BULL. AUSTRAL. MATH. SOC. 86A15
VOL. 17 (1977), 309-314.

Rayleigh wave group velocities and attenuation coefficients

Joseph M. Mills, Jr

The analysis of group velocities and attenuation coefficients for Rayleigh waves in the period range 50 to 600 seconds provides information on the average elastic and anelastic properties of the earth. The Direct Filtering Method has been developed which provides estimates of group arrival times and spectral amplitudes from gaussian filtered seismograms. Two estimates of the standard error of the group arrival time are based on the regression statistics of parabolas which are fitted to each envelope maximum. One estimate reflects the quality of the fit to the maximum while the other is determined by the half amplitude width of the maximum. Estimates of the period at the envelope maximum are also available in order to estimate the purity of the filtered signal at the envelope maximum. Estimates of group velocities and spectral amplitudes determined by the Direct Filtering Method are comparable to those provided by other multiple filter analyses, but the Direct Filtering Method provides objective estimates of the standard errors of group velocity measurements. Spectral amplitudes and attenuation coefficients determined from seismograms filtered with narrow band-pass gaussian filters do not require a correction for geometric spreading if filters are sufficiently sharp.

The Direct Filtering Method has been applied to seismograms of 4 Kurile Island earthquakes ranging in magnitude from 6.6 to 8.3 . These events are all located within a small region so that Rayleigh waves from all events traverse the same great circle paths. All events have focal mechanism solutions which show that the fault motion is predominantly dip-slip.

Received 26 August 1977. Thesis submitted to the Australian National University, April 1977. Degree approved, August 1977. Supervisor: Professor A.L. Hales.

https://doi.org/10.1017/S0004972700010558 Published online by Cambridge University Press

Great circle group velocities have been determined for the surface wave magnitude 8.3 event by averaging of group velocities of Rayleigh phases arriving after R_3 . Errors in the great circle group velocities caused by averaging group velocities of arrivals later than R_3 are much smaller than the standard errors of the estimates for individual Rayleigh phases. These group velocities extend from 100 to 600 seconds in period. Kanamori's [8] estimates for the same great circle paths are in good agreement with these estimates. Attenuation coefficients have also been determined from spectral amplitude ratios estimated by 2 methods:

1. from the rate of decay of envelope maxima of gaussian filtered Rayleigh phases, and
2. from the rate of decay of spectral amplitudes taken as the sum of products of a pure sine wave with segments of each Rayleigh phase within a group velocity window.

Both methods provide attenuation coefficients which agree well with attenuation coefficients derived from Kanamori's [8] group velocities and Q's , but those derived from the envelopes of the filtered seismograms show less scatter.

Group velocities and spectral amplitudes determined for the smaller 3 Kurile Islands earthquakes have extended the range of accurate measurements to periods as short as 50 seconds. These measurements, taken with those for the larger event, provide averages for group velocities and attenuation coefficients for 9 great circle paths. These 9 paths are evenly distributed in azimuth at the source. The averaging of the path group velocities and attenuation coefficients over all paths provides a reliable estimate of global average group velocities for periods between 50 and 600 seconds and attenuation coefficients for periods between 50 and 450 seconds. Global average phase velocities, determined by integration of the global average group velocities, agree well with oceanic phase velocities determined by Weidner [12] for periods between 50 and 120 seconds. The global average group velocities are in good agreement with oceanic velocities determined by Forsyth [4] and Landisman, Dziewonski, and Satô [9]. These group velocities are, however, much lower than those predicted by several recent earth models.

https://doi.org/10.1017/S0004972700010558 Published online by Cambridge University Press

Equivalent spheroidal oscillation periods derived from the global average phase velocities are also progressively shorter in period, for periods less than 150 seconds, than fundamental spheroidal mode periods calculated for model *QM*2 (Hart, Anderson, and Kanamori [5]) which incorporates corrections for anelastic dispersion for free oscillation periods. In the future, data sets for average earth models should include equivalent free oscillation periods or surface wave phase or group velocities in the period range 50 to 150 seconds since body wave travel times together with free oscillation data for periods in excess of 140 seconds do not adequately constrain the upper mantle structure of such models.

Q_R^{-1} which are calculated from global average attenuation coefficients and group velocities are similar to the largest Q_R^{-1} computed from fundamental mode spheroidal oscillations by Jobert and Roult [7] and are lower than those predicted by model *MM*8 of Anderson, Ben-Menahem, and Archambeau [1]. Q_R^{-1} from Ben-Menahem's [2] measurements lie between the global average Q_R^{-1} and those predicted by model *MM*8 for periods between 50 and 100 seconds. In this period range, attenuation coefficients of Mitchell, Leite, Yu, and Herrmann [11] for Pacific Ocean paths and by Mitchell [10] and Hermann and Mitchell [6] for the central United States are all within a factor of 2 of the global average attenuation coefficients. From the agreement of the global average attenuation coefficients and group velocities with other long and short period measurements it is concluded that these measurements are estimates of global average properties.

The global average group velocities and attenuation coefficients provide a basis for modelling the shear velocity and attenuation structure of the average earth. Shear velocity models for the upper mantle which fit 50 to 300 second global average group velocities within one standard deviation require the presence of a low velocity zone. Models have been produced from the global average group velocities alone which have the top of the low velocity zone at depths of both 70 and 100 km , so that the average thickness of the lithosphere (taken as the depth to the top of the

https://doi.org/10.1017/S0004972700010558 Published online by Cambridge University Press

low velocity zone) cannot be determined with precision. Global average models for shear wave attenuation $\left(Q_\beta^{-1}\right)$ indicate that a zone of high attenuation is coincident with the low velocity zone. Models for attenuation which have lithospheric thicknesses of 70 km place the highest attenuation layer in the lower half of the low velocity zone, which indicates that on the average the lithosphere is thicker than 70 km. Average Q_β for the lithosphere, low-velocity zone, and sub-low velocity layer (asthenosphere) are approximately 200, 85 to 110, and 170 to 200, respectively. Although losses caused by elastic scattering have not been taken into account, they are small compared to anelastic attenuation in the 50 to 300 second period range.

Pure path averages for group velocities and specific attenuation have been calculated from path averages and from individual observations for 2 regionalization schemes, one original to this study and the other devised by Wu [13]. Both regionalization schemes are based on 4 upper mantle provinces: continent, ocean basin, island arc, and mid-ocean ridge. Pure path group velocities and specific attenuation have also been calculated for combinations of regions, namely, ocean basin plus mid-ocean ridge and continent plus island arc provinces. Several of these regionalizations have provided well separated regional group velocities for such composite regions. Results of regionalizations using Wu's [13] choice of regions have given pure path group velocities for continent, ocean basin, continent plus island arc, and ocean basin plus mid-ocean ridge provinces which are in good agreement with group velocity dispersion observed at periods shorter than 100 seconds and which also agree with the pure path group velocities derived from great circle measurements of Dziewonski [3] and Wu [13]. Dziewonski's pure path group velocities for shields lie at most less than one standard error above continental group velocities derived in this study, while his oceanic group velocities lie slightly more than one standard error below ocean basin plus mid-ocean ridge province group velocities. Shear velocity models derived from pure path group velocities for pure and combined regions indicate that low velocity zones are required beneath the oceans, but are not required beneath the continents, although 3 and 4 region separations produce a range of models which include low velocity zones at depths greater than 200 km. A regional study of group

https://doi.org/10.1017/S0004972700010558 Published online by Cambridge University Press

velocity dispersion and thrust faulting in eastern Australia shows that a low velocity zone is required at depths greater than 140 km and probably greater than 180 km in order to fit observed fundamental and higher mode Love and Rayleigh waves and *ScS* travel times.

Specific attenuation for shear waves, Q_β^{-1} , determined from path average group velocities and attenuation coefficients has also been regionalized successfully for 2 and 3 region combinations. The resulting pure path specific attenuation for continents is much lower than that for ocean basins and ocean basin plus mid-ocean ridge provinces. Island arc and mid-ocean ridge provinces both show higher attenuation than ocean basins for periods shorter than 100 seconds for the 4 region separation, but results deteriorate at longer periods due to multipathing and defocusing. Models derived for ocean basin plus mid-ocean ridge province specific attenuation show that the sub-oceanic mantle has an average Q_β of about 80 to 100 for the upper 200 km . The results of the attenuation studies show that with additional data it will be possible to obtain significantly higher precision estimates of the differences between different types of upper mantle provinces.

References

[1] Don L. Anderson, Ari Ben-Menahem, and C.B. Archambeau, "Attenuation of seismic energy in the upper mantle", *J. Geophys. Res.* 70 (1965), 1441-1448.

[2] Ari Ben-Menahem, "Observed attenuation and *Q* values of seismic surface waves in the upper mantle", *J. Geophys. Res.* 70 (1965), 4641-4651.

[3] Adam M. Dziewonski, "On regional differences in dispersion of mantle Rayleigh waves", *Geophys. J. Roy. Astronom. Soc.* 22 (1971), 289-325.

[4] Donald W. Forsyth, "The early structural evolution and anisotropy of the oceanic upper mantle", *Geophys. J. Roy. Astronom. Soc.* 43 (1975), 103-162.

https://doi.org/10.1017/S0004972700010558 Published online by Cambridge University Press

[5] R.S. Hart, D.L. Anderson and H. Kanamori, "The effect of attenuation on gross earth models", submitted.

[6] Robert B. Herrmann and Brian J. Mitchell, "Statistical analysis and interpretation of surface-wave anelastic attenuation data for the stable interior of North America", *Bull. Seis. Soc. Amer.* **65** (1975), 1115-1128.

[7] N. Jobert and G. Roult, "Periods and damping of free oscillations observed in France after sixteen earthquakes", *Geophys. J. Roy. Astronom. Soc.* **45** (1976), 155-176.

[8] Hiroo Kanamori, "Velocity and Q of mantle waves", *Phys. Earth. Planet Int.* **2** (1969), 259-275.

[9] M. Landisman, A. Dziewonski and Y. Satô, "Recent improvements in the analysis of surface wave observations", *Geophys. J. Roy. Astronom. Soc.* **17** (1969), 369-403.

[10] Brian J. Mitchell, "Radiation and attenuation of Rayleigh waves from the southeastern Missouri earthquake of October 21, 1965", *J. Geophys. Res.* **78** (1973), 886-899.

[11] B.J. Mitchell, L.W.B. 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. Seis. Soc. Amer.* **66** (1976), 1189-1201.

[12] Donald J. Weidner, "Rayleigh wave phase velocities in the Atlantic Ocean", *Geophys. J. Roy. Astronom. Soc.* **36** (1974), 105-139.

[13] F.T. Wu, "Mantle Rayleigh wave dispersion and tectonic provinces", *J. Geophys. Res.* **77** (1972), 6445-6453.

https://doi.org/10.1017/S0004972700010558 Published online by Cambridge University Press