Reports

Regional Differences in the Phase Velocity and the Quality Factor Q of Mantle Rayleigh Waves

Abstract. *The phase velocity and the quality factor (Q) of mantle Rayleigh waves from the great Kurile Islands earthquake of 1963 have a close azimuthal correlation with each other and differ considerably among different paths. Serious error may be introduced in the interpretation of observed regionality in phase velocity if regional differences in Q are ignored.*

The earth is not a perfectly elastic body. In an anelastic earth, the intrinsic seismic velocities are dependent on frequency (*1*). The attenuation of seismic waves is usually represented by the quality factor, Q. Assuming a nearly constant Q over the seismic frequency band and solving Boltzmann's aftereffect equation, Liu *et al.* (*2*) determined that the fractional change in the phase velocity due to Q is proportional to Q^{-1} rather than to Q^{-2} and that the Q of surface waves must be taken into account in a simultaneous inversion of surface wave and body wave data. Since the anelastic properties of the earth are probably determined by thermally activated processes (*3*) and are strongly dependent on temperature, inherent in the Q of a seismic wave there is potentially much information about the thermal state of the earth's interior.

Although numerous determinations (*4–6*) of the Q of surface waves and free oscillations have been made, there are significant differences in these values. There are several reasons for the discrepancies. First, the path coverage has not been sufficient to establish a regionality of Q. Second, the theoretical treatment for the lateral heterogeneities of seismic wave velocity, which cause refraction, reflection, and conversion of surface waves (*7*), has not been developed. I report here large regional differences in the surface wave Q which is closely correlated with a regionality in phase velocity.

The observational material consists of digitized records of 33 vertical long-period seismograms from the World-Wide Standard Seismograph Network (Fig. 1). I analyzed the long-period Rayleigh waves that were generated by the Kurile Islands earthquake of 13 October 1963 (surface wave magnitude = 8.3). The path coverage is more uniform than those of any earlier studies. The seismograms were "group velocity–windowed" with fixed group velocities of 3.45 and 3.9 km/sec.

The propagation of Rayleigh waves along a great circle path can be formulated as

$$R_{2n+1} = W * R_{2n-1} \quad (1a)$$

or

$$R_{2n+2} = W * R_{2n} \quad (1b)$$

where R_{2n+1} describes the Rayleigh wave that propagates in the direction of the minor arc and travels n times around the world, R_{2n+2} denotes the wave that travels in the direction of the major arc, and W is the unknown transfer function of one circuit around the world. I used a new technique of time series analysis (*8*) to calculate the phase velocity and Q. The procedure consists of (i) the deter-

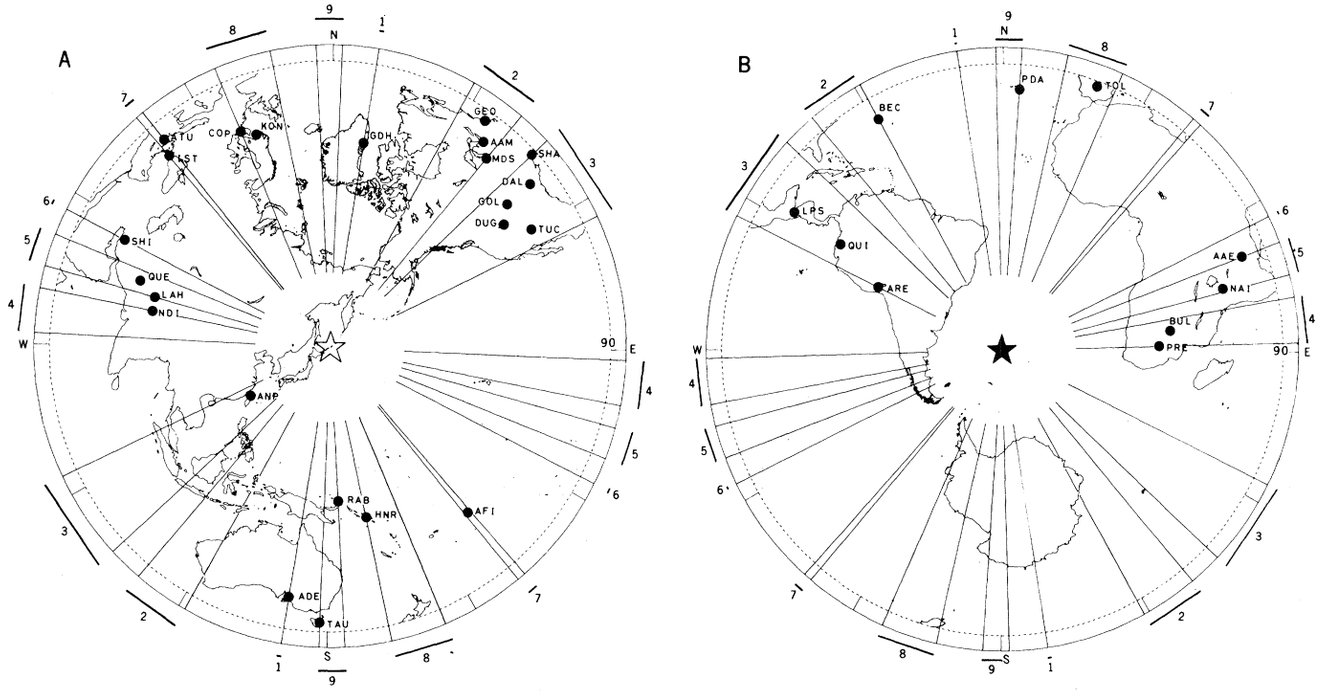

Fig. 1. Station locations and azimuthal windows. Equidistant azimuthal projections of two hemispheres of the earth (A and B) are shown with the Kurile Islands earthquake of 13 October 1963 located at one pole. The source and its antipode are indicated by the closed and open stars, respectively. Circles indicate the station locations. Nine azimuthal windows are shown in both hemispheres and identified by numerals.

0036-8075/78/0623-1379$00.50/0

mination of the optimum W in Wiener's sense based on the use of the Levinson algorithm (*8*, *9*) and (ii) calculation of the phase velocity and Q through the Fourier transformation of the optimum W.

Since the existence of a regionality in phase velocity has been relatively well established, all stations were grouped into nine azimuthal windows according to similarity of phase velocity. I then calculated the average phase velocity and Q for each window in order to see if there was any azimuthal correlation between them. I describe below the results for three typical windows (windows 2, 5, and 8) (*10*).

Window 2 has the highest phase velocities and Q of all the windows. This window contains long paths over the Canadian and Brazilian shields (Fig. 1). The average phase velocity is systematically higher than that of model 5.08M (C5.08M) (*6*) in the period range from 150 to 300 seconds, the velocity difference being 0.011 km/sec at 200 seconds. The Q for this window is higher than that of model MM8 (*5*) in the period range between 150 and 300 seconds. The average Q at 200 seconds is 190, whereas the Q of MM8 is 170. This high Q indicates that in the upper mantle under the shield region seismic waves suffer relatively small attenuation and supports the idea that temperatures are relatively low under the shields. Window 5 has the lowest phase velocities and Q of all the windows. It contains long paths over such tectonic regions as the Himalayas and the Rift Valley of Africa. The average phase velocity at 200 seconds is 0.016 km/sec lower than that of C5.08M. The average Q at the same period is 150, whereas the Q of MM8 is 170. This low Q indicates that in the upper mantle under tectonic regions seismic wave attenuation is large and suggests that the temperatures are relatively high under tectonic regions. The average phase velocity and Q for window 8 have values intermediate between those of windows 2 and 5. The average phase velocity at 200 seconds is only 0.002 km/sec lower than that of C5.08M. The average Q at the same period is 170, equal to the Q of MM8.

The deviations of the observed phase velocity from C5.08M and the observed Q are plotted as a function of azimuth reduced to the 180° range in order to clarify the path dependence of the phase velocity and Q (Fig. 2). It is apparent that both the phase velocity and Q are azimuthally dependent and that their azimuthal dependences are closely correlated with each other.

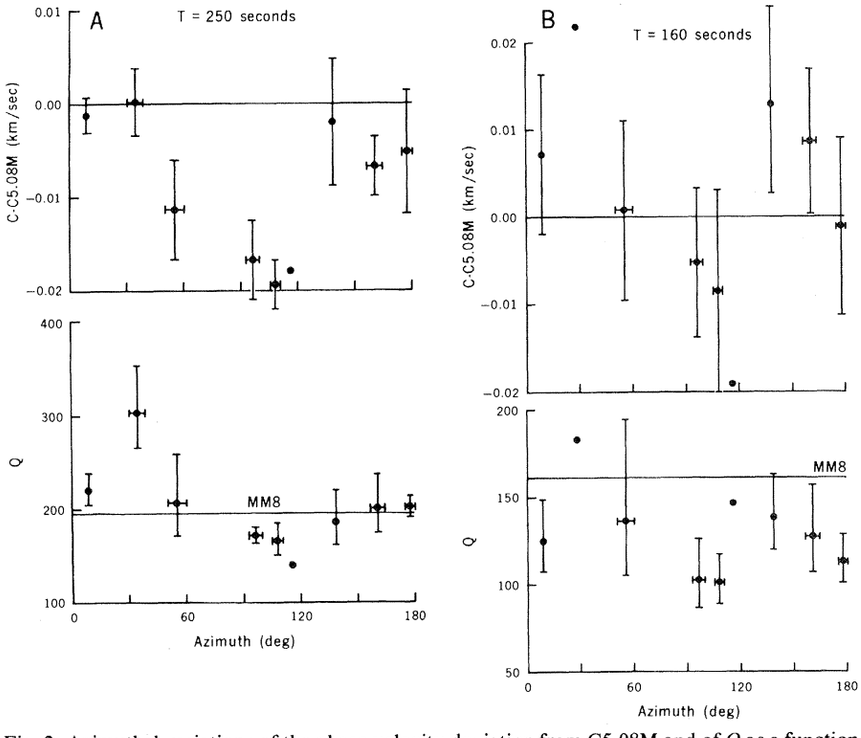

Fig. 2. Azimuthal variations of the phase velocity deviation from C5.08M and of Q as a function of azimuth reduced to the 180° range: (A) at 250 seconds; (B) at 160 seconds. Standard deviations of phase velocity and Q are indicated by vertical bars, and standard deviations of the station azimuth are indicated by horizontal bars. When only one observation is available, the bars are not shown. There exist regional differences in both phase velocities and Q, and the azimuthal variations of Q are closely related with those of the phase velocities. Values of Q calculated for MM8 are shown for comparison.

This correlation between the phase velocity and Q is seemingly reasonable, but some caution is required to interpret it. According to Liu *et al.* (*2*), the correction of phase velocity for attenuation is expressed as

$$\Delta C = \frac{C}{\pi Q}\,\ell\mathrm{n}\,(T) \qquad (2)$$

where T is the period and C is the phase velocity. The reference period is equal to 1 second. If we correct the observed phase velocities by means of Eq. 2, using the observed Q values, we find that there are not any large regional differences in phase velocity. As an example, the deviations of the phase velocities, corrected for attenuation, from C5.08M are 0.060, 0.061, and 0.064 km/sec at 160 seconds for windows 2, 5, and 8, respectively. There appears to be no significant azimuthal variation for the corrected phase velocity. This result demonstrates how one must interpret the observed regionality of C carefully by taking regional differences in Q into account. The above discussion does not, however, necessarily mean the absence of a significant regional difference in phase velocity at 160 seconds, because a frequency-independent Q is the basic assumption of Eq. 2.

The following conclusions may be drawn from this work. (i) The Rayleigh waves suffer small attenuation along paths where the phase velocity is high and large attenuation over regions where the phase velocity is low. (ii) Although the Q of MM8 is appropriate as an average representation of the observed Q in the period range from 200 to 300 seconds, the differences for different great circle paths are very large; for example, the maximum discrepancy at 250 seconds is 140, 70 percent of the Q of MM8 (195). This lateral heterogeneity of Q may be too large to permit one to construct an average Q model of the upper mantle. One should take into account the regional difference in Q in order to correctly interpret the observed regional difference of phase velocity. (iii) All the windows except window 2 have lower Q than the Q of MM8 at periods below 200 seconds. I obtained Q values almost equal to 100 at periods near 160 seconds. This fact indicates that the low-Q zone, which may be identical with the low-velocity zone, in the upper mantle must be wider than that of MM8 or that the intrinsic Q in this zone must be smaller than that of MM8.

ICHIRO NAKANISHI*

Department of Earth Sciences,
Nagoya University,
Chikusa, Nagoya 464, Japan

References and Notes

1. W. Futterman, *J. Geophys. Res.* **67**, 5279 (1962).
2. H. Liu, D. Anderson, H. Kanamori, *Geophys. J. R. Astron. Soc.* **47**, 41 (1976).
3. D. Anderson, *ibid.* **14**, 135 (1967); D. Jackson and D. Anderson, *Rev. Geophys. Space Phys.* **8**, 1 (1970).
4. S. Smith, *Tectonophysics* **13**, 601 (1972); A. Ben-Menahem, *J. Geophys. Res.* **70**, 4641 (1965); F. Wu, *ibid.* **77**, 6445 (1972); N. Jobert and G. Roult, *Geophys. J. R. Astron. Soc.* **45**, 155 (1976); R. Sailor and A. Dziewonski, *ibid.*, in press; J. Mills and A. Hales, *Phys. Earth Planet. Inter.* **14**, 109 (1977).
5. D. Anderson, A. Ben-Menahem, C. Archambeau, *J. Geophys. Res.* **70**, 1441 (1965).
6. H. Kanamori, *Phys. Earth Planet. Inter.* **2**, 259 (1970).
7. L. Reiter, *Bull. Seismol. Soc. Am.* **63**, 1709 (1973).
8. M. Saito, abstract for the annual meeting of the Seismological Society of Japan, Tokyo, 1976.
9. N. Levinson, *J. Math. Phys.* **25**, 261 (1947); E. Robinson and S. Treitel, *Geophys. Prospect.* **15**, 311 (1967).
10. In addition to the Kurile Islands earthquake (1963), I also analyzed its largest aftershock plus the Alaskan (1964), the Rat Island (1965), and the Tokachi-oki (1968) earthquakes. A detailed report on the results for these earthquakes will be presented elsewhere.

11. I thank Dr. Fukao for numerous discussions and suggestions, Dr. M. Saito for sending me the unpublished notes and the program of Wiener filtering, Prof. T. Utsu for reading the manuscript, and T. Tsuzuki who made available to me the computer program for equidistant azimuthal projection.

* Present address: Earthquake Research Institute, University of Tokyo, No. 1-1, Yayoi 1-chome, Bunkyo-ku, Tokyo 113, Japan.

16 December 1977; revised 17 March 1978

Immunofluorescent Detection of Nuclear Double-Stranded RNA in situ in Vero and Mosquito Cells

Abstract. *Double-stranded RNA (dsRNA) was detected in situ by indirect immunofluorescence with antibodies to dsRNA. It was seen in nuclei of Vero and* Aedes albopictus *cells, but not in BHK cells, KB cells, chick embryo fibroblasts, or HeLa cells. Reactive dsRNA was present in the nucleoplasm, but not in nucleoli or cytoplasm. Extracted RNA from the whole cell contained from 0.08 percent (BHK) to 0.46 percent (HeLa) dsRNA, as estimated by serological methods. This dsRNA, found in molecules having the size distribution of heterogeneous nuclear RNA, did not renature rapidly after denaturation. The quantity of dsRNA in total extracted RNA did not correlate with the presence or absence of nuclear staining in situ.*

A number of reports have described double-stranded RNA (dsRNA) in extracted nuclear RNA, particularly in the large, heterogeneous nuclear RNA (hnRNA) fraction (*1*-*5*). Interpretation of the possible functional significance of dsRNA from in vitro studies of extracted RNA had been limited, since it is unknown whether any double-stranded regions exist in native intracellular structures. A significant portion of the dsRNA probably forms only during deproteinization, and consists either of intermolecular complexes (*6*) or of intrachain complementary sequences that have annealed during phenol extraction (*6*-*8*). However, a small fraction of dsRNA has been identified in nuclear ribonucleoprotein particles prepared without deproteinization (*7*).

Antibodies that specifically recognize dsRNA (anti-dsRNA) can be used to examine whether dsRNA exists in native intracellular structures. Similar techniques have served to identify reovirus dsRNA (*9*) and Sindbis and dengue virus replicative form RNA (*10, 11*) in infected cells and in extracted RNA; the viral dsRNA could be visualized in situ by immunofluorescence without extraction and deproteinization (*9, 10*). In these experiments, control or uninfected BHK or KB cells showed little or no fluorescence when tested with the combination of anti-dsRNA prepared in rabbits (rabbit anti-dsRNA) and fluorescein-labeled antibodies to the rabbit globulin prepared in goats (goat anti-rabbit globulin) (*10*). With these same reagents, we have observed that other cell lines display a striking nuclear fluorescence, specifically localized in the nucleoplasm. We report here (i) the in situ demonstration of dsRNA in the nucleoplasm of uninfected Vero cells and the *Aedes albopictus* mosquito cell line of Singh (*13*) and (ii) the size distribution and nuclear origin of extracted RNA that contains serologically reactive dsRNA. The antibodies for these experiments recognize dsRNA structure specifically (*14, 15*). Both the gamma globulin fraction of serum and antibodies that had been immunospecifically purified with heteroduplex molecules of polyinosinic acid and polycytidylic acid [poly(I)·poly(C)] (*10, 15*) gave similar results.

When acetone-fixed Vero cells were tested with purified rabbit anti-dsRNA followed by fluorescein-labeled goat anti-rabbit globulin, there was diffuse staining of the nucleoplasm in virtually all cells; in contrast, the nucleoli and the cytoplasm were unstained (Fig. 1a). Vero cells, tested at varying times over a period of several years, reacted similarly. When normal rabbit immunoglobulin was used instead of purified antibody, no staining was seen. Unlike Vero cell nuclei, BHK cell nuclei were not stained by the antibody reagents (Fig. 1b). *Aedes albopictus* cells were stained with the gamma globulin fraction from anti-dsRNA (Fig. 1c), but not with gamma globulin from normal serum. The specific fluorescence was confined to the nucleoplasm. The reactive antigen in these cells gave a speckled pattern, rather than the more homogeneous pattern seen in Vero cells.

The immunofluorescence reaction was specific; it was blocked by poly(I)·poly(C) (Fig. 1d), but not by total yeast RNA or calf DNA. The appearance of faintly stained nucleoli against the dark nuclear background seen with poly(I)·poly(C)-absorbed serum was not specific immune fluorescence; it was also observed in some cells stained with normal rabbit gamma globulin.

As with BHK cells, the nuclei of chick embyro fibroblasts and KB cells consistently failed to stain with anti-dsRNA and fluorescent anti-globulin. HeLa cells were also negative in the one test done. Occasionally, a few stained granules were seen in the cytoplasm of these cell lines.

Since different cell lines vary in their immunofluorescent reactivity, the total phenol-extracted RNA from several cell lines was tested in quantitative complement-fixation assays with purified anti-dsRNA. Although positive reactions were seen, the total amount of RNA required was from 200 to 1200 times the amount of purely double-stranded poly(I)·poly(C) that was reactive. From these results, we estimated that from 0.08 percent (BHK) to 0.46 percent (HeLa) of the total RNA behaved as if it were double-stranded (Table 1). The dsRNA represented a higher percentage

Table 1. Serological estimation of dsRNA in total RNA extracted from varying cell lines. RNA was extracted (*12*) from either whole cells (2 to 5 × 10^8) or isolated nuclei. Varying concentrations of RNA were tested with purified antibodies to dsRNA in quantitative complement fixation assays (*22*). The amount of dsRNA was estimated by comparison with the amount of poly(I) · poly(C) required for a standard reaction curve (*11, 12*). The values for total RNA from BHK, Vero, and *A. albopictus* cells are averages of four separate experiments.

Cell line	Percentage of extracted RNA reactive with antibodies to dsRNA	
	Total	Nuclear
BHK	0.08 ± 0.027	
Vero	0.29 ± 0.1	0.51
A. albopictus	0.2 ± 0.05	0.7
HeLa	0.46	
KB	0.1	

0036-8075/78/0623-1381$00.50/0