AAAS-Newcomb Cleveland Prize
To Be Awarded for a Report or Article Published in *Science*

The AAAS-Newcomb Cleveland Prize is awarded annually to the author of an outstanding paper published in *Science* from September through August. The competition year starts with the 2 September 1977 issue of *Science* and ends with that of 25 August 1978. The value of the prize is $5000; the winner also receives a bronze medal.

Reports and Articles that include original research data, theories, or syntheses and are fundamental contributions to basic knowledge or technical achievements of far-reaching consequence are eligible for consideration for the prize. The paper must be a first-time publication of the author's own work. Reference to pertinent earlier work by the author may be included to give perspective.

Throughout the year, readers are invited to nominate papers appearing in the Reports or Articles section. Nominations must be typed, and the following information provided: the title of the paper, issue in which it was published, author's name, and a brief statement of justification for nomination. Nominations should be submitted to AAAS-Newcomb Cleveland Prize, AAAS, 1515 Massachusetts Avenue, NW, Washington, D.C. 20005. Final selection will rest with a panel of distinguished scientists appointed by the Board of Directors.

The award will be presented at a session of the annual meeting at which the winner will be invited to present a paper reviewing the field related to the prizewinning research. The review paper will subsequently be published in *Science*. In cases of multiple authorship, the prize will be divided equally between or among the authors; the senior author will be invited to speak at the annual meeting.

Reports

Spectral Analyses of High-Frequency P_n and S_n Phases Observed at Great Distances in the Western Pacific

Abstract. *Both* P_n *and* S_n *phases recorded at distances greater than 3000 kilometers in the western Pacific have substantial amounts of energy at high frequencies, in some instances as high as 12 hertz for* P_n *and 15 hertz for* S_n. *A comparison of* P_n *and* S_n *spectra reveals generally higher energy levels and higher proportions of high-frequency to low-frequency energy for* S_n *than for* P_n. *Estimates of the effective quality factor, Q, indicate that the efficiency of* S_n *propagation may be two or three times that of* P_n. *First arrivals of* P_n *and* S_n *have apparent velocities in agreement with values for the uppermost mantle, whereas maximum-energy arrivals have apparent velocities in agreement with values for the lower crust.*

In earlier studies of high-frequency P_n and S_n phases in the Pacific, P_n and S_n have been observed to distances in excess of 30° with frequencies as high as 6 Hz (*1-3*). Although detailed information on the spectra of the guided phases could be of great value in determining the efficiency of the wave guide and the mode of P_n and S_n propagation, such information was not available because of the recording medium used (paper recordings made at a rate of 1 mm/sec). We discuss here spectral studies of recently obtained tape recordings of P_n and S_n in the western Pacific. Figure 1 shows the epicenters of six principal shocks recorded by an ocean-bottom hydrophone array near Wake Island during February and March 1976. Four of the events had travel paths to Wake Island that were under the deep Northwestern Pacific Basin, whereas the other two events had travel paths under the shallower Ontong Java Plateau. Data from each of these areas will be discussed separately.

Spectrograms of the P_n and S_n phases for events having travel paths under the Northwestern Pacific Basin are shown in Fig. 2, a–d. Frequencies well in excess of 6 Hz are present in many of the P_n and S_n phases—with frequencies perhaps as high as 12 Hz for P_n and 15 Hz for S_n (*4*). One qualitative indication that the S_n wave guide may be more efficient than the P_n wave guide is the increasing amount of high-frequency energy in the S_n wave train relative to that in the P_n wave train as distance increases (*5*); another is the increasing overall strength of the S_n signal relative to that of the P_n signal as distance increases. A physical parameter often used to quantitatively measure a medium's efficiency in transmitting energy is the quality factor, Q. Although Q may be expressed mathematically in a variety of ways, for the purposes of this discussion it is best approximated by $-20\pi d/2.3\nu s$, where d is the epicentral distance, ν is the velocity of the phase, and s is the slope (in decibels per hertz) of the ratio of the spectrum of P_n or S_n to that of the T-phase from the same earthquake (*6*). Efficient wave guides will therefore have high Q values, whereas inefficient wave guides will have low Q values. Using the spectral ratios shown in Fig. 3 and similar plots for the Kuril Islands earthquake, we computed Q values for P_n and S_n. Values for both P_n and S_n are high, with the Q for S_n phases being much higher than the Q for P_n phases [Q values for P_n and S_n are 3700 ± 200 (*7*) and 8500 ± 600, respectively, for the Hokkaido earthquake and 8400 ± 1300 and 19,100 ± 3700, respectively, for the Kuril Islands earthquake (*8*)]. No computations of Q were made for the two Marianas Islands events since the method is dependent on the recording of the T-phase (*6*) and these earthquakes did not generate an observable T-phase at Wake Island. For one of these events, amounts of high-frequency energy are larger in the S_n spectrum than in the P_n spectrum; for the other event, amounts of high-frequency energy are about the same in the P_n and S_n spectra. Because of the lower velocity of S_n, these observations also indicate that S_n propagation is more efficient than P_n propagation.

Other noteworthy aspects of the spectrograms (Fig. 2) are the duration of the wave trains and the arrival times of peak energies for P_n and S_n. The P_n wave train appears to extend to the onset of the S_n

 0036-8075/78/0324-1333$00.75/0

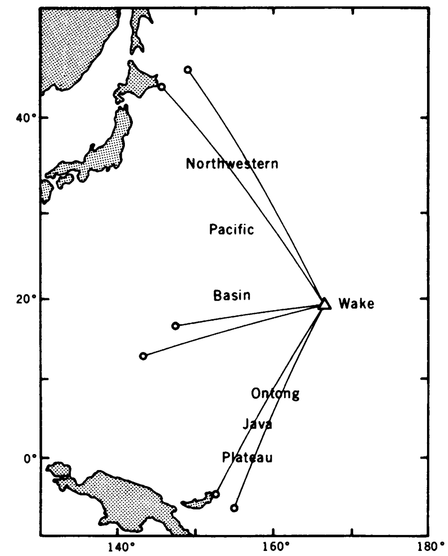

Fig. 1. Epicenters of six principal earthquakes recorded on the reactivated Wake Island hydrophone array.

wave train; the S_n wave train appears to have a much shorter duration. Some of the energy appearing after the onset of P_n and before the onset of S_n could be the result of the conversion of P_n to S_n, or of S_n to P_n. Although the travel times of the first-arriving P_n and S_n phases are in agreement with the times observed in earlier studies (*1-3*), maximum amplitudes occur well after the onsets of P_n and S_n (Fig. 4). These peaks, which appear farther behind the first arrivals of P_n and S_n as distances increase, travel with velocities (about 7.6 and 4.5 km/sec for P_n and S_n, respectively) comparable to basal crustal propagation rates (*9*) rather than with the Moho or mantle velocities of the first-arriving P_n and S_n phases [8.3 or 7.8 and 4.8 km/sec for P_n and S_n, respectively (*1-3*)]. Thus, it appears that an appreciable portion of P_n and S_n energy may propagate within the lower portion of the oceanic crust.

Four earthquakes were recorded at Wake Island that have travel paths across the Ontong Java Plateau as well as across portions of the Northwestern Pacific Basin (Fig. 1). The epicenter of one event was near New Britain; epicenters of the other three earthquakes were at virtually identical locations in the Solomon Islands. Spectrograms for the New Britian earthquake and for the two smaller Solomon Islands earthquakes are similar to the spectrogram for the largest Solomon Islands event, which is shown in Fig. 2e. The most obvious difference between this spectrogram and those of events having travel paths across the Northwestern Pacific Basin is that no S_n is observed for the Solomon Islands earthquake. Similar findings have been reported earlier (*10*). Recent studies indicate that S_n is fairly well propagated for travel paths entirely within the Ontong Java Plateau, but S_n appears to be severely attenuated, or filtered, as it moves from the shallow Ontong Java Plateau to the deep Northwestern Pacific Basin. [Some of the events having good

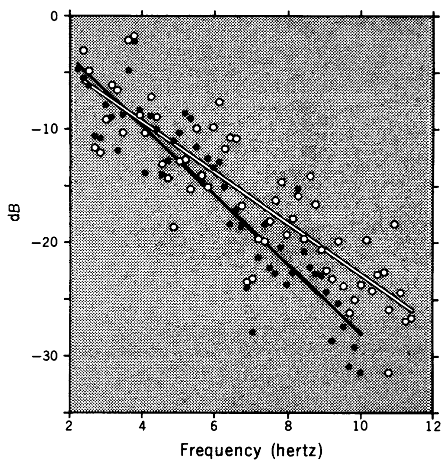

Fig. 3. Spectral ratios for P_n-T (closed circles) and S_n-T (open circles) for the Hokkaido earthquake (Fig. 2d). Because of the great efficiency of T-phase propagation in the ocean's SOFAR channel and because of the proximity of T-phase source locations to earthquake epicenters, the T-phase spectrum is considered to be similar to the source spectrum (*6*). If we compare the slopes of the P_n-T and S_n-T spectra (-3.02 ± 0.19 and -2.21 ± 0.17, respectively), S_n-T obviously has a higher proportion of high-frequency to low-frequency energy. This finding suggests that the propagation of S_n is much more efficient than the propagation of P_n.

P_n and S_n propagation to Ponape, on the northernmost edge of the Ontong Java Plateau, have epicenters, magnitudes, and focal depths that are nearly identical to those of the Solomon Islands and New Britain earthquakes, which did not produce a recordable S_n at Wake Island (*11*).] However, P_n is not similarly affected. Strong P_n and S_n phases have been observed (*3*) for travel paths to Ponape from the other direction (that is, from earthquakes in the Marianas Islands, Japan, and the Kuril Islands).

These observations reveal several spectral differences between the Solomon Islands earthquake (Fig. 2e) and those earthquakes having travel paths across the Northwestern Pacific Basin (Fig. 2, a–d). Both P_n and S_n are well propagated across the Northwestern Pacific Basin and across the Ontong Java Plateau, P_n is well propagated in both directions across the transition zone between the Ontong Java Plateau and Northwestern Pacific Basin, and S_n appears to be severely attenuated as it travels across the boundary between the Ontong Java Plateau and the Northwestern Pacific Basin. Another apparent difference between the spectrograms for the Solomon Islands earthquake and those of events having travel paths across the Northwestern Pacific Basin is that a normal, mantle-refracted P (direct arrival) is observed for the Solomon Islands event. Although normal, mantle-

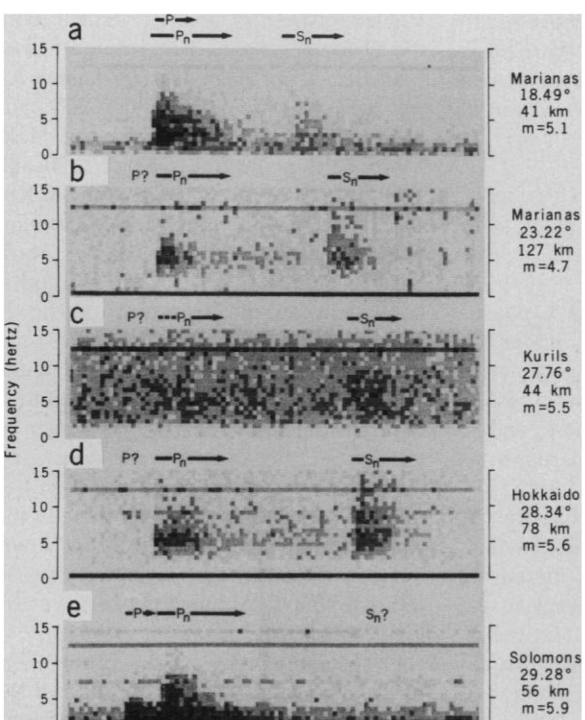

Fig. 2. Spectrograms of earthquakes having travel paths under the Northwestern Pacific Basin (a through d) and under the Ontong Java Plateau (e). The contour interval is 10 dB; m = magnitude. In (a) through (d), note (i) the increasing strength of the S_n phase with respect to the P_n phase as distance increases, (ii) energy at frequencies as high as 12 Hz for P_n and 15 Hz for S_n at 28.34°, and (iii) the apparent absence of P. For (e), which is comparable in its epicentral distance, focal depth, and magnitude to the Hokkaido earthquake (d), note the absence of S_n and the presence of P. Similar spectrograms have been found for other earthquakes in the Solomon Islands and in New Britain.

refracted P phases for travel paths under the Northwestern Pacific Basin have been observed on more conventional (1-Hz) island seismic stations, no such phases are obvious for the Marianas Islands, Hokkaido, or Kuril Islands events recorded in this study, probably because of differing sensitivities of the conventional seismographs and hydrophones at low frequencies ($\lesssim$ 2 Hz). The absence of P on the Wake Island hydrophone for travel paths under the Northwestern Pacific Basin and the presence of P on the Wake Island hydrophone for travel paths under the Ontong Java Plateau seem to suggest substantial differences in the mantle underlying these two regions. Additional observations are needed to substantiate these suggestions. A third difference in the spectra is in the character of the P_n arrival. Although the Hokkaido and Solomon Islands earthquakes are roughly comparable in terms of epicentral distance, magnitude, and focal depth, the P_n wave train for the Hokkaido event is much longer than the wave train for the Solomon Islands event. This short duration of P_n for the Solomon Islands earthquake, and the corresponding absence of S_n, further suggest that the long P_n wave trains (Fig. 2) may be a result of conversion of P_n to S_n, or of S_n to P_n.

Using the T-phase method, we have estimated Q for P and P_n for the Solomon Islands and New Britain earthquakes. Values for the Solomon Islands earthquakes average 3100 ± 1100 and 5200 ± 900 for P and P_n, respectively; similar values for the New Britain event are 1100 ± 200 and 2300 ± 300. The Q value of 5200 is roughly comparable to values found for the Kuril Islands (8400) and Hokkaido (3700) earthquakes, whereas the Q value of 2300 is low. The Q values for P (3100 and 1100) are somewhat higher than usual for normal mantle-refracted P phases calculated by other methods (generally around 1000), a possible indication that the T-phase spectrum is already somewhat attenuated when it reaches the ocean.

Many observations and conclusions of earlier studies of P_n and S_n propagation in the western Pacific have been confirmed and complemented by this investigation. The most important observations are the high frequencies of the P_n and S_n wave trains at great distances and the fact that S_n propagation is much more efficient than P_n. The remarkably high frequencies of S_n at great distances and the fact that the efficiency of S_n propagation is unquestionably greater than the efficiency of P_n propagation defies conventional thinking. Selective

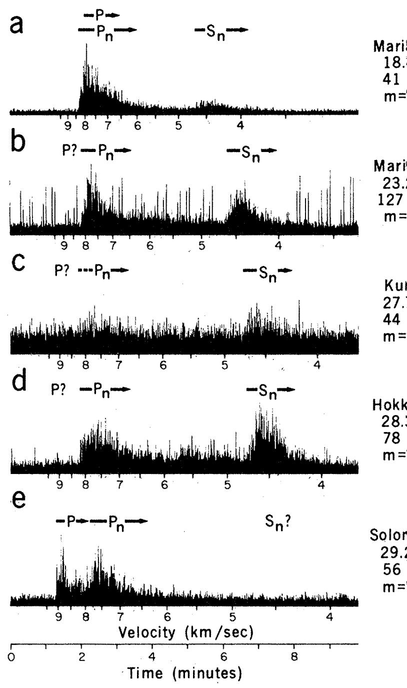

Fig. 4. Digitally rectified and compressed plots of P_n and S_n for the earthquakes shown in Fig. 2. The P_n and S_n arrivals have their maximum amplitudes at apparent velocities (approximately 7.6 and 4.5 km/sec for P_n and S_n, respectively) in agreement with values for the lower crust.

leakage of low-frequency energy from the P_n, S_n wave guide, as suggested by Fuchs and Schulz (*12*), would tend to raise the calculated Q. Greater leakage for S_n than for P_n would be required to explain the observations. For a given Q, this leakage would tend to reduce all signal amplitudes. Consideration of absolute amplitudes suggests that this effect is not strong in the frequency band studied (about 2 to 15 Hz).

Daniel A. Walker
Charles S. McCreery
George H. Sutton
Frederick K. Duennebier
Hawaii Institute of Geophysics, University of Hawaii, Honolulu 96822

References and Notes

1. D. Walker and G. Sutton, *Bull. Seismol. Soc. Am.* **61**, 65 (1971); G. Sutton and D. Walker, *ibid.* **62**, 631 (1972).
2. D. A. Walker, *Science* **197**, 257 (1977).
3. ——, *J. Geophys. Res.* **82**, 3350 (1977).
4. Similar high-frequency S_n phases were reported by B. Isacks and C. Stephens [*Bull. Seismol. Soc. Am.* **65**, 235 (1975)]. Predominant frequencies of 3 to 8 Hz, and detectable frequencies as high as 20 to 25 Hz, were recorded by hydrophones near Bermuda for path lengths of about 14°. For the Hokkaido event at 28° (Fig. 2d), we also observe predominant frequencies of 3 to 8 Hz, with detectable frequencies as high as 15 Hz.
5. Beyond about 20°, it now appears that S_n begins to have more energy at high frequencies than P_n, whereas at shorter distances the opposite is true. This finding suggests that a greater amount of high-frequency P_n energy is initially trapped in the wave guide. Since most of our earlier work was based on earthquakes at distances less than 20°, the stronger signals generally observed for P_n led us, in our earlier investigations, to suspect that P_n was more efficiently propagated than S_n.
6. The mathematical expression on which our estimate of Q is based is $E(f) = T(f)\, E_0(f)\, d^{-n}\, 10^{-2\pi f d/2.3 \nu Q}$, where $E(f)$ is the observed energy at frequency f, $T(f)$ is the response of the instrument at f, $E_0(f)$ is the source energy at f, d is the distance, n is the spreading parameter, and ν is the group velocity [G. Sutton, W. Mitronovas, P. Pomeroy, *Bull. Seismol. Soc. Am.* **57**, 249 (1967)]. Our formulation for Q is then derived by the following procedures: taking the logarithm of the above expression, deriving an equation for the ratio of the P_n or S_n spectrum to that of the T-phase from the same earthquake recorded on the same instrument, assuming that Q and ν are independent of frequency, and assuming that the T-phase spectrum approximates the spectrum of the source. The T-phase usually originates in close proximity to an earthquake's epicenter by the entrapment of energy within the ocean's SOFAR (sound fixing and ranging) channel. The extremely high efficiency of the SOFAR channel (probably the earth's most efficient acoustical wave guide) and the fact that T-phase locations are usually very close to earthquake epicenters (that is, the T-phase travel path is approximately equal to the epicentral distance) suggest that the T-phase spectrum may approximate the spectrum of the source. Another assumption implicit in this method is that substantial distortions of the source spectrum do not occur when the T-phase is generated. This assumption certainly breaks down below a few hertz but is probably valid at higher frequencies.
7. The standard deviations given are based on the uncertainties of the slopes of the P_n-T and S_n-T spectra. Additional sources of error related to the assumptions of the method are also present.
8. Value of Q based on the propagation of normal mantle-refracted P and S phases and surface waves are generally around 1000 or less. Estimates of Q for the high-frequency P_n, S_n wave guide have been made by other investigators for travel paths much shorter than those examined here: 3000 to 7000 for S_n from earthquakes in the West Indies to North America at distances of about 20° [P. Molnar and J. Oliver, *J. Geophys. Res.* **74**, 2468 (1969)]; 4000 for S_n at Bermuda for distances of about 14° [B. Isacks and C. Stephens, *Bull. Seismol. Soc. Am.* **65**, 235 (1975)]; 6000 or more for P_n and S_n in the western Pacific at distances less than 10° [T. Asada and H. Shimamura, in *The Geophysics of the Pacific Ocean Basin and Its Margin* (Geophysical Monograph Series 19, American Geophysical Union, Washington, D.C., 1976), p. 135]; 4000 to 6000 for S_n in the western Pacific at distances less than 5° [J. Kasahara and R. Harvey, *Hawaii Inst. Geophys. Rep. 76-9* (1976)]; and 1000 for S_n in the Tonga-Fiji-Samoa area at distances less than 10° [J. Oliver and B. Isacks, *J. Geophys. Res.* **72**, 4259 (1967); W. Mitronovas, B. Isacks, L. Seeber, *Bull. Seismol. Soc. Am.* **59**, 1115 (1969)]. Although a few of these values are roughly comparable to the values we have obtained, many of the estimates utilize differing sets of assumptions and the calculated value of Q may be strongly dependent on the method (assumptions) used. Therefore, the most significant aspect of our Q estimates may not be their actual values but rather the much higher values of Q for S_n relative to the Q for P_n.
9. G. L. Maynard, *Science* **168**, 120 (1970); G. H. Sutton, G. L. Maynard, D. M. Hussong, in *The Structure and Physical Properties of the Earth's Crust* (Geophysical Monograph Series 14, American Geophysical Union, Washington, D.C., 1971), p. 193.
10. In (*1*) S_n arrivals were reported as being quite prominent for travel paths entirely within the Northwestern Pacific Basin and unclear, or not apparent, for travel paths that crossed portions of the Ontong Java Plateau as well as portions of the Northwestern Pacific Basin.
11. For example, one earthquake having a prominent P_n and S_n at Ponape had coordinates of 6.3°S, 154.8°E, a body-wave magnitude of 5.8, and a focal depth of 50 km. The Solomon Islands earthquake 3 years later, which did not have an observable S_n at Wake Island, occurred at 6.3°S, 154.8°E, with a body-wave magnitude of 5.9 and a focal depth of 56 km. Also, great circle travel paths to Ponape and to Wake Island are nearly identical.
12. K. Fuchs and K. Schulz, *J. Geophys.* **42**, 175 (1976).

13. The order of authors was determined by lot. Contribution No. 869. This investigation was supported by the Earth Physics Program of the Office of Naval Research.

12 October 1977