Characteristics of the Vertically Heterogeneous and Anisotropic Plate Structure in the Pacific: Implication of the Plate Thickness

Mitsuru Yoshida

Earthquake Research Institute, The University of Tokyo, Tokyo 113, Japan

A detailed shear wave velocity structure in the Pacific lithosphere for an ocean-floor age greater than 100 m.y. has been obtained in high resolution by means of several isotropic and anisotropic surface wave inversions. The vertically heterogeneous velocity structure of the vertically polarized shear wave has the following 3 characteristics: (1) has a small-scale low velocity zone near a depth of 30 km; (2) reaches a maximum value at a depth of 70 km; (3) obtains a minimum value at a depth of 130 km in the large-scale low velocity zone. The velocity increases with depth between 130–220 km. The velocity structure of the horizontally polarized shear wave does not possess Characteristics 1 and 2. Characteristics 2 and 3 give strong constraints on the rigorous estimation of the plate thickness. If the bottom of the heterogeneous lithosphere is tentatively defined as a mid-point between the depths indicating Characteristics 2 and 3, the plate thickness is estimated to be 100 km for the region where the age is greater than 100 m.y. A relationship between Characteristic 1 and the double-planed seismic zone is also discussed.

1. Introduction

After applying an anelasticity correction to surface wave data, the regional structure of the Pacific lithosphere and asthenosphere has been constructed through the use of several modern inversion techniques. These techniques have been used by a number of investigators (Mitchell and Yu, 1980; Regan and Anderson, 1984; Kawasaki, 1986; Yoshida, 1986; Nishimura and Forsyth, 1989). With respect to the plate thickness, a number of the lithospheric structures are classified according to either a thick model or a thin model. The plate thickness is compared with the elastic thickness inferred from studies of the lithospheric flexure (Watts *et al.*, 1980; Ida, 1984). The elastic thickness is estimated to be between 30–60 km (Watts *et al.*, 1980) for the ocean floor with an age of 150 m.y.

If the thickness estimated by surface waves is designated as the seismic thickness, it is found that the thickness is 2–3 times greater than the elastic thickness. It should be noted that the regional models developed by various authors using surface waves for the same region show distinct differences in the structure of the lithosphere, the

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asthenosphere, or both. This is due to the fact that both the thick and thin models involve some errors and uncertainties associated with uniqueness and/or resolution. Therefore, the background for the solutions should be critically studied in order to correctly interpret the solutions.

The present paper attempts to obtain a vertically heterogeneous shear wave velocity structure in the Pacific lithosphere and asthenosphere for a region where the age is greater than 100 m.y. The generalized inverse method (Wiggins, 1972; Jackson, 1972) is applied to several anisotropic and isotropic inversions. Trade-off curves are calculated in order to select the optimized solution defined in terms of the generalized eigenvectors. The heterogeneous lithospheric structure will create a new image of the plate model that will then afford extensive views of seismic thickness and the double-planed seismic zone.

2. Thick and Thin Models

The plate model developed by Mitchell and Yu (1980) having a thickness of 100 km for the region where the age is > 100 m.y. is selected as the thick model. This model is modified by assuming a fixed value of 4.20 km/s in the low velocity zone (LVZ) and a fixed depth of 180 km for the bottom of the LVZ. The starting model used by Mitchell and Yu had a plate thickness of 110 km corresponding to the region having an age of 120 m.y. in the very thick model obtained by Leeds *et al.* (1974). The very thick model has a plate thickness of 150 km in the region where the age is 150 m.y.

Thin models with a thickness of 60 km for the region where the age is > 100 m.y. have been developed by Anderson and Regan (1983), Regan and Anderson (1984), and Kawasaki (1986), making use of anisotropic inversions of the data sets of Mitchell and Yu (1980). A distinct feature of the three thin models is that the shear wave velocity structure in the LVZ exhibits a drastic change between young and old regions of the Pacific. It should also be noted that prominent differences exist between the models of Regan and Anderson (1984) and those of Kawasaki (1986), particularly in the structure of the LVZ in the region where the age is > 100 m.y., and for other regions, as will be discussed below.

3. Calculation of the Detailed Structure of the Lithosphere and Asthenosphere

3.1 Data

The data sets consisting of the group and phase velocities of Rayleigh and Love waves in the regions where the age is > 100 m.y. and between 50–100 m.y., as reported by Mitchell and Yu (1980), are used in the present anisotropic and isotropic inversions. In order to check the nonuniqueness of the resulting structures, data sets consisting of group velocities of Rayleigh waves in the adjacent areas, i.e., > 150 m.y. (Yoshida, 1978), > 90 m.y. and between 50–90 m.y. (Yoshii, 1975), are used in isotropic inversions. The data sets of group velocities in the young region of 20–50 m.y. (Yoshii, 1975; Mitchell and Yu, 1980) are also used in isotropic inversions for comparison purposes. The anelasticity correction (Liu *et al.*, 1976; Kanamori and Anderson, 1977) is performed on the above data sets at a reference period of 1 s, using the Q data of

Mitchell (1976). The period of waves in the data sets ranges from 30 to 110 s.

The oceanic model 8099 presented by Dorman *et al.* (1960) and the global model PREM (Dziewonski and Anderson, 1981), which greatly differs from the 8099 model at depths shallower than 220 km, are employed as starting models. The 8099 model is used without the addition of any modifications. The PREM model is slightly modified for layer parameters at depths shallower than 220 km. These modifications consist of constant densities of 3.3791 and 3.3682 g/cm³ at depths between 11.4–60 and 60–220 km, respectively, while compressional wave velocities of 8.1012 and 8.0399 km/s are assumed for depths between 11.4–60 and 60–220 km, respectively. For the structure of shear wave velocity, the values of the 8099 model are used while the crustal structure employs the 3 layer parameters of Cara (1979). A water depth of 5 km is assumed in both starting models. The two models are used to check the nonuniqueness of the resulting structures due to starting-model dependence.

3.2 Method

The partial derivatives of the group and phase velocities are employed in the present linearized inversion. The theoretical relationship between these derivatives, as shown by Rodi *et al.* (1975), is given by

$$\left. \frac{\partial U}{\partial m} \right|_{\omega} = \frac{U}{C} \left(2 - \frac{U}{C} \right) \left. \frac{\partial C}{\partial m} \right|_{\omega} + \omega \frac{U^2}{C^2} \left. \frac{\partial}{\partial \omega} \left(\left. \frac{\partial C}{\partial m} \right|_{\omega} \right) \right|_m \quad (1)$$

and

$$\left. \frac{m}{U} \frac{\partial U}{\partial m} \right|_{\omega} = \frac{m}{C} \frac{\partial C}{\partial m} + \frac{U}{C} \omega \left. \frac{\partial}{\partial \omega} \left(\left. \frac{\omega}{C} \frac{\partial C}{\partial m} \right|_{\omega} \right) \right|_m \quad (2)$$

Here, U and C are the group and phase velocities at a given frequency ω ; $\partial U / \partial m|_{\omega}$ and $\partial C / \partial m|_{\omega}$ are the partial derivatives of the group and phase velocities with respect to a layer parameter m , taken while holding ω fixed.

The partial derivatives of the phase velocity can be obtained through use of the energy integrals given in Takeuchi and Saito (1972) as follows:

$$\frac{\beta_H}{C} \left[\frac{\partial C}{\partial \beta_H} \right]_{\omega, \rho, \beta_V} = \frac{1}{\omega^2 I_1^L} \left(\frac{U}{C} \right) k^2 N (y_1^L)^2 \quad (3)$$

and

$$\frac{\beta_V}{C} \left[\frac{\partial C}{\partial \beta_V} \right]_{\omega, \rho, \beta_H} = \frac{1}{\omega^2 I_1^R} \left(\frac{C}{U} \right) \left(\frac{1}{L} (y_4^R)^2 + \frac{4kFL}{A-2L} y_1^R y_3^R \right), \quad (4)$$

where the superscripts L and R denote Love and Rayleigh waves, respectively. I_1^L and I_1^R represent the energy integrals. β_H and β_V are the horizontally and vertically polarized shear wave velocities, respectively, while ρ is the density and k is the wave number. N , L , F , and A are elastic constants, with y_1^R , y_2^R , y_3^R , and y_4^R representing the eigenfunctions; y_1^R stands for the derivative of y_1^R with respect to depth.

The generalized inverse method (Wiggins, 1972; Jackson, 1972), weighted by the

layer thickness, is employed in order to determine the model parameters. The optimized solution $\hat{x}$ is obtained by

$$\hat{x} = A_q^\dagger y. \quad (5)$$

Here, y is the data vector, and the generalized inverse of the coefficient matrix

$$A_q^\dagger = V_q A_q^{-1} U_q^T, \quad (6)$$

is an arbitrary $m \times n$ matrix of rank q ($< n, m$). A_q^{-1} is a semidiagonal $q \times q$ matrix of singular values. V_q and U_q^T , formed from the eigenvectors v_i and u_i ($i=1, \dots, q$), are an orthonormal $m \times q$ matrix and a transposed orthonormal $q \times n$ matrix, respectively. Following Yoshida (1986), the number of the largest singular values (lsv), degree of freedom in the data, is determined in such a way as to optimize the combination of the criteria given below (e.g., see Jackson, 1972; Saito, 1983).

$$R_q = A_q^\dagger A_q = V_q V_q^T = r_{ij} \sim I_m, \quad (7)$$

$$S_q = A_q A_q^\dagger = U_q U_q^T = s_{ij} \sim I_n \quad (8)$$

and

$$\sigma_k^2 = \text{var}(\hat{x}_k) = \sum_{j=1}^q (v_{k,j}/\lambda_j)^2 \sim \text{small} (< 0.04 \text{ km/s}), \quad (9)$$

where λ_j is the singular value. R and S are the resolution matrix and the information matrix, respectively, while σ_k^2 is the variance of $\hat{x}_k$.

In order to determine the proper choice of the optimized solution, the following five quantities are calculated, which include the criteria mentioned above.

(i) The average perturbations of the unknown parameters in percent,

$$\overline{XP} = \sum_{i=1}^m |\Delta x_i / x_i| \times 100 / m, \quad (10)$$

where x_i is the initial value and Δx_i the perturbation.

(ii) The root mean square of the group (or phase) velocity residuals, given by

$$\overline{OC} = \sqrt{\sum_{i=1}^n |O_i - C_i|^2 / n}, \quad (11)$$

where O_i and C_i are the observed and calculated group (or phase) velocities for the i th component, respectively.

(iii) The average of the standard deviations

$$\overline{SD} = \sum_{i=1}^m |\sigma_i| / m, \quad (12)$$

where σ_i is the standard deviation of the i th component. For the following two quantities, the resolution matrix Eq. (7) and information matrix Eq. (8) are normalized by the maximum value in each row.

(iv) The measure of the resolution matrix.

$$\bar{R} = \sum_{i=1}^m \sum_{j=1}^m |r_{ij} - \delta_{ij}| / m^2 \quad (13)$$

where δ_{ij} is the Kronecker's delta. If $\bar{R}=0$, then the solution is uniquely determined.

(v) The measure of the information matrix, given by

$$\bar{I} = \sum_{i=1}^n \sum_{j=1}^n |s_{ij} - \delta_{ij}| / n^2. \quad (14)$$

If $\bar{I}=0$, then the data is highly independent.

The partial derivatives of surface wave velocities with respect to physical parameter changes (Yoshida, 1986) show that the shear wave velocity influences most strongly the dispersion characteristics of surface waves. Therefore, in the present work, the measure $\bar{R}$ for only the β_V - β_V or the β_H - β_H is shown in the trade-off curves.

4. Results and Interpretation

4.1 The β_V and β_H structures in the region >100 m.y.

First, two types of isotropic inversions were carried out using the Rayleigh wave

Fig. 1. Shear wave velocity structures (A) and (B) in the region >100 m.y. obtained from Rayleigh wave group velocities, using the 8099- and PREM-type starting models, respectively. Structures of the starting models are denoted by dotted lines and the one used by Mitchell and Yu (1980) by dash-dot lines. The structures b, c, d, and e correspond to the solutions for $q=2, 3, 4$, and 5 , respectively, (q : the number of the largest singular values). The arrows with the abbreviation min. indicate depth taking a minimum velocity. The plate thicknesses, denoted by numerals in parentheses, are estimated from the models RA (Regan and Anderson, 1984), K (Kawasaki, 1986), and MI (Mitchell and Yu, 1980). They are marked by arrows with their model abbreviations. Note that the number and kind of parameters solved are different for structures (A) and (B) (See the text for details).

Fig. 2. Trade-off curves between the perturbations of parameters ($\overline{XP}$), group velocity residuals ($\overline{OC}$), standard deviations ($\overline{SD}$), resolutions ($\overline{R}$), and information densities ($\overline{I}$) for the structures (A) and (B) given in Fig. 1. The vertical arrow on the abscissa indicates the number (q) of the largest singular values (lsv) that yields the optimized solution.

group velocities of Mitchell and Yu (1980) for the region where the age is > 100 m.y. The structures (A) and (B), given in Fig. 1, were obtained by using the 8099- and PREM-type starting models, respectively. For the former case, only the β_v was determined, while in the latter the density ρ , β_v , vertically (α_v) and horizontally (α_H) polarized compressional wave velocities along with the anisotropic factor η were simultaneously determined.

The trade-off curves, calculated on the basis of the expressions given by Eqs. (10)–(14), are shown in Fig. 2. The values of $\overline{XP}$, $\overline{OC}$, $\overline{SD}$, $\overline{R}$, and $\overline{I}$ at $q=4$ for Case A were determined as approximately 2.2%, 0.01 km/s, 0.18 km/s, 0.3, and 0.4, respectively. The values of $\overline{SD}$ at $q=5$, for Cases A ($=0.6$) and B ($=0.7$), are too large, while those of $\overline{R}$, $\overline{I}$, and $\overline{OC}$ become small. It should be noted that the $\overline{XP}$ curve is increasing more rapidly with the increase in q for Case A than for Case B. Taking the trade-off curves into consideration, two structures, determined by the d models ($q=4$) for Cases A and B, are candidates for the region > 100 m.y. The d models possess three characteristics: 1) a small-scale LVZ at a depth of 30 km in the lithosphere; 2) a maximum velocity at a depth of 60 km; 3) a minimum velocity at a depth of 130 km. The resolutions (Fig. 3(a)) at depths of 30, 70, 130, and 170 km are very high for Cases A and B. The characteristics of the information densities (Fig. 3(b)) for Case A are very similar to those for Case B. The group velocity residuals, shown in Fig. 3(c), are somewhat larger for Case A than for Case B.

Second, in order to check the validity of the d models shown in Fig. 1, the structures for neighboring areas (Fig. 4) were determined using the Rayleigh wave group velocities of Yoshii (1975) and Yoshida (1978) for the regions > 90 m.y. and > 150 m.y.,

Fig. 3. Resolving kernels for the shear wave velocities (a), information densities (b), and group velocity residuals (c) calculated for the d models ($q=4$) of structures (A) (solid lines) and (B) (dotted lines) given in Fig. 1.

respectively. The 8099-type starting model was used for the inversion. The trade-off curves (Fig. 5) show that the variations of $\overline{XP}$, $\overline{OC}$, and $\overline{SD}$ curves versus q are not as great when compared with those in Fig. 2. The values of $\overline{SD}$ at $q=5$ are within 0.2 km/s for the two regions. The resolutions, information densities, and group velocity residuals (Fig. 6) for the d ($q=4$) and e ($q=5$) models show that three measures for the latter model are superior to the former. The β_v structures obtained (the e models in Fig. 4) are essentially similar to the d models for the region >100 m.y. in Fig. 1.

Third, anisotropic inversions were carried out using both group and phase velocity data of Rayleigh and Love waves of Mitchell and Yu (1980) in the regions >100 m.y.

Fig. 4. Shear wave velocity structures in the regions >90 m.y. and >150 m.y. obtained from Rayleigh wave group velocities, using the 8099-type starting model (dotted lines). The structures c, d, e, and f correspond to the solutions for $q=3, 4, 5$, and 6 , respectively. The plate thicknesses denoted by numerals in parentheses, estimated by YI (Yoshii, 1975) and YD (Yoshida, 1978), are marked by arrows with their model abbreviations.

Fig. 5. Trade-off curves for the structures in the regions >90 m.y. (solid lines) and >150 m.y. (dotted lines) given in Fig. 4.

and between 50–100 m.y. It was assumed that the lithosphere and asthenosphere are transversely isotropic with a vertical symmetric axis. The PREM-type model was used as the starting model, in which the β_H and β_v , as well as the α_H and α_v , are assumed to be equal. Even though the six parameters (β_v , β_H , α_v , α_H , ρ , and η) were simultaneously

Fig. 6. Resolving kernels and information densities (a) and group velocity residuals (b) for the d (dotted lines) and e (solid lines) models given in Fig. 4.

determined in these inversions, the structures of only the β_V and β_H are shown in Fig. 7(a), since the focus here was concentrated on the shear wave velocity. The trade-off curves (Fig. 7(b)) show that the values of SD of the β_H are always smaller than those of the β_V , while the values of R are reversed at $q \geq 3$.

The β_V structure for the region >100 m.y., obtained at $q=4$ from the group velocities, is very similar to the d models ($q=4$) in Fig. 1. It possesses the three characteristics previously described but Characteristic 2 should be modified in that the structure has a maximum velocity at a depth of 70 km. It should be noted that the β_V increases with depth, being larger in the structure shown in Fig. 7(a) than in the d models in Fig. 1 at depths between 130–220 km. In the β_V structures, the locations that indicate the three characteristics derived from phase velocities occur at somewhat deeper depths than those derived from the group velocities.

The characteristic of the β_V structure for the region 50 to 100 m.y., derived from

Fig. 7. (a) The β_V and β_H structures in the regions 50 to 100 m.y. and >100 m.y., obtained from anisotropic inversions, using the PREM-type starting model (dotted lines). The structure of the starting model used by Mitchell and Yu (1980) is indicated by chain lines (MI). The structures obtained from phase and group velocities are denoted by C and U, respectively: The former is indicated by thick solid (β_V) and dotted (β_H) lines; the latter by thin broken (β_V) and dotted (β_H) lines. The arrows with the abbreviation min.^c denote the depths for a minimum velocity in the large-scale LVZ of the β_V structures inferred from phase velocities. (b) Trade-off curves for the β_V and β_H structures in the regions 50 to 100 m.y. and >100 m.y. obtained from group velocities of Rayleigh and Love waves. The measures for the β_V and β_H structures are denoted by solid and dotted lines, respectively. For an explanation of the vertical arrows on the abscissa, see the caption in Fig. 2.

group velocities, is close to that for the region > 100 m.y. (Fig. 7(a)). This agreement holds except that the minimum velocity at a depth of 130 km in the large-scale LVZ for the former is lower by about 0.1 km/s than for the latter. One of the most important characteristics of the β_H structures derived from the phase and group velocities, both for the regions 50–100 m.y. and > 100 m.y., is the absence of the small-scale LVZ at a depth of 30 km. Accordingly, the large polarization anisotropy ($\beta_H > \beta_V$) is clearly found in the region near that depth. It is also noted that the β_H is significantly higher in the lithosphere than in the entire asthenosphere.

4.2 The vertically heterogeneous β_V structure and several plate models with uniform thickness

For the β_V profiles in the region > 100 m.y. (Figs. 1 and 7), the plate thicknesses estimated by several investigators have been indicated by arrows along with the model abbreviation: RA (Regan and Anderson, 1984), K (Kawasaki, 1986), and MI (Mitchell and Yu, 1980). The vertically heterogeneous β_V structure obtained in the present work reaches, as previously described, a maximum value at a depth of 70 km (Characteristic 2) and a minimum value at a depth of 130 km (Characteristic 3). These two characteristics give objective constraints on the determination of plate thickness.

Three β_V structures, representing the model obtained in the present study, along with the thin and thick models, are schematically illustrated in Fig. 8. Here, the lithosphere of the first model is subdivided into layers I, II, III, and IV. The subdivided layers appear to give useful indicators for comparison among the three plate models. The bottom of the thin plate model, denoted by RA and K for the region > 100 m.y., is located at the boundary between layers II and III. This boundary, however, corresponds to the upper parts of the highest β_V , so the plate thickness of 60 km estimated by the thin model seems to be underestimated.

The plate bottom of the thick model, denoted by MI for the region > 100 m.y., is located in the lower portion of layer IV, rather close to 130 km, where the velocity reaches a minimum. However, a plate thickness of 110 km estimated by the thick model cannot be determined uniquely, since layer IV is transitional with the velocity decreasing downward.

When dealing with a vertically heterogeneous plate structure, a proper definition of the plate bottom is needed to define the plate thickness. If the plate is simply defined as the location that is indicated by Characteristic 2 or 3, the thickness is estimated to be 70 or 130 km. If the plate bottom is tentatively defined as the mid-point between the depths indicating these characteristics, the thickness can be estimated as 100 km.

It should be noted that the differences in the β_V structures between the two thin models, denoted by RA and K, are remarkable for both the regions > 100 m.y. and 50 to 100 m.y. The RA model is relatively close to the b ($q=2$) or c ($q=3$) models shown in Figs. 1 and 4. This implies that the RA model is small in $\overline{SD}$ but has large $\overline{R}$ compared with the heterogeneous d ($q=4$) and e ($q=5$) models.

The elastic thickness (T_e), schematically indicated in Fig. 8, is too thin when compared with the seismic thickness (T_s). However, as previously revealed in Fig. 7(a), the β_H structures in the region > 100 m.y. are significantly different from the β_V structures. The β_H reaches its maximum in the uppermost parts of the lithosphere, decreasing

Fig. 8. Schematic representation of the profiles showing the vertically heterogeneous β_v structure in the region >100 m.y. obtained from the present study, together with those of the thin (A) and thick (B) plate models. The vertically heterogeneous β_v structure is divided into four layers: I, II, III, and IV. The elastic thickness (T_e) and the seismic thickness (T_s) are approximated by solid lines with arrows. The structures for the thin models RA (Regan and Anderson, 1984), K (Kawasaki, 1986), and thick models MI (Mitchell and Yu, 1980) are plotted for the regions >100 m.y. and 50 to 100 m.y., with the ages in parentheses after their model abbreviations. The shear wave velocities in the LVZ are denoted by V_c for the RA model, by V_a and V_b for the K model, and by V_d for the MI model near 130 km ($V_{a,b,c} > V_d$).

sharply with depth, especially below depths of 60 km. Hence, the plate thickness inferred from the β_H structures is markedly thinner than that from the β_v structures. There is a possibility that the β_H structure is highly correlated with the elastic thickness inferred from studies of the plate flexure.

4.3 The β_v structures in younger regions

In order to advance the study of a vertically heterogeneous lithospheric structure, several inversions were carried out for younger regions using the 8099-type starting model, in which only the β_v is determined. For this purpose, the data sets of the Rayleigh wave group velocities by Mitchell and Yu (1980) for the regions 50 to 100 m.y. and 20 to 50 m.y. along with data sets by Yoshii (1975) for the regions 50 to 90 m.y. and 20 to 50 m.y. were independently used. The results are shown in Figs. 9 and 10. The e model ($q=5$) for the region 50 to 90 m.y. in general resembles that for the region 50 to 100 m.y. (Fig. 9(a)), except for layer I near a depth of 30 km. In this isotropic inversion, layer I for the region 50 to 100 m.y., being slightly different from that obtained for the anisotropic inversion (Fig. 7(a)), is not likely to be well determined. It is notable that the c ($q=3$) and d ($q=4$) models for the region 50 to 100 m.y. (Fig. 9(a)) resemble

Fig. 9. (a) Shear wave velocity structures c, d, e, and f in the regions 50 to 90 m.y. and 50 to 100 m.y. obtained from Rayleigh wave group velocities, using the 8099-type starting model (dotted lines). (b) Trade-off curves. For the arrows, see the caption in Fig. 2.

the RA model for the same region given in Fig. 8. The trade-off curves (Fig. 9(b)) show that the values of $\overline{OC}$ and $\overline{XP}$ drastically change at $q=5$, and the resultant e model may be an unstable solution for this isotropic inversion.

The β_v structures for the region 20 to 50 m.y. are shown in Fig. 10(a), in which the structures for Cases 1 and 2 are obtained using the data sets by Mitchell and Yu (1980) and Yoshii (1975), respectively. The A and C models denote the simplified lithospheric structure while the B and D models represent the detailed structures. The four structures clearly show that the Characteristic 1 for the region >100 m.y. (the small-scale LVZ at a depth of 30 km) cannot be determined. If the plate bottom is defined as the mid-point between the depth indicating the maximum velocity in the lithosphere and the minimum velocity in the large-scale LVZ, the plate thickness can be estimated as 45 km. The values of $\overline{SD}$ and $\overline{OC}$ taken from the trade-off curves (Fig. 10(b)) for Case 2 are smaller than those for Case 1, due to the difference in the properties of the two data sets.

5. Discussion

The structure of the oceanic lithosphere in the Northwestern Pacific was investigated by Asada *et al.* (1983), by long-range explosion seismological experiments using ocean-bottom seismometers (OBS). The compressional wave velocity structure shows that the bottom of the oceanic lithosphere with a velocity of 8.60 km/s is located at a depth of 80 km, and a thin LVZ with a velocity of 8.40 km/s at depths between 80.10–120.00 km. The velocity increases from 8.60 to 8.80 km/s with depth between

Fig. 10. (a) Shear wave velocity structures in the region 20 to 50 m.y. using the 8099-type starting model (dotted lines). The models (A) and (B) are obtained from Case 1 (Rayleigh wave group velocities of Mitchell and Yu, 1980), and the models (C) and (D) from Case 2 (those of Yoshii, 1975). The starting model used by Mitchell and Yu (1980) and the final model obtained by Yoshii (1975) are denoted by chain lines. (b) Trade-off curves for the structures obtained from Case 1 and Case 2. The two arrows on the abscissa indicate that the model (B) for Case 1 is obtained at $q=3$, and the model (D) for Case 2 at $q=4$.

120.10–300.00 km. This velocity profile is in harmony with the β_v structure (Fig. 7(a)) in the region >100 m.y., inferred from the group velocity. Hence, if the bottom of the vertically heterogeneous lithosphere is defined by Characteristic 2, the plate thickness of 80 km inferred from the β_v structure agrees with that inferred from the OBS experiments. From OBS long-range explosion experiments, Nagumo *et al.* (1981) obtained a sub-Moho seismic profile composed of alternating high- and low-velocity

Fig. 11. Shear wave velocity structures in the regions 50 to 170 m.y. The structures (C) and (D) are obtained by anisotropic inversions using the PREM-type starting model and the others by isotropic inversions using the 8099-type starting model.

layers in the Mariana basin, with an age of >130 m.y. But the profile is different from the β_v structure mentioned above and may suggest a locality in the velocity distribution.

The β_v structures, previously obtained for the regions 50 to 170 m.y., are shown in Fig. 11. It is clear from this figure that the three characteristics for the region >100 m.y. almost always appear. If the heterogeneous plate (D) in the figure, corresponding to the Pacific plate having an age between 110–130 m.y. found near the Japan trench (Sclater *et al.*, 1981), is descending beneath the Japan arcs, Characteristic 1 would produce a difference in rigidity between layers I and II (see also Fig. 8). The solid parts in layer II are likely to form a fracture zone when the exerted tensile stress exceeds the strength of the layer. It seems that the fracture zone corresponds geometrically to the lower seismic plane of the double-planed seismic zone, observed in the regions near the Japan trench (e.g., Umino *et al.*, 1984; Suzuki *et al.*, 1983; Mizoue *et al.*, 1983). However, further study is needed to discuss it more precisely. It will be developed in a separate work.

The β_v structure in the region >100 m.y. obtained in the present work is generally similar to that in the region >110 m.y. obtained by Nishimura and Forsyth (1989), who used a different modelling philosophy and data, along with a robust inversion technique (Tarantola and Valette, 1982).

6. Conclusions

The structure and thickness of the Pacific plate for the region where the age is greater than 100 m.y. have been investigated by performing several anisotropic and isotropic inversions, making use of the trade-off curves among five quantities calculated for the choice of the optimal solution. The principal results obtained are summarized

as follows:

(1) The β_v structure of the lithosphere consists of four vertically heterogeneous layers and has three characteristics.

(2) Characteristic 1 is that the structure has a small-scale LVZ at a depth of 30 km in layer I.

(3) Characteristic 2 is that the structure reaches a maximum value at a depth of 70 km in layer III. Layer II shows a sharp increase of the velocity with depth between 35–60 km. Layer IV between 80–110 km is a transitional layer with the velocity decreasing downward.

(4) Characteristic 3 is that the structure has a minimum value at a depth of 130 km in the large-scale LVZ. The velocity increases with depth between 130–220 km.

(5) The vertically heterogeneous structure obtained, being very different from the simple thin and thick plate models, suggests that the bottom of the oceanic lithosphere has to be properly defined in order to precisely define the plate thickness.

(6) The β_H is greatest in the uppermost portion of the lithosphere and decreases downward to 150 km. Hence the β_H structure does not possess characteristics similar to Characteristics 1 and 2, and seems to be related to the very thin elastic thickness.

(7) There is a possibility that Characteristic 1 is a factor that may generate the double-planed seismic zone.

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