ATTENUATION OF LOVE AND RAYLEIGH WAVES ACROSS THE ATLANTIC

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Using the two-station-method, average fundamental mode surface-wave velocities and attenuation coefficients have been determined in the Atlantic Ocean. The average Rayleigh-wave attenuation coefficients decrease from $3.04 \times 10^{-4} \text{ km}^{-1}$ at a period of 15 sec to about $0.40 \times 10^{-4} \text{ km}^{-1}$ at the longer periods. The average Love-wave attenuation coefficients, in the period range 26 to 100 sec, vary from a value of about $2.20 \times 10^{-4} \text{ km}^{-1}$ at the shorter periods to a minimum value of $0.92 \times 10^{-4} \text{ km}^{-1}$ at the longest period.

Backus-Gilbert inversion theory applied to the attenuation data yields an average Q_{β}^{-1} model for the Atlantic that shows a clear and well-developed low- Q zone situated approximately between 40 and 220 km depth. The maximum Q_{β}^{-1} value ($\sim 13 \times 10^{-9}$) occurs at 100 km depth.

1. Introduction

Extensive use of seismic surface-wave velocities has provided good knowledge of the regional elastic properties in the Pacific Ocean (e.g., LEEDS *et al.*, 1974; KAUSEL *et al.*, 1974; FORSYTH, 1975 a, 1975 b; YOSHII, 1975; YU and MITCHELL, 1979; CANAS and UDIAS, 1980). The observed surface wave velocities obtained in these studies generally increase with increasing age and thickness of the oceanic lithosphere.

Fewer studies of attenuation of seismic surface waves have been carried out in the Pacific, especially due to the difficulty in obtaining good amplitude data. TSAI and AKI (1969), using a single event, determined attenuation of surface waves in the period range of 15 to 50 sec. MITCHELL *et al.* (1976) obtained average attenuation coefficients for Rayleigh- and Love-waves in a broad region of that ocean. MITCHELL (1976) determined internal friction models using observed attenuation coefficients (MITCHELL *et al.*, 1976), the best model being the one obtained from only Rayleigh-wave attenuation coefficients. CANAS and MITCHELL (1978) determined regionalized Rayleigh-wave attenuation coefficients and shear-wave internal friction for three regions of the Pacific plate, showing that the attenuation and internal friction are functions of the oceanic age, with the attenuation values being higher for younger oceanic regions. CANAS *et al.* (1980)

determined internal friction models for the East Pacific Rise and the Nazca plate. The results indicate that the internal friction under the East Pacific Rise and the Nazca plate is much higher than the corresponding one in the region 0–50 m.y. of the Pacific plate.

Fewer studies of surface wave velocities and attenuation have been carried out in the Atlantic Ocean. OSSING (1964), using group velocity dispersion curves from earthquakes in the Mid-Atlantic Ridge, deduced that the Mid-Atlantic Ridge had little influence on the dispersion of Rayleigh waves. Results obtained by BRAVO and UDIAS (1974) from Rayleigh wave group velocity observations agree with those of OSSING (1964). WEIDNER (1974) and GIRARDIN and JACOBY (1979), using phase and group velocities from paths nearly parallels to the Mid-Atlantic Ridge, found that the influence of the ridge is to decrease the observed velocities. Attenuation studies include that of BEN-MENACHEM (1965) who obtained attenuation values for Love and Rayleigh waves in the period range 50–330 sec for mixed paths across oceans and continents. ANDERSON *et al.* (1965) obtained specific quality factors of Rayleigh waves for a single path across the Atlantic. SOLOMON (1973), using shear-wave amplitudes, found evidence for a narrow low- Q zone under the Mid-Atlantic Ridge.

The purpose of the present study is to obtain representative averages of the Rayleigh- and Love-wave attenuation coefficients in the Atlantic Ocean. Inversion theory (BACKUS and GILBERT, 1967, 1968, 1970) in its stochastic form (DER *et al.*, 1970; JORDAN and FRANKLIN, 1971) applied to the Rayleigh-wave attenuation data yields an average internal friction model of shear waves for this ocean.

2. Data Analysis

The two-station-method has been applied to 28 events and 12 seismograph stations (Table 1, Fig. 1), situated on the American and European coastal regions and on islands in the Atlantic Ocean, to determine fundamental mode Rayleigh-wave attenuation coefficients for the Atlantic Ocean. Love wave attenuation coefficients have been obtained using 9 events and 7 seismograph stations (Table 1, Fig. 1).

Spectral amplitudes of the fundamental modes of Rayleigh and Love waves as a function of period and group velocity were obtained from the vertical component of Rayleigh waves and from the transverse component of Love waves; the transverse component being calculated using a coordinate transformation of the North-South and East-West components. All the seismograph stations belong to the WWSSN system, except two that belong to the Canadian network. Departures from expected amplitude responses of the WWSSN system can be checked by comparing daily calibration pulses with theoretical responses (MITCHELL and LANDISMAN, 1969). Magnification curves for the Canadian network can be obtained from the Seismological Bulletin of the Dominion Observatory of Ottawa (Canada).

Table 1. Earthquakes and stations used for velocity, attenuation and specific quality factor determinations.

Date	Location	Origin time	Stations used for Rayleigh waves	Stations used for Love waves
2 Nov 64	4.1 S, 76.9 W	6:50:58.2	PTO-TRN	
28 Nov 66	6.7 N, 82.6 W	7:32:53.6	PDA-SJG	
26 Jan 67	14.9 N, 93.0 W	16:10:33.7	BEC-PTO	BEC-PTO
19 Apr 68	42.6 S, 16.0 W	9:04:27.3	HAL-NAT	
15 Jun 68	5.6 N, 82.6 W	7:08:48.1	PTO-SJG, PDA-SJG	BEC-PTO
29 Dec 68	14.5 N, 92.4 W	17:36:29.9		BEC-PTO
7 Jul 68	5.8 S, 77.1 W	23:48:08.2	PDA-TRN	
4 Feb 69	8.2 S, 80.2 W	4:10:13.3	PDA-TRN	
4 Apr 69	24.4 N, 109.8 W	16:16:17.2	OGD-PTO	
5 May 69	36.0 N, 10.4 W	5:34:23.5	BEC-PDA	
24 Jul 69	11.9 S, 75.1 W	2:59:21.0	AKU-SJG, AKU-CAR TRN-VAL	
20 Oct 69	10.8 N, 72.5 W	13:11:37.0	SJG-VAL	
21 Jan 70	7.0 N, 104.3 W	17:51:38.5		BEC-PTO
14 Feb 70	9.9 S, 75.6 W	11:17:16.1	TRN-VAL, AKU-CAR	
1 Jun 70	5.9 N, 82.5 W	17:44:15.0	PDA-SJG, PTO-SJG	
16 Jun 70	5.4 N, 82.5 W	5:10:33.0	PDA-SJG, PTO-SJG	
17 Jun 70	15.8 S, 71.8 W	4:44:20.9	AKU-TRN	
30 Jun 70	9.2 S, 79.0 W	6:21:03.9	PTO-TRN	PTO-TRN
27 Aug 70	15.4 N, 95.6 W	19:44:42.0	BEC-PTO	
26 Oct 70	79.8 N, 2.7 W	20:53:32.4	AKU-NAT	
3 Dec 70	7.4 N, 76.1 W	4:59:53.4	SJG-VAL	
14 Dec 70	1.3 S, 80.9 W	7:32:52.5	SJG-VAL	
19 Sep 72	19.5 N, 70.1 W	1:36:52.4	STJ-AKU	
3 Apr 73	4.7 N, 75.6 W	13:54:01.8		SJG-VAL
24 Apr 73	5.2 N, 75.8 W	18:42:31.9		SJG-VAL
16 Sep 73	5.2 N, 78.0 W	4:52:50.9	SJG-VAL	SJG-VAL
3 Oct 73	27.6 N, 112.4 W	4:27:40.5	STJ-PTO	OGD-PDA
27 Apr 74	15.0 S, 72.2 W	6:01:47.3	AKU-TRN	
9 Jun 74	5.8 S, 81.0 W	14:16:03.7	PTO-TRN	
18 Mar 75	10.1 S, 75.3 W	1:10:53.6	TRN-VAL	
5 Apr 75	10.0 N, 69.8 W	9:34:36.6	AKU-SJG	
21 Nov 75	7.5 N, 77.6 W	1:15:00.8	PTO-SJG	

A constant interval of 1.0 sec, obtained applying a linear interpolation to the irregularly digitized seismograms, was chosen to carry out the multiple filter analysis (DZIEWONSKI *et al.*, 1969; HERRMANN, 1973). To avoid, as much as possible, scatter in the amplitude data, only events with departures of less than 4 azimuthal degrees from the common great-circle path with two seismograph stations have been used. To minimize the effects due to the waves crossing oceanic-continental margins, stations were chosen situated on islands and on coastal regions of the Atlantic. It was also tried to avoid problems due to the interference of the fundamental mode by the higher ones. This effect is much more

Fig. 1. Mercator projection map of the Atlantic, including the location of epicenters (x) and stations (●).

Fig. 2. Average observed Rayleigh and Love wave group velocities in the Atlantic Ocean. Vertical bars indicate standard deviations.

important for Love than for Rayleigh waves. DRAKE and BOLT (1980) have shown that there is more energy associated with the higher modes of Love waves than with the fundamental mode for periods equal to or less than 30 sec. Therefore, it may be possible that Love wave amplitude data at periods of around 30 sec may be contaminated by higher mode energy. The Rayleigh and Love observed group velocities (Fig. 2) are oceanic in character, being close to the 8-1-2 and 8-3-2 oceanic models of SAITO and TAKEUCHI (1966) respectively.

3. Average Attenuation Coefficients

The attenuation coefficients of surface waves, using the two-station method, are given by,

$$\gamma(\omega) = \left\{ \ln \frac{A_1(\omega, r_1) I_2(\omega) (\sin \Delta_1)^{1/2}}{A_2(\omega, r_2) I_1(\omega) (\sin \Delta_2)^{1/2}} \right\} / (r_2 - r_1),$$

where $\gamma(\omega)$ is the attenuation coefficient as a function of angular frequency ω . A_1 and A_2 are the spectral amplitudes corresponding to the stations situated at shorter and longer distances (r_1, r_2). I_1 and I_2 are the instrumental responses of the seismographs and $(\sin \Delta_1)^{1/2}$ and $(\sin \Delta_2)^{1/2}$ correct for geometrical spreading of the energy.

Table 2. Rayleigh- and Love-wave group velocities, attenuation coefficients, and specific quality factors for the Atlantic Ocean.

T	U_R (km/sec)	$\gamma_R \times (10^{-1} \text{ km}^{-1})$	Q_R	U_L (km/sec)	$\gamma_L \times (10^{-1} \text{ km}^{-1})$	Q_L
15	3.307 ± 0.235	3.04 ± 1.26	208			
16	3.358 0.212	2.63 1.01	222			
17	3.384 0.188	2.27 0.93	240			
18	3.494 0.162	2.13 1.07	233			
19	3.539 0.194	1.90 1.12	245			
20	3.629 0.161	1.83 1.13	236			
22	3.695 0.144	1.75 1.00	220			
24	3.752 0.125	1.77 0.98	196			
26	3.810 0.113	1.64 1.00	193	4.438 ± 0.121	2.21 ± 1.78	123
28	3.853 0.095	1.58 0.91	183	4.446 0.106	2.18 1.61	116
30	3.883 0.090	1.60 0.79	168	4.450 0.103	2.26 1.66	104
35	3.951 0.100	1.70 0.81	133	4.462 0.099	1.98 1.47	102
40	3.962 0.077	1.56 0.82	127	4.485 0.089	1.71 0.94	102
45	3.952 0.067	1.39 0.81	126	4.502 0.086	1.65 1.03	94
50	3.964 0.086	1.36 0.83	115	4.528 0.086	1.43 0.96	97
60	3.912 0.086	1.24 0.54	107	4.539 0.082	1.21 0.98	95
70	3.856 0.060	1.01 0.29	114	4.540 0.073	1.43 0.91	69
80	3.830 0.086	0.94 0.27	108	4.575 0.074	1.34 1.13	64
90	3.808 0.058	0.58 0.30	156	4.580 0.065	1.24 1.03	62
100	3.766 0.090	0.38 0.48	218	4.584 0.072	0.92 0.52	75
110	3.711 0.176	0.43 0.08	176

Fig. 3. Average observed Rayleigh- and Love-wave attenuation coefficients in the Atlantic Ocean. Vertical bars indicate standard deviations.

Table 2 lists the average Atlantic attenuation coefficients for Rayleigh and Love waves together with the observed inter-station group velocities and corresponding specific quality factors of Rayleigh and Love waves (Q_R , Q_L). Q values were determined using the expression $Q = \pi/\gamma UT$, where U is the group velocity as a function of the period T . Figure 3 presents the average Rayleigh- and Love-wave attenuation coefficients as a function of the period together with their standard deviations. It can be observed (Fig. 3), that the attenuation coefficients decrease with decreasing frequency.

4. Average Internal Friction Model

Using inversion theory (BACKUS and GILBERT, 1967, 1968, 1970) in its stochastic form (DER *et al.*, 1970; JORDAN and FRANKLIN, 1971) as applied by MITCHELL (1976), CANAS and MITCHELL (1978), CANAS *et al.* (1980), and CANAS and CORREIG (1981), Rayleigh-wave attenuation coefficients have been inverted to obtain an average Q_β^{-1} model for the Atlantic Ocean. Love-wave attenuation coefficients have not been inverted due to the lack of data for periods less than 26 sec, and due also to the possible contamination of the shorter periods by higher mode energy. Rayleigh-wave data, used to determine the Q_β^{-1} model, were obtained from 34 paths (Table 1) across the Atlantic and for a period range of 15 to 110 sec, therefore the Q_β^{-1} model constructed using the Rayleigh data can be considered as a representative one for the Atlantic Ocean.

To invert the Rayleigh wave attenuation coefficients, the approximation of ANDERSON *et al.* (1965) was used. In the approximations it is assumed that Q_β^{-1} is independent of frequency and that $Q_\beta^{-1} = (4/3)(\beta/\alpha)^2 Q_\alpha^{-1}$, with α and β being compressional and shear-wave velocities, and Q_α^{-1} the internal friction of compressional waves. The frequency-independent approach is a reasonable one for the period range used in this study, since only frequencies higher than 1 Hz are affected by the frequency-dependent approach (KANAMORI and ANDERSON, 1977; MINSTER, 1978; SIPKIN and JORDAN, 1979; ANDERSON and MINSTER, 1980).

Fig. 4. Q_{β}^{-1} model and standard deviations (horizontal bars) for the Atlantic obtained from the average Rayleigh-wave attenuation coefficients of Fig. 3 and Table 2.

The Earth model used to compute the partial derivatives for the inversion is the 8-3-2 model of SAITO and TAKEUCHI (1966).

Figure 4 shows the average Q_{β}^{-1} model for the Atlantic Ocean. Major features of this model are: (1) A clear low- Q region is situated between depths of around 40 and 220 km, (2) The maximum Q_{β}^{-1} value ($\sim 13 \times 10^{-3}$) occurs at 100 km depth, and (3) The resolving kernels calculated at several selected depths (Fig. 5), corresponding to the model in Fig. 4, become broader with increasing depth, indicating that the resolution is good at shallow depths, but becomes poorer at greater depths. Due to the poor resolution obtained, especially for depths greater than 200 km, Q_{β}^{-1} values at these depths must be interpreted only as tentative. Hopefully, studies of the attenuation for higher mode Rayleigh waves, presently in progress, may provide representative Q_{β}^{-1} values for the poor resolved part of the Atlantic model (Fig. 4).

Figure 6 presents the theoretical attenuation coefficients obtained from the Q_{β}^{-1} model in Fig. 4, together with the observed Rayleigh-wave attenuation coefficients. The agreement between observed and theoretical coefficients is a

Fig. 5. Resolving kernels for the model of Fig. 4. The depth which each one is calculated is indicated by the vertical dash below each kernel.

Fig. 6. Comparison between observed Rayleigh-wave attenuation coefficients ($\bullet$), and theoretical ones (solid line) corresponding to the Q_β^{-1} model of Fig. 4. The dotted line represents the observed Rayleigh-wave attenuation coefficients for the Pacific (MITCHELL *et al.*, 1976).

reasonable one, indicating that the average internal friction model adequately explains the observed attenuation in the Atlantic Ocean.

Fig. 7. Comparison between the Q_{β}^{-1} model for the Atlantic Ocean and the one obtained for the Pacific (MITCHELL, 1976).

5. Comparison with Pacific Ocean Internal Friction

MITCHELL's (1976) work includes an average Q_{β}^{-1} model obtained from Rayleigh-wave attenuation coefficients (Fig. 6) corresponding to different paths that cover most of the Pacific with several of these paths crossing the East Pacific Rise. Since all the paths used in this study cross the Mid-Atlantic Ridge, the comparison will be done with MITCHELL's (1976) model.

Figure 7 shows the comparison between the Q_{β}^{-1} models corresponding to the Atlantic and Pacific Oceans. Principle features are:

- (1) Decrease in Q_{β} values at depths near 40 km in the Atlantic model, and near 60 km in the Pacific model.
- (2) The maximum Q_{β}^{-1} value being $\sim 13 \times 10^{-3}$ in the Atlantic model at ~ 100 km depth, and $\sim 13 \times 10^{-3}$ in the Pacific model at ~ 130 km depth.
- (3) Both the models show that, at depths of around 200–240 km, the value of Q_{β}^{-1} have approximately the same values as those in the lithosphere. This result, although a tentative one because of the broad resolving kernels that the models exhibit at these depths (Fig. 5; Fig. 6 in MITCHELL, 1976), provides an estimation at which the bottom of the low- Q zone may occur.

More recent studies in the Pacific (CANAS and MITCHELL, 1978; CANAS *et al.*, 1980; CANAS and CORREIG, 1981) have shown that the Q_{β}^{-1} models are a function of the oceanic age. Since the Atlantic average model obtained in this study is

similar to the MITCHELL's (1976) model, it may indicate that the distribution of the low- Q zones under both the oceans may be approximately the same.

6. Conclusions

Average Rayleigh-wave attenuation coefficients for the Atlantic Ocean decrease from values of $3.04 \times 10^{-4} \text{ km}^{-1}$ at 15 sec to about $0.4 \times 10^{-4} \text{ km}^{-1}$ at longer periods. Love-wave attenuation coefficients range from a maximum of $2.26 \times 10^{-4} \text{ km}^{-1}$ to a minimum value of $0.92 \times 10^{-4} \text{ km}^{-1}$ in the period range of 26 to 100 sec.

Inversion theory applied to the Rayleigh-wave attenuation coefficients indicates that a clear low- Q zone exists in the upper mantle under the Atlantic Ocean, with the top and bottom of the low- Q zone situated at depths near 40 and 220 km, respectively.

Comparison between Atlantic and Pacific results indicates that similar low- Q distributions may be expected in both the oceans.

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REFERENCES

- ANDERSON, D. L. and J. B. MINSTER, The physics of creep and attenuation in the mantle (preprint), 1980.
- ANDERSON, D. L., A. BEN-MENACHEM, and C. B. ARCHAMBEAU, Attenuation of seismic energy in the upper mantle, *J. Geophys. Res.*, **70**, 1441-1448, 1965.
- BACKUS, G. E. and F. GILBERT, Numerical applications of a formalism for geophysical inverse problems, *Geophys. J. R. Astron. Soc.*, **13**, 247-276, 1967.
- BACKUS, G. E. and F. GILBERT, The resolving power of gross Earth data, *Geophys. J. R. Astron. Soc.*, **16**, 169-205, 1968.
- BACKUS, G. E. and F. GILBERT, Uniqueness in the inversion of inaccurate gross Earth data, *Philos. Trans. R. Soc.*, **A266**, 123-192, 1970.
- BEN-MENACHEM, A., Observed attenuation and Q values of seismic surface waves in the upper mantle, *J. Geophys. Res.*, **70**, 4641-4651, 1965.
- BRAVO, C. and A. UDÍAS, Rayleigh wave group velocity dispersion in North Atlantic region, *Geophys. J. R. Astron. Soc.*, **37**, 297-304, 1974.
- CANAS, J. A. and A. M. CORREIG, Modelo de fricción interna de las ondas de cizalla para las placas Nazca-Cocos, *Geofísica Internacional*, 1981 (in press).
- CANAS, J. A. and B. J. MITCHELL, Lateral variation of surface-wave anelastic attenuation across the Pacific, *Bull. Seismol. Soc. Am.*, **68**, 1637-1650, 1978.
- CANAS, J. A. and A. UDÍAS, Variación lateral de las velocidades de las ondas de cizalla en función de la edad del suelo oceánico del Pacífico, *Anal. de Fis. de la R. S. E. de Fis. y Quím.*, **76**, 278-284, 1980.
- CANAS, J. A., B. J. MITCHELL, and A. M. CORREIG, Q_p^{-1} models for the East Pacific Rise and the Nazca plate, in *Mechanisms of Continental Drift and Plate Tectonics*, ed. P. A. Davies and S. K. Runcorn, pp. 123-133, Academic Press, London, 1980.

- DER, Z. A., R. MASSE, and M. LANDISMAN, Effects of observational errors on the resolution of surface waves at intermediate distances, *J. Geophys. Res.*, **75**, 3399–3409, 1970.
- DRAKE, L. A. and B. A. BOLT, Love waves normally incident at a continental boundary, *Bull. Seismol. Soc. Am.*, **70**, 1103–1123, 1980.
- DZIEWONSKI, A., S. BLOCH, and M. LANDISMAN, A technique for the analysis of transient seismic signals, *Bull. Seismol. Soc. Am.*, **59**, 427–444, 1969.
- FORSYTH, D. W., A new method for the analysis of multi-mode surface-wave dispersion: Application to Love wave propagation in the east Pacific, *Bull. Seismol. Soc. Am.*, **65**, 323–342, 1975 a.
- FORSYTH, D. W., The early structural evolution and anisotropy of the oceanic upper mantle, *Geophys. J. R. Astron. Soc.*, **43**, 103–162, 1975 b.
- GIRARDIN, N. and W. R. JACOBY, Rayleigh wave dispersion along Reykjanes Ridge, *Tectonophysics*, **55**, 155–171, 1979.
- HERRMANN, R. B., Some aspects of band-pass filtering of surface waves, *Bull. Seismol. Soc. Am.*, **63**, 663–671, 1973.
- JORDAN, T. H. and J. N. FRANKLIN, Optimal solutions to a linear inverse problem in geophysics, *Proc. Nat. Acad. Sci. Am.*, **68**, 291–293, 1971.
- KANAMORI, H. and D. L. ANDERSON, Importance of physical dispersion in surface wave and free oscillation problems; Review, *Rev. Geophys. Space Phys.*, **15**, 105–112, 1977.
- KAUSEL, E. G., A. R. LEEDS, and L. KNOPOFF, Variations of Rayleigh wave phase velocities across the Pacific Ocean, *Science*, **186**, 139–141, 1974.
- LEEDS, A. R., L. KNOPOFF and E. G. KAUSEL, Variations of upper mantle structure under the Pacific Ocean, *Science*, **186**, 141–143, 1974.
- MINSTER, J. B., Transient and impulse responses of a one-dimensional linearly attenuating medium-II. A parametric study, *Geophys. J. R. Astron. Soc.*, **52**, 503–524, 1978.
- MITCHELL, B. J., Anelasticity of the crust and upper mantle beneath the Pacific Ocean from the inversion of observed surface wave attenuation, *Geophys. J. R. Astron. Soc.*, **46**, 521–533, 1976.
- MITCHELL, B. J. and M. LANDISMAN, Electromagnetic seismograph constants by least-squares inversion, *Bull. Seismol. Soc. Am.*, **59**, 1335–1348, 1969.
- MITCHELL, B. J., L. W. LEITE, Y. K. YU, and R. B. HERRMANN, Attenuation of Love and Rayleigh waves across the Pacific at periods between 15 and 110 seconds, *Bull. Seismol. Soc. Am.*, **66**, 1189–1201, 1976.
- OSSING, H. A., Dispersion of Rayleigh waves originating in the Mid-Atlantic Ridge, *Bull. Seismol. Soc. Am.*, **54**, 1137–1196, 1964.
- SAITO, M. and H. TAKEUCHI, Surface waves across the Pacific, *Bull. Seismol. Soc. Am.*, **56**, 1067–1091, 1966.
- SIPKIN, S. and T. JORDAN, Frequency dependence of Q_{RES} , *Bull. Seismol. Soc. Am.*, **69**, 1055–1079, 1979.
- SOLOMON, S. C., Shear wave attenuation and melting beneath the Mid-Atlantic ridge, *J. Geophys. Res.*, **78**, 6044–6059, 1973.
- TSAI, Y. B. and K. AKI, Simultaneous determination of the seismic moment and attenuation of seismic surface waves, *Bull. Seismol. Soc. Am.*, **59**, 275–287, 1969.
- WEDNER, D. J., Rayleigh wave phase velocities in the Atlantic Ocean, *Geophys. J. R. Astron. Soc.*, **36**, 105–139, 1974.
- YOSHII, T., Regionality of group velocities of Rayleigh waves in the Pacific and thickening of the plate, *Earth Planet. Sci. Lett.*, **25**, 305–312, 1975.
- YU, G. K. and B. J. MITCHELL, Regionalized shear velocity models of the Pacific upper mantle from observed Love and Rayleigh wave dispersion, *Geophys. J. R. Astron. Soc.*, **57**, 311–341, 1979.