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Surface Wave Polarization Anisotropy near the East Pacific Rise as Revealed from Group Velocities and Synthetic Waves

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Abstract

Anomalous dispersion curves of Rayleigh waves with group velocity maxima of 3.9 to 4.0 km/sec at a period of 25 sec, near the East Pacific Rise, can be well explained by the upper mantle structure consisting of a very thin oceanic plate with a thickness of about 30 km and a low velocity zone with an extremely low shear velocity of 4.13 km/sec. The Love wave response for the upper mantle structure is signigicantly different, namely group velocities of 4.30 km/sec observed for periods from 20 to 110 seconds can be finely explained by a high shear velocity of 4.25 km/sec in the low velocity zone. A surface wave polarization anisotropy of 3% in shear velocity is clearly present in the youngest region in the Pacific. If a volume fraction of involved molten pockets of 0.05 to 0.10 in the low velocity zone is assumed, the ratio of the minor to the major axes of an oblate spheriod of the molten pockets is estimated to be about one half. The surface wave polarization anisotropy in this region is inferred to be caused by the alignment of these partially molten pockets.

1. Introduction

Surface wave dispersion in the regions near the East Pacific Rise has been investigated by SANTO (1963). In early times, however, the interpretation of the dispersion curves of Rayleigh waves with maximum group velocities of 3.9 or 4.0 km/sec located at a period of 25 seconds was difficult, although oceanic models were proposed by KOVACH and PRESS (1961), and SAITO and TAKEUCHI (1966). Recently the dispersion characteristics of Rayleigh and Love waves propagating in the above regions were investigated by FORSYTH (1975), SCHLUE and KNOPOFF (1977), and YU and MITCHELL (1979) with special reference to the azimuthal or polarization anisotropies of surface waves.

Anomalously high heat values (VON HERZEN and UYEDA, 1963), and gravity anomaly (YOSHII, 1973) and the shallow ocean depth along the East Pacific Rise suggest the existence of a hot rising plume beneath the rise and it is expected that the low velocity zone (*LVZ*) will be greatly extended and the *LVZ* composed of hot materials will significantly lower the amplitude and velocity of surface waves.

For studying the surface wave polarization anisotropy in the oceanic upper mantle, the observation of Love waves in high accuracy is indispensable. SCHLUE and KNOPOFF (1977) determined the phase velocities of Love waves and suggested the inconsistency between the shear velocities of SV and SH in the *LVZ*. However, MITCHELL and YU (1980) found no discrepancy between them in the *LVZ*.

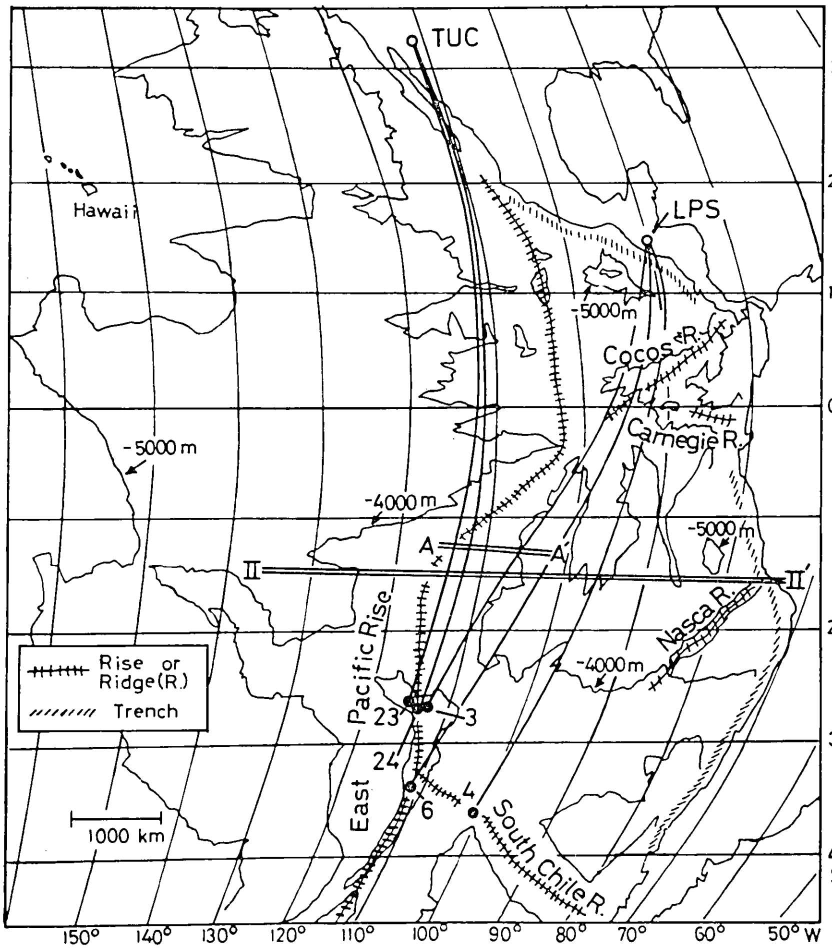


Fig. 1. Geometry of the epicenters (solid circles) and the stations (open circles). The axes of the East Pacific Rise and other ridges are also shown together with the ocean depths of 4000 and 5000 m. Earthquake numbers attached to the epicenters correspond to numbers in Table 1. For horizontal sections of *A-A'* and *II-II'* across the East Pacific Rise see the caption given in Fig. 2.

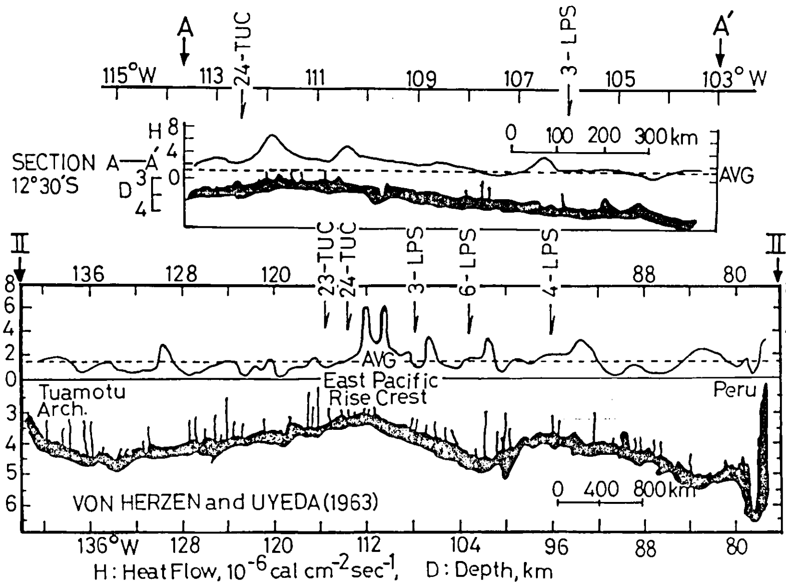


Fig. 2. Profiles of heat flow and topography along the horizontal sections *A-A'* and *II-II'* shown in Fig. 1 (After VON HERZEN and UYEDA, 1963).

The present paper aims to investigate the peculiar group velocity dispersion characteristics of Rayleigh and Love waves, both propagating in the same path, and it presents direct evidences for surface wave polarization anisotropy in the region near the East Pacific Rise. Theoretical seismograms will be generated for the help of the resolutions.

2. Geophysical features

The average depth of the ocean bottom along the East Pacific Rise is about 3 km, and the ocean depth increases with the distance from the axis of the ridge crest. In Fig. 1 the East Pacific Rise and the ocean depth are shown together with the typical ridges spreading in the southeast Pacific ocean. The study of geomagnetic lineations (ATWATER and MENARD, 1970; LARSON and CHASE, 1972) revealed that the ocean-floor age near the ridge crest is very young, several tens of million years. In Fig. 2 the profile of heat flow and the ocean bottom topography in the southeast Pacific, as determined by VON HERZEN and UYEDA (1963), are shown. Heat flow values at the ridge crest are about $6 \sim 7 \times 10^{-6}$ cal/cm^2 sec, exceeding significantly the average one of 1.5×10^{-6} cal/cm^2 sec. In these regions of high heat flow the gravity is low (LEE and MACDONALD, 1963; WANG, 1965; HORAI and SIMMONS, 1969), implying that the depressions on the geoid are related

Table 1. Earthquake elements reported by *USGS* and station coordinates.

Number	Date			Time h	m	s	Latitude	Longitude	Focal Depth (km)	Magnitude	Code
3	6	June	1964	19	07	51.4	26.6° S	114.4°W	33	5.8	LPS
4	6	October	1964	07	17	57.1	36.2° S	100.9°W	33	5.5	LPS
6	16	June	1965	03	55	17.5	34.4° S	112.3°W	33	5.7	LPS
23	14	September	1976	15	46	08.6	26.432° S	115.067°W	33	5.5	TUC
24	25	September	1976	21	47	23.2	26.578° S	114.999°W	33	5.5	TUC

Table 1a.

Code	Station	Region	Latitude	Longitude
LPS	La Palma	El Salvado	14.292°N	89.162°W
TUC	Tucson	Arizona	32.310°N	110.782°W

Table 1b.

to hotter and lighter materials in the interior of the earth.

3. Earthquake data and method

For the determination of the group velocity of Rayleigh and Love waves propagating along the East Pacific Rise, earthquakes occurring on the rise were used, and the *WWSSN* stations located at the edge of the rise were selected (Fig. 1). Table 1 lists the earthquake elements and the station coordinates.

From Fig. 1 we see that great circle paths to station *TUC* run almost parallel to the rise and are extended at the shallow part of the ocean where depths are less than 4000 m. The paths to station *LPS* run partly parallel to the rise and traverse the Cocos Ridge. On the way to *LPS* the paths cross some regions of the ocean where depths are more than 4000 m.

The paths, except for the one from the earthquake number 4 to *LPS* (4-*LPS*), cross *A-A'* section in Fig. 1. This section records higher heat flow values than the other regions (see Fig. 2). The path 4-*LPS* crosses the *II-II'* section at longitude 95°, where the heat flow value is also high. Thus all the paths selected here traverse the regions with high heat flow values. We see from Table 1 that the focal depth of all earthquakes is estimated to be very shallow, and the earthquake magnitude ranges from 5.5 to 5.8. The epicentral distances are about 6000 km (see Fig. 1).

The *WWSSN* records of Rayleigh and Love waves were digitized at intervals of 2 sec. Group velocities were calculated using the multiple filtering technique (DZIEWONSKI, BLOCH and LANDISMAN, 1969) as carried out by YOSHIDA (1982) for investigations of multi-mode Rayleigh and Love waves (YOSHIDA, 1983a, b).

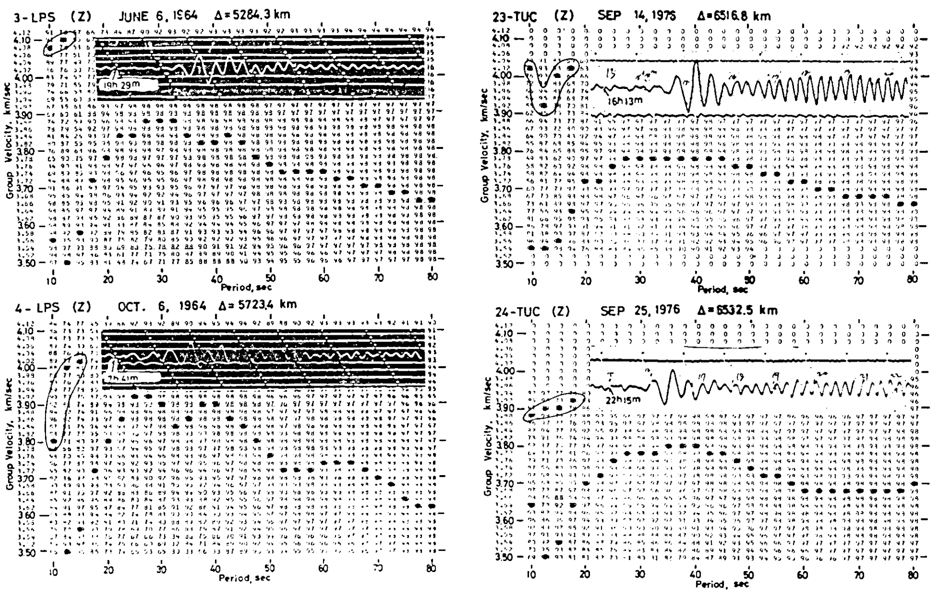
4. Result and interpretation

Rayleigh and Love waves recorded at *TUC* and *LPS* were analyzed and the group velocities determined are shown in Figs. 3 and 6, respectively, in which a portion of the waves analyzed is inserted.

4.1 Rayleigh waves

The group velocities for 3-*LPS* and 4-*LPS* have a maximum of 3.90 km/sec in the period range from 25 to 30 sec (Fig. 3). For periods longer than 30 sec the group velocity decreases gradually down to about 3.65 km/sec at a period of 80 sec. The wave forms between 3-*LPS* and 4-*LPS* are very similar, suggesting a similar focal mechanism of two earthquakes of *Nos.* 3 and 4. Group velocities with a maximum of about 3.8 km/sec for 23-*TUC* and 24-*TUC* near a period 30 sec are lower than those for 3-*LPS* and 4-*LPS*.

In Fig. 4 all the observed group velocities of Rayleigh waves are shown together with theoretical curves associated with the ocean-floor age, using the upper mantle model *PC-MIN* (YOSHIDA, 1978) and those in which the lithospheric thickness varies with the ocean-floor age (t) as $7.5\sqrt{t}$, estimated by YOSHII (1973) from 'Residual Gravity Anomaly'



(a) (b)

Fig. 3. Group velocities (solid circles) of Rayleigh waves as calculated for the Z-component. The seismogram of a part of Rayleigh waves is inserted in the figure. The group velocities enclosed by solid lines belong to those of other phases except the fundamental mode of Rayleigh waves.

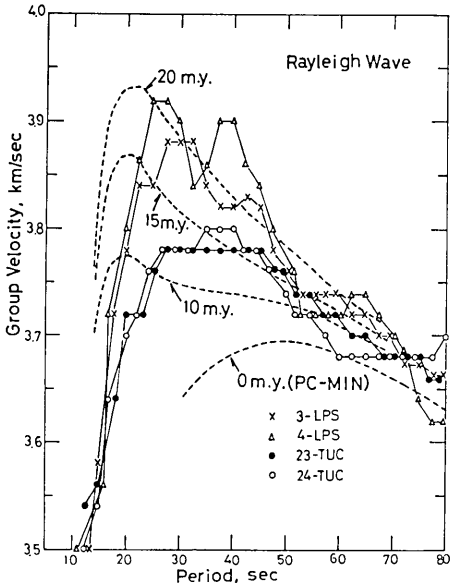


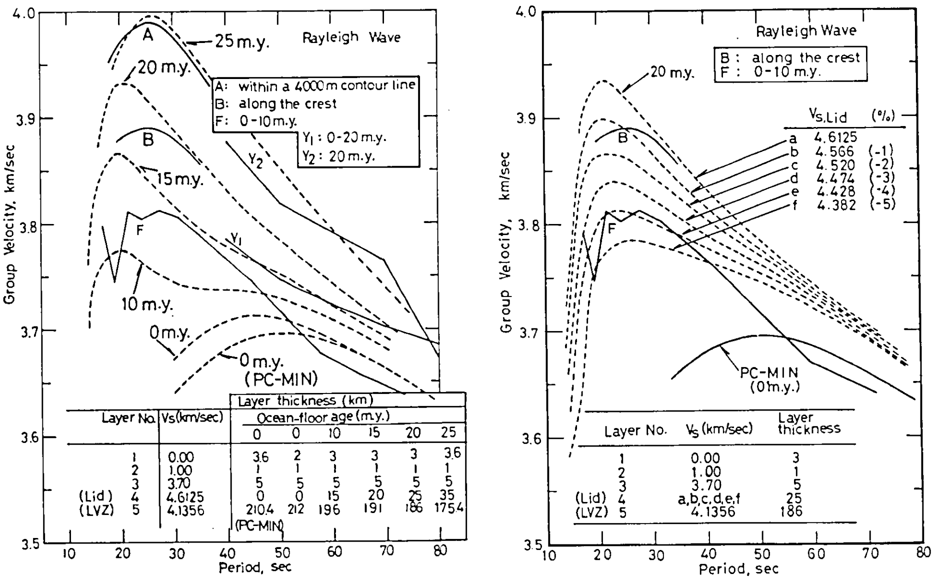
Fig. 4. Group velccites of Rayleigh waves observed at stations *LPS* and *TUC*, and theoretical ones calculated for the models associated with the ocean-floor ages of 0, 10, 15 and 20 m.y. The details on the models are described in Fig. 5 and in the text.

data. We see that the observed velocities are within the ages from 10 to 20 m.y. for periods larger than 25 sec, and the velocities for 3-*LPS* and 4-*LPS* fit the curves of 20 m.y.

The details of the upper mantle models calculated above are shown in Fig. 5a together with typical observed velocities near the East Pacific Rise. A model for 20 m.y. is temporarily designated as *EP*20-*L*. Two theoretical group velocity curves for 0 m.y. indicate that group velocity variations of 0.025 and 0.030 km/sec are caused at periods of 40 and 30 sec by an ocean depth difference of 1.6 km.

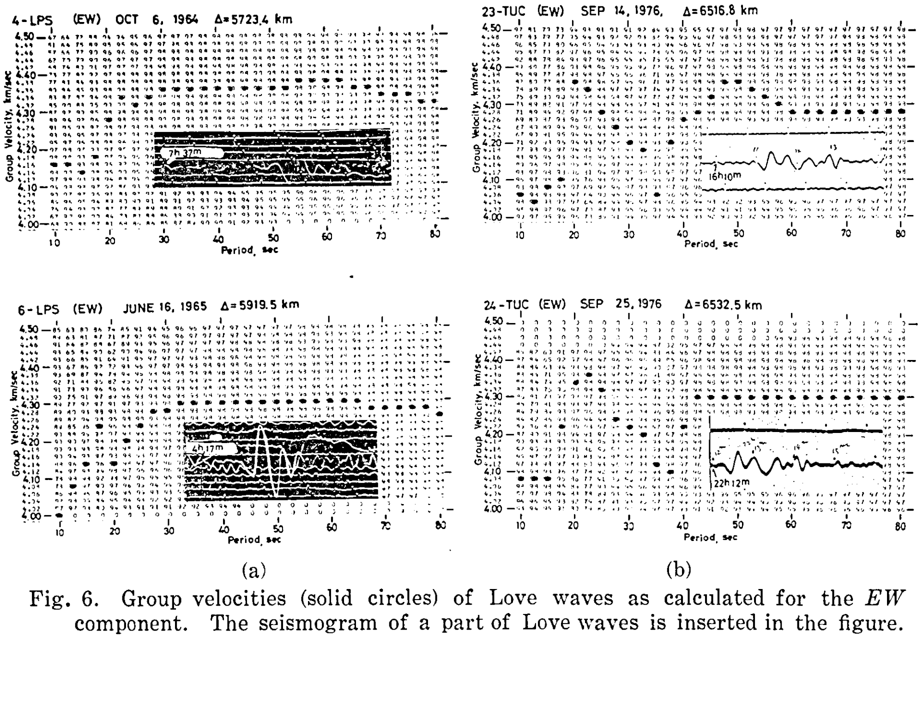
We notice from Fig. 5a that the anomalous dispersion curves designated as '*A*' and '*B*' are well explained by the models corresponding to ocean-floor ages of 25 and about 17.5 m.y. with thickness of about 36 km and 28.5 km respectively. The thickness means that covering layers from *Nos*. 2 to 4. A remarkable difference between the models considered here and the oceanic model 8099 exists in a very low shear velocity in the *LVZ*, about 4.13 km/sec for the present models. SCHLUE and KNOPOFF (1977) estimated the shear velocity 4.10 km/sec in the *LVZ*, which is lower than the present estimation. The models they proposed limit the *LVZ* to a depth of 180 km, while the depth of the *LVZ* in the models shown in Fig. 5a reaches 220 km.

The curves 'Y_2', 'Y_1' and '*F*' show representative characteristics of observed group velocities for regions of young ages of 20, 0-20, and 0-10 m.y. respectively. It should be noted that the periods pointing the peaks of the group velocities for the curves '*F*' and '*B*' are slightly longer than those for theoretical curves of '10', '15' and '20' m.y. (Fig. 5a). These differences decrease by lowering the shear velocity in the oceanic lid in the upper mantle model from 4.6125 km/sec



(a) (b)

Fig. 5 (a). Observed (solid lines) and theoretical (dashed lines) group velocities calculated for the models asscciated with the ocean-floor ages of 0, 10, 15, and 20 m.y. Layer parameters of the density and P-wave velccity are assumed to be the same as those on the oceanic model 8099. A, B: SANTO (1963), F: FORSYTH (1975), Y_1: YOSHII (1975), Y_2, $PC\text{-}MIN$: YOSHIDA (1978). (b) Observed (solid lines) and theoretical (dashed lines) group velocities calculated for the models with different shear velccities in the Lid designated as a, b, c, d, e and f. The decrease in shear velccies is indicated in %.



(a) (b)

Fig. 6. Group velocities (solid circles) of Love waves as calculated for the EW component. The seismogram of a part of Love waves is inserted in the figure.

to 4.43 and 4.57 km/sec for the curves '*F*' and '*B*' respectively (Fig. 5b). The group velocity difference between solid and dotted lines at periods longer than 40 sec is caused by the difference of the depth extent of the *LVZ* associated with different ages of 0 and 20 m.y.

4.2 Love waves

Love waves of the fundamental mode were well recorded for 4-*LPS* and 6-*LPS*, and a part of the wavetrains is inserted in Fig. 6 which shows calculated group velocities. At a period of 15 sec the velocity is about 4.10 km/sec for both the two paths, and the velocities for periods longer than 30 sec are about 4.35 and 4.30 km/sec for 4-*LPS* 6-*LPS* respectively. The velocities for 23-*TUC* and 24-*TUC* in Fig. 6 are not well determined, especially for periods less than 60 and 40 for 23-*TUC* respectively, with the velocities oscillating in the range from 4.05 to 4.35 km/sec. This oscillation may be caused by the interference by the higher modes of Love waves or scattered waves which might have been generated on the way of the wave path involving the lateral heterogeneity. The flat portion of the group velocity indicates 4.30 km/sec for the two paths at long periods. It should be noted that the stable group velocity of 4.30 km/sec or so is about 0.2 km/sec lower than those of Love waves in the west Pacific (YOSHIDA, 1983b).

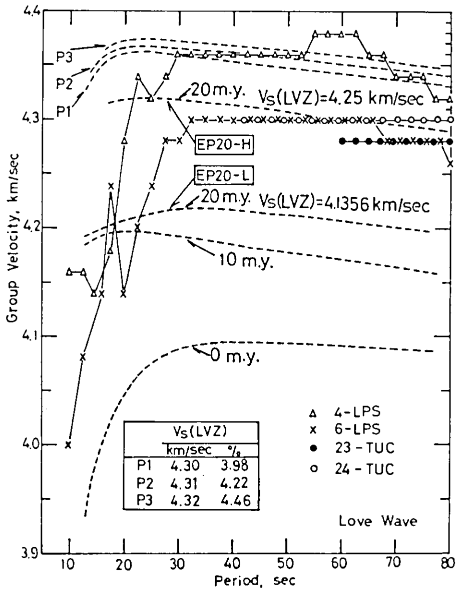


Fig. 7. Group velocities of Love waves observed at *LPS* and *TUC*, and theoretical ones (dashed lines) calculated for the models associated with the ages of 0, 10, and 20 m.y. (lower three curves). The upper four curves associated with the age of 20 m.y. are calculated for the models with shear velocities of 4.25, 4.30 (*P*1), 4.31 (*P*2) and 4.32 (*P*3) km/sec in the *LVZ*. The anisotropy is expressed in %.

In Fig. 7 the observed and theoretical group velocities associated with the ocean-floor ages of 0, 10, and 20 m.y. are shown, in which the velocities determined unstably are rejected. The three lower theoretical ones were calculated for the models given in Fig. 5a, including *EP*20-*L*. However, these models cannot explain the group velocities of observed Love waves.

The model (*EP*20-*H*) associated with the ocean-floor age of 20 m.y. in which the shear velocity in the *LVZ* is 4.25 km/sec and other layer parameters are fixed to those for *EP*20-*L*, were calculated and compared with the observed group velocities (Fig. 7) of Love waves for 6-*LPS*, 23-*TUC* and 24-*TUC*, and a curve calculated for a model *P*2 whose shear velocity in the *LVZ* is 4.31 km/sec fits the one for 4-*LPS*.

We notice in Fig. 7 that the group velocity difference between the models for the ocean-floor ages of 10 and 20 m.y., with the velocity of about 4.2 km/sec, is smaller at periods less than 30 sec than at periods near 70 sec. In order to clarify the strange characteristics, the eigenfunction of the displacement y_1 and the partial derivatives of the eigenfrequency $\partial\omega_n/\partial v_s$ were calculated by means of the Runge-Kutta-Gill method (TAKEUCHI and SAITO, 1972), for periods of about 25 and 70 sec and are shown in Fig. 8. For Rayleigh wave the displacement and the derivatives at a period of about 25 sec are predominantly affected by the medium in shallow parts of the upper mantle, especially at depths less than 50 km. The physical property of the oceanic plate chiefly determines the dispersion parameters. However for Love wave the maxima of the displacement and the derivative curves for a period of about 25 sec are located near a depth 100 km, approximately the intermediate portion of the *LVZ*. The maxima for a period of about 75 sec are located, however, near the shallow depth range of the oceanic plate from 0 to 30 km. Therefore for Love waves the group velocity for short periods near 25 sec has no signi-

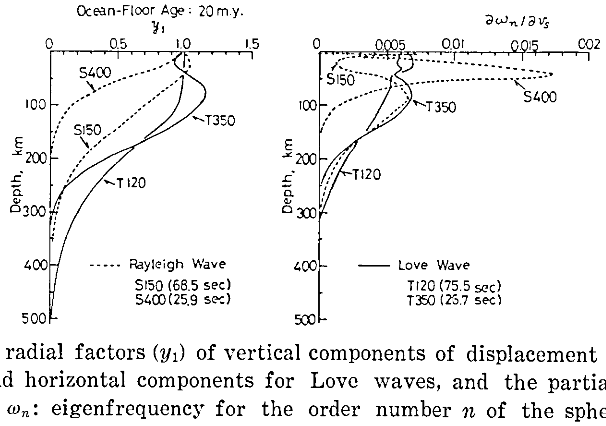


Fig. 8. The radial factors (y_1) of vertical components of displacement for Rayleigh waves and horizontal components for Love waves, and the partial derivatives ($\partial\omega_n/\partial v_s$). ω_n: eigenfrequency for the order number n of the spherical surface harmonics. v_s: shear wave velocity. The displacement and the partial derivative are calculated for the model associated with the ocean-floor age of 20 m.y., with the shear velocity 4.1356 km/sec in the *LVZ*, and they are given in units of cm and 1/km respectively.

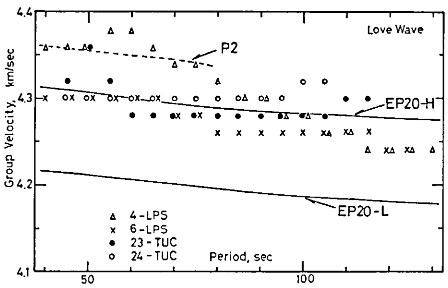


Fig. 9. Observed and calculated (*EP*20-*H* and *EP*20-*L*) group velocities of Love waves of the fundamental mode for periods up to 130 sec, together with those for *P*2.

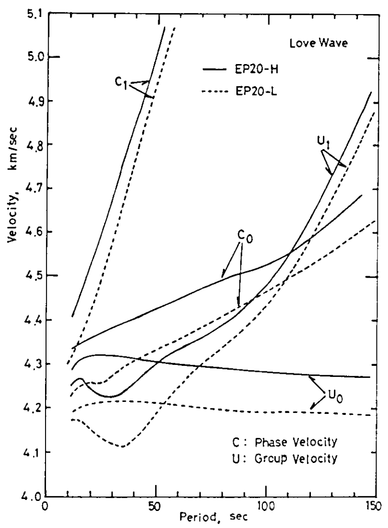


Fig. 10. Phase and group velccities of the fundamental and first higher modes of Love waves calculated for *EP*20-*H* and *EP*20-*L*. The suffixes 0 and 1 indicate the fundamental and first higher modes respectively.

ficant discrepancy between the different regions near the East Pacific Rise.

Long period group velocities of about 4.3 km/sec of observed Love waves for periods up to 130 sec are shown in Fig. 9, and they agree with those calculated for *EP*20-*H*. It is understood from the study of higher mode excitation (FUKAO and ABE, 1971; YOSHIDA, 1983a) that the first higher Love mode is very weakly excited by shallow earthquakes of the strike slip fault type as used in the present analysis, and the group velocities of the first higher Love mode, estimated to be 4.45 and 4.55 km/sec at periods of 100 and 110 sec, respectively, are clearly separated from those of the fundamental mode (Fig. 10). Therefore, the observed group velocities described above can be identified as those of the fundamental mode.

Two synthetic fundamental Love modes for 4-*LPS* were generated to see the travel time difference using the excitation theory of toroidal oscillations (SAITO, 1967) and are shown in Fig. 11. Source mechanism solutions reported by FORSYTH (1975) and *Q* values in the oceanic region (TSAI and AKI, 1969) were employed for the wave synthesis. The arrival time of the waves for *EP*20-*L* is about 40 sec later than those for *EP*20-*H* and observed waves, indicating that the model *EP*20-*H* is superior to *EP*20-*L* from a viewpiont of wave forms.

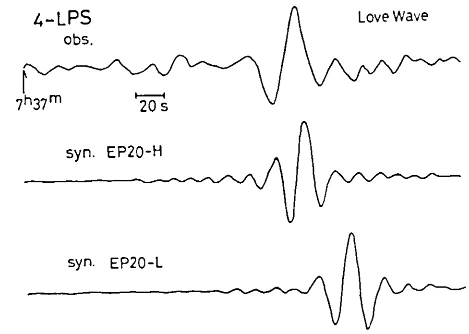


Fig. 11. Observed and synthesized Love waves of the fundamental mode for 4-*LPS*, calculated for *EP*20-*H* and *EP*20-*L*.

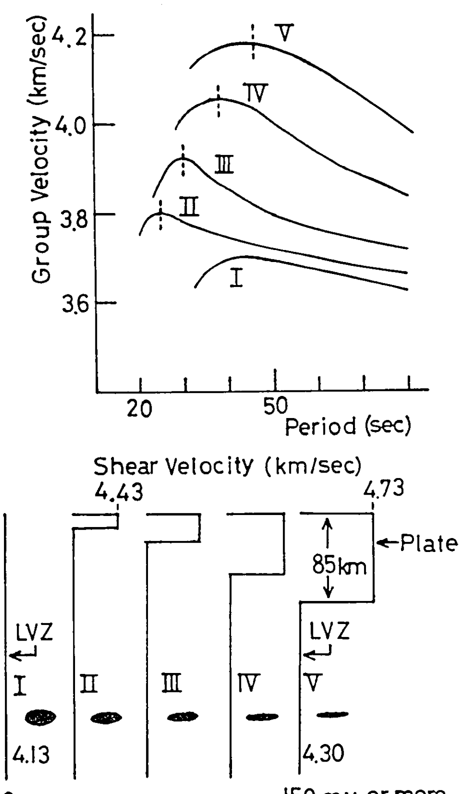


Fig. 12. Rayleigh waves in the Pacific. Roman numerals attached to the curves indicate the stage varying with the ocean-floor age, and correspond to those given in the lower figure, showing schematically the upper mantle structures. The shear wave velocities in the lithosphers and the LVZ are given in units of km/sec.

5. Discussions

In Fig. 5b the group velocity maxima for regions where the ocean-floor age ranges from 10 to 20 m.y. appeared near a period of 25 sec, the maxima ranging from 3.8 to 3.9 km/sec. The oceanic model 8099 (DORMAN, EWING and OLIVER, 1960), corresponding to the region with an age of 85 m.y. (YOSHIDA, 1978), has a maximum of 4.02 km/sec at a period of 35 sec and the model *PC-MAX* constructed for the highest-velocity-area in the Pacific (YOSHIDA, 1978) has a maximum of about 4.20 km/sec at a period of 50 sec.

The relationship between the maximum group velocity of Rayleigh waves and the period indicating the maximum is schematically pictured in Fig. 12, associated with the ocean-floor age. In a lower half of the figure the transitional process of the oceanic lithosphere and the *LVZ* with respect to the varying stage of the ocean-floor age is depicted. Near the East Pacific Rise stages *I* and *II* are predominant and in the west Pacific the stages *IV* and *V* dominate. The maximum group velocity and its wave period are mainly controlled by the shear velocity of the oceanic lithosphere and its thickness, while the gradient of the curve at periods longer than those indicating the maximum is affected by the shear velocity in the *LVZ* and the depth extent covering the *LVZ*.

When we interpret the Rayleigh and Love wave dispersions in the Pacific it should be noted that the shear velocities in both the oceanic plate and the *LVZ* increase from 4.43 to 4.72 km/sec and from 4.13 to 4.30 km/sec, respectively, in proportion to the ocean-floor age ranging from 0 to 150 m.y. or more. The plate thickness also increases from 0 to 85 km at the expense of the extension of the *LVZ* (YOSHIDA, 1978), reaching a depth of 220 km.

The shear velocities in the *LVZ* in the vertical and horizontal components near the East Pacific Rise, 4.13 and 4.25 km/sec respectively, are compared with those in the west Pacific (Table 2), indicating evidence of a surface wave polarization anisotropy of 3% in the east and west Pacific. Those value are similar to the one of 3.4% through the Pacific obtained by SCHLUE and KNOPOFF (1977). Numerical experiments as examined by assuming several thin layers in the *LVZ* will appear in a separate publication and a resolution will be discussed since the resolution is related with a start model

Table 2. Shear velocities in the horizontal $(V_S)_H$ and vertical $(V_S)_V$ directions in units of km/sec. The ratio of the rigidities in horizontal and vertical directions is also given.

Surface Wave Polarization Anisotropy

	West Pacific	East Pacific
$(V_S)_H$	4.43	4.25
$(V_S)_V$	4.30	4.1356
μ_H/μ_V	1.06	1.06

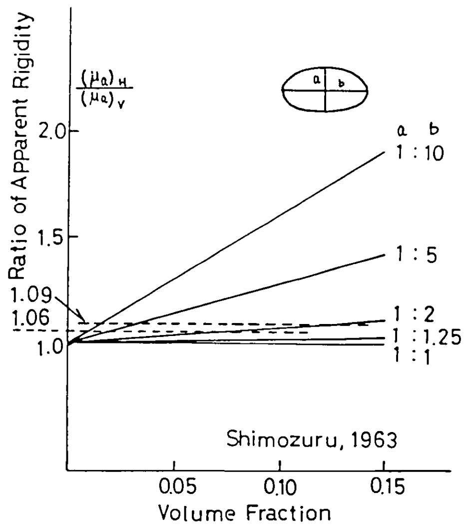


Fig. 13. Relation between the ratio of apparent shear modulus in a horizontal direction to that in a vertical direction and the volume fraction of involved molton pockets (After SHIMOZURU. 1963). The ratio of 1.06 is indicated in the figure. The ratio of 1.09, in which shear velocities in the vertical and horizontal directions correspond to 4.1356 (Model: *EP*20-*L*) and 4.31 (Model: *P*2 in Fig. 7), respectively, is also shown for reference.

(KIRKWOOD, 1978; ANDERSON and REGAN, 1983; MITCHELL, 1984).

In Table 2 a ratio of rigidities in the horizontal and vertical directions of about 1.06 in the east and west Pacific is shown. According to SHIMOZURU (1961) the volume fraction of involved molten pocket in the *LVZ* is estimated to be several percent to interpret Lehman's *LVZ*. Fig. 13 shows the relation between the ratio of apparent shear modulus in the two directions and the volume fraction of involved molten pockets (SHIMOZURU, 1963). From the figure we understand that the shape of molten pockets forms an oblate spheroid with the axis of rotation vertical in which the ratio of the minor to the major axes ranges from 1/2 to 1/10. If we assume the horizontal shear flow in the *LVZ*, where the gravity is exerted vertically downward, the shape of molten pockets will possibly vary as shown in Fig. 13. As the stage progresses the oblate spheroid becomes very flat.

Although possible mechanisms for the upper mantle anisotropy, such as preferred orientations of open cracks in rocks, alignment of partial molten pockets in the *LVZ* and preferred orientation of olivine aligned either by glide-plane slip in shear zones or by syntectonic recrystallization, have been considered in many studies (e.g., KIRKWOOD and CRAMPIN, 1981; KAWASAKI, 1982; ANDO, ISHIKAWA and YAMAZAKI, 1983; YOSHIDA, 1983b), the results discussed above suggest that in the regions studied here the surface wave polarization anisotropy is caused by the existence of partially molten pockets filled with liquid in the *LVZ*.

6. Conclusions

The structures of the oceanic plate and *LVZ* in the regions near the East Pacific Rise have been investigated. The shear velocities of *SV* and *SH* in the *LVZ* were determined to be 4.13 and 4.25 km/sec respectively, showing the surface wave polarization anisotropy of 3% in shear volocities and the ratio of horizontal to vertical rigidities of 1.06. This anisotropy is caused by the presence of partially molten materials of peridotite in the *LVZ*. If we assume a volume fraction of involved molten pockets of 0.05 to 0.10, the ratio of the minor to the major axes of an oblate spheroid of the molten pockets is about one half.

Peculiar dispersion curves of Rayleigh waves with group velocity maxima of 3.9 km/sec located at a period of 25 sec, which appear only in the regions where the ocean-floor age is 0–20 m.y., can be solved by a plate-mantle system of a very thin plate with a thickness of 25 km and an extemely low shear velocity of 4.13 km/sec in the *LVZ* extending to a depth of 220 km.

Shear velocities of SV are found to increase with age from 4.13 to 4.30 km/sec in the LVZ and from 4.43 to 4.73 km/sec in the oceanic plate, the plate thickness increasing with age from 0 to 85 km. These varying plate-mantle systems have successfully solved the relation between the varying maximum group velocities of Rayleigh waves and the periods indicating the maxima through the Pacific.

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群速度及び合成波から明らかにされた東太平洋海膨付近における表面波異方性

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東太平洋海膨付近に於ける周期 25 秒でレイリー波群速度の最大値 3.9 から 4.0 km/sec を示す異状な分散曲線は，厚さおよそ 30 km の非常に薄い海洋レプートと 4.13 km/sec という非常に遅い S 波速度からなる低速度層で構成される上部マントル構造によって良く説明される．このような構造に対するラブ波の応答は著しく異なる．即ち，周期 20 秒から 110 秒に於いて観測された群速度 4.3 km/sec は低速度層における高い S 波速度 4.25 km/sec によって見事に説明される．水平と上下方向の S 波速度の食い違いが 3% という表面波の polarization anisotropy は太平洋の最も若い地域で明瞭に存在する．低速度層における部分溶融状態のマグマポケットの volume fraction の割合を 0.05 から 0.10 に仮定すると，部分溶融したポケットの扁球体の短軸と長軸の長さの比は約 0.5 と見積られる．このマグマポケットの配列が表面波の polarization anisotropy を生成させていると推定される．