (1977)
ScS polarization anisotropy	0.9 s	~1 s	ANDO (1983)

Fig. 6. Azimuthal variations of quasi body waves, QP, QSH, and QSV, within a horizontal plane of the HDM (Table 4) of the possible form for the constituent olivine in the uppermost mantle.

2.2.4 SH-SV anisotropy of 3–6%

One of the problems in dispersion analyses of surface waves has been the discrepancy between the mantle Rayleigh and Love waves. The earth model giving a good agreement with Rayleigh wave data did not always give satisfactory results for the Love waves (e.g., KAMINUMA (1966) for the Japanese Islands region, and FORSYTH (1975) and SCHLUE and KNOPOFF (1977) for the Pacific Ocean). S-wave velocity deduced from the Love wave data was always larger than that from the Rayleigh waves. This discrepancy is conventionally called the SH-SV anisotropy. The amount of the SH-SV anisotropy is ~ 0.15 km/s (FORSYTH, 1975), which is predicted to be ~ 0.11 km/s by the HDM.

The recognition of the SH-SV anisotropy has been considered to indicate the existence of soft and thin magma pockets (TAKEUCHI *et al.*, 1968). If the anisotropy model HDM is introduced, such magma pockets are not needed to interpret the surface wave dispersion.

2.2.5 ScS polarization anisotropy

If we take HDM, it follows that velocity of one of two shear waves propagating in a vertical direction, polarized perpendicular to ridge, should be faster by ~ 0.2 km/s than that of the other shear wave polarized parallel to ridge. If the lithosphere with a thickness of about 100 km is subducting under the Eurasian and the South America plates, it yields arrival time difference of about 1 s between the two shear waves polarized orthogonally to each other, which explains ANDO's (1983) discovery at WWSSN stations, SHK, MAT, BHP, ARE, ANT, and PEL as reproduced in Fig. 7.

DZIEWONSKI and ANDERSON (1981) recently presented the earth model, PREM, inverted from a great deal of seismic data. They derived the transverse isotropy with the symmetrical axis vertical in the outer 220 km of the mantle, and less pro-

Fig. 7. Arrival time differences between two shear waves of ScS. Bars denote directions of particle motion of one of the two shear waves, which arrived at the stations faster than the other shear wave polarized normal to it. Length of the bar is proportional to the arrival time difference of the two shear waves. Reproduced from ANDO (1983).

nounced distinction between LVZ (low velocity zone) and LID (region above the LVZ). In the outer 220 km of the mantle, the horizontal P velocity is smaller by about 4% than the vertical P velocity and the horizontal S velocity is smaller by about 2% than the vertical S velocity.

In a strict sense, these two anisotropic models are not the same. But the assertion of DZIEWONSKI and ANDERSON (1981) is not about the transverse isotropy. Their data represent an average over many azimuths and azimuthal anisotropy would be averaged out as described in their paper. The present authors would like to emphasize that if we average out the anisotropy pattern of the HDM over azimuths, it yields the same type of anisotropy as the PREM. A large part of the nature of the outer 220 km of the PREM should be accounted for by the oceanic uppermost mantle, in which the constituent olivine crystals possess the same type of preferred orientation as the HDM.

CHRISTENSEN and SALISBURY (1979) inferred that the olivine nodules found in the Bay of Islands ophiolite complex were mantle materials and that the ophiolite complex was the segment of the paleo-oceanic lithosphere. It was shown in this paper that the model HDM deduced from their olivine nodules can elucidate the overall feature of the observations on the large-scale anisotropy. This fact seems to support the Christensen and Salisbury's suggestion.

3. Conclusions

In the first part of this paper, surface wave group velocities in the eastern part of the Pacific Ocean were obtained. The observed anisotropy pattern of the surface waves is that the Rayleigh waves are the fastest normal to ridge with the azimuthal anisotropy amounting to 3–5% and that the Love waves show little anisotropy (less than 1%), similar to the FORSYTH's (1975) discovery mainly for the Nazca plate. The area investigated is limited to the latitude range N35°–S40° and azimuthal coverage of the propagation paths is N60°E–N140°E. However, because isochron of the age of the ocean floors is simply trending north-south in this area, the effects of the lateral heterogeneity due to the ocean floor age could be neglected. This is a very favorable setting to see unobstructed azimuthal anisotropy.

In the second part, we have proposed the HDM (Table 4) for the possible orientation type of the constituent olivine in the uppermost mantle beneath the Pacific Ocean, slightly modifying the elastic constants of the dunite of Hidaka (KASAHARA *et al.*, 1968). The basic nature of the model is the axial symmetry about the *a*-axis aligned normal to ridge in the horizontal plane. The HDM thus proposed can basically explain the overall features of the seismological observations on the large-scale anisotropy presented so far (Table 5) in the Pacific Ocean, assuming that the type of preferred orientation is age-independent and universal in the oceanic lithosphere. Though the details may be changed, depending on depth, spreading rate of the oceanic plates, and other factors, the gross nature of the type of preferred orientation may not be changed. Thus, the HDM should be regarded as the starting model and constraint for the general inversion in the next step.

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