Microseisms at Palisades
2. Rayleigh Wave and Love Wave Characteristics and the Geologic Control of Propagation

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The wave type of the microseisms recorded at Palisades, New York, is investigated to determine the Love and/or Rayleigh wave content. It is found that microseisms arriving from the southeast and northwest consist almost entirely of Rayleigh waves, while microseisms from the northeast and southwest have significant Love wave energy. The Love waves appear to be generated in the same source region as the Rayleigh waves. To account for the variation in Love wave energy as a function of source direction, the geologic structure along the various propagation paths is reviewed, and it is found that Love waves appear to be inhibited when propagating across the discontinuity surface between ocean and continental crust and when propagating across continental shield regions, both obstacles to a continuous surface layer. Observations from around the world are discussed, and we show that these two generalities appear to account for many of the reported discrepancies in microseism composition.

INTRODUCTION

The theoretical explanation for microseisms is that interacting ocean waves of nearly opposite wave number produce a nonlinear, second-order pressure perturbation which travels vertically from the ocean surface to the ocean bottom with no attenuation [*Longuet-Higgins* 1950; *Hasselmann,* 1963]. This wave travels at a high enough velocity to excite a seismic wave, and with the involvement of a train of ocean waves the excitement will be coherent over long distances. The resulting seismic wave, having been produced by the vertical force associated with the changing potential energy of ocean waves, travels along the surface of the ocean bottom with vertical as well as horizontal particle motion—hence a Rayleigh wave. The ability of ocean waves to produce the appropriate pressure oscillations at the bottom has been observed in the laboratory [*Cooper and Longuet-Higgins,* 1951] and is now accepted. Relationships based on this explanation, such as the two to one ratio between ocean wave period and period of microseism energy, have often, although by no means always, been observed. Of course, it has not been possible to determine the exact area of possible wave interference responsible for the microseisms, so the comparison of appropriate periods has this additional uncertainty.

Investigations of microseisms have generally verified the existence of appreciable Rayleigh wave energy from observations on continents (for example, see the historical review of *Ikegami and Kishinouye* [1951], and *Haubrich and McCamy* [1969]) and on the ocean bottom [e.g., *Latham et al.,* 1967]. There is some disagreement about how well the ideal Rayleigh wave characteristics are observed, in that the phase of the horizontal particle motion is not always 90° from the vertical [e.g., *Iyer,* 1958]. There is also some uncertainty as to whether the fundamental or first higher-mode Rayleigh wave is being observed [*Haubrich and McCamy,* 1969; *Douze,* 1964; *Gutenberg,* 1958; *Latham and Sutton,* 1966; *Oliver and Ewing,* 1957]. Despite observational uncertainties the existence of Rayleigh wave energy in microseisms, however, is relatively well established both theoretically and observationally.

The presence of Love waves is also well documented. Although not always evident, Love waves have been observed in microseisms from widely disparate regions (for example, North America, *Haubrich and McCamy* [1969]; England, *Iyer and Hinde* [1959]; Scandanavia, *Båth* [1962]; Japan, *Ikegami* [1962]; South Africa, *Darbyshire* [1963]). Love waves have been observed both on single-station, three-component seismographs and with large multipartite arrays, both inland and near the coast, and on the continent as well as the ocean bottom [*Bradner et al.,* 1965]. Thus the presence of waves with particle motion transverse to the direction of propagation and no vertical component is common at certain locations.

The explanations for the presence of Love waves have been varied and always tentative. The location of the source has been indicated to be that of the Rayleigh wave source [*Haubrich and McCamy,* 1969], although no mechanism was offered. Conversion from Rayleigh waves during propagation was suggested [*Iyer and Hinde,* 1959; *Toksoz and Lacois,* 1968], as was conversion during refraction while crossing from ocean to continent crustal structure. There has been no attempt to account theoretically for the presence of such waves, which require a transverse stress applied to the vertical plane (P_{zy} for a source from the east), coherent for some distance (wavelength for these waves is about 17 km).

In this paper we will examine the microseisms recorded at Palisades, New York (41°N, 74°W), relatively close to strong Atlantic Ocean sources. We will discuss the Rayleigh wave and Love wave characteristics of sources from different locations, both on and off the continental shelf, for propagation paths of varying distances in order to determine which suggested cause for Love waves seems preferable. We will also attempt to comment on some of the discrepancies noted by previous investigators.

MICROSEISM SOURCE LOCATIONS

The instrumentation and procedure for locating microseism source locations have been described by *Rind and Donn* [1978]. Microseisms are received with the use of a three-component, single-station seismograph and recorded on magnetic tape. The horizontal and vertical components of particle motion are cross-correlated with an analogue correlator, and the direction of propagation is determined by the relative amplitudes of the cross-correlation peak of each horizontal-vertical correlation. The greater the amplitude of the correlation between a given horizontal component and the vertical, the larger the ellipse axis in that direction. The lag or lead relationship of the

Paper number 9B0522.
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horizontal-vertical correlation allows the retrograde particle motion to be determined. The microseism source location is estimated by determining where the propagation vector intersects a region of strong winds and high ocean waves. The refraction of rays, as shown by *Rind and Donn* [1978], will only alter the source location for grids 10° × 10° in a few situations.

RAYLEIGH WAVE CHARACTERISTICS

An ideal Rayleigh wave will be characterized by particle motion with a phase difference of 90° between the horizontal and vertical components and with either 0° or 180° phase difference between the two horizontal components. Cross-correlation between the vertical and each horizontal component for each hour has allowed us to investigate these relationships for every source direction and suspected source location. The results were determined with the use of an analogue correlator (Saicor model SAI-52) for approximately 600 hours of data collected from the years 1968–1971. In over 90% of the cases the horizontal components were out of phase with the vertical and in phase with each other, verifying the Rayleigh wave assumption.

A schematic representation of the usual relationship is shown in Figures 1*a* and 1*b*. For all source directions except from the southeast, the observations at Palisades, New York, indicated that the vertical and horizontal particle motions were 90° out of phase as expected. The verification of this ideal result has previously been observed in the western half of North America [*Haubrich and Iyer,* 1962; *Haubrich and McCamy,* 1969]. Interestingly, it goes counter to the theoretical supposition of *Strobach* [1965], who argued that if the observed ground motion was the result of a large number of superimposed elementary waves each with the ideal phase relationship, the phase angle resulting from the superposition of the waves from the random oscillators would also be random. As our location is often quite close to Atlantic Ocean sources, where the random effect would be most evident, a completely random characteristic of the source components is thus shown to be unlikely.

For sources from the southeast, ground motion to the north and west leads motion upward by only about 45° (actually, it can be anywhere between 15° and 60°). The sources to the southeast are generally in the region just off the continental shelf (which is close to our location in this direction). If the

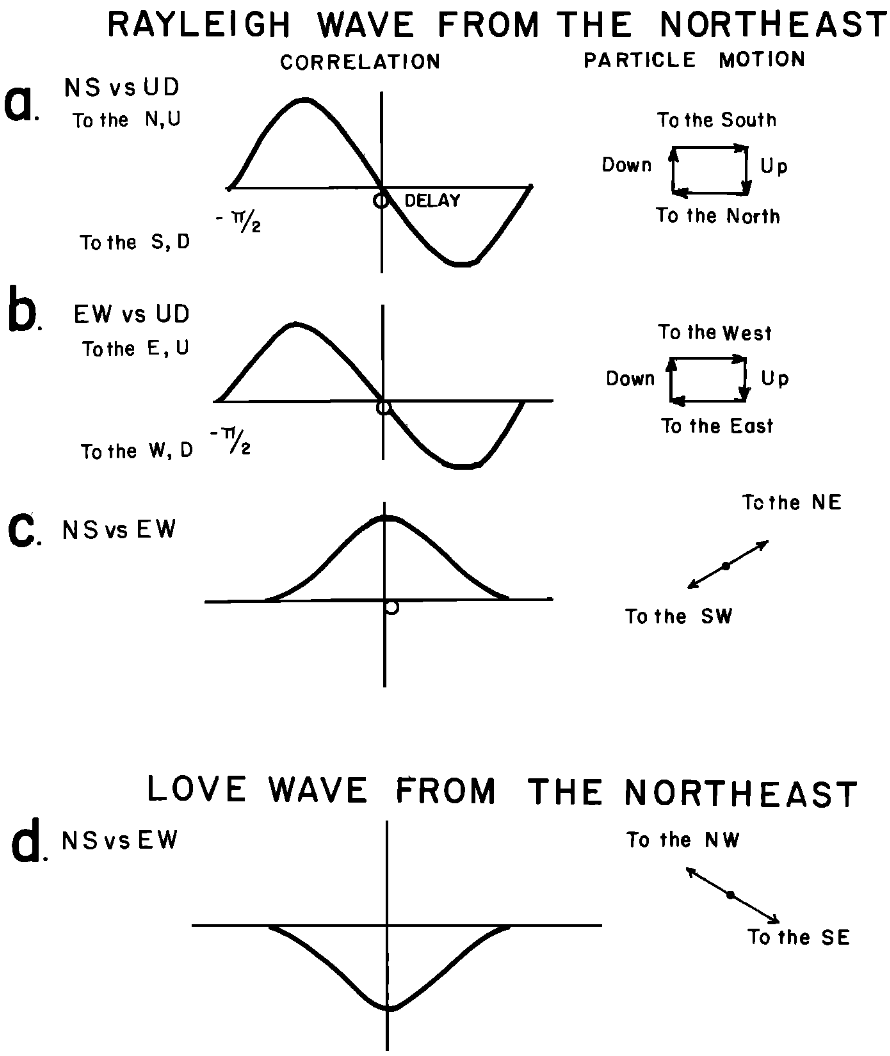

Fig. 1. Ideal cross-correlation relationship and particle motion for Rayleigh and Love waves from the northeast. (*a*) N-S versus U-D for Rayleigh wave, (*b*) E-W versus U-D for Rayleigh wave, (*c*) N-S versus E-W for Rayleigh wave, and (*d*) N-S versus E-W for Love wave.

recorded Rayleigh waves were the result of ground motion propagating horizontally along the shelf, a 90° phase lag between horizontal and vertical components would be expected. If it resulted from wave motion propagating with some vertical component due to excitation at the base of the continental slope, thus providing concurrent motion in our horizontal and vertical reference frame, no phase lag would occur. Our observations show an intermediate result, which may indicate contributions from both effects. Multipath propagation, with random phase of arrival, may also account for the observations; *Rind and Donn* [1978, Figure 1] show that such propagation is a possibility. However, microseisms from the northeast which also follow some multipath propagation do show the ideal phase relationship.

Another characteristic of Rayleigh waves is that the ratio of the horizontal to vertical particle motion varies with ground structure and mode. *Lee* [1932, 1934] derived the theoretical motion as a function of geologic structure. For the ground structure at Palisades (0.25 km of diabase overlying 0.25 km of shales and sandstones above a thick base of crystalline rock) the ratio for the fundamental mode is $u/w = 0.68$.

Toksöz and Lacois [1968] and *Haubrick and McCamy* [1969] observed in Montana the fundamental mode dominating for microseisms at periods greater than about $6\frac{2}{3}$ s; at shorter periods, higher modes predominated. In records in deep wells in the southwest, *Douze* [1964] observed fundamental and higher-mode Rayleigh waves at periods shorter than 6 s. Observations on the ocean floor off Bermuda, however, showed only the fundamental modes for 3- to 4-s microseisms [*Latham and Sutton,* 1966]. The question thus is, Are the higher modes which have been observed far inland but not on the ocean bottom the result of travel onto the continental margin, or do they result from long travel distances across the continent? Our location is quite close to the coastal sources, on the continental margin, and could provide an answer.

The ratio of the horizontal to vertical ground motion amplitude for microseisms was determined for 340 hours of data for which cross correlation between the components showed there was only one source direction (this was almost always from an eastern azimuth). The u/w ratio was found to be equal to 0.58 + 0.17. There was no essential difference between the mean north-south/vertical and east-west/vertical ratios. As mentioned earlier, for the fundamental mode the ratio would be approximately 0.70. For the first higher mode the ratio for waves of 5-s period (the average period of the observed microseisms) would be equal to 0.5 [*Oliver and Ewing,* 1957]. The result at this station is not statistically different from either result, although the mean value is intermediate and so cannot be used to decide which mode, if either, is dominant. It should be noted that the first higher-mode Rayleigh wave will still have elliptical-retrograde particle motion due to the low contrast of the crust-mantle system in our region [*Oliver and Ewing,* 1957].

LOVE WAVE CHARACTERISTICS

Microseisms From the Northeast

Figures 1*a*–1*c* display the characteristic correlations expected between the three different components of ground motion for a Rayleigh wave from the northeast. As noted previously, the effects predicted in Figures 1*a* and 1*b* are observed during correlation for 1 hour, verifying the existence of Rayleigh wave energy in the incoming signal. However, the in-phase correlation between the two horizontal components of ground motion depicted in Figure 1*c* is not seen. Theoretically, the correlation between the two horizontal components should be equal to the product of the correlation between each and the vertical. For approximately 200 hours of data in which the signal was coming from the northeast, the expected NS-EW ground motion correlation should be 0.18 (see Table 1). Instead, the correlation was observed to be −0.34; the negative result indicates that instead of ground motion to the north and to the east being in phase, as appropriate for Rayleigh waves from the northeast, motions to the north and west were actually in phase when averaging over a complete hour. However, the horizontal-vertical correlation definitely indicated a Rayleigh wave from the northeast. The explanation is obviously that an out-of-phase correlation between the two horizontal components occurs also and that no vertical component is present. Such an occurrence would be characteristic of a Love wave, also from the northeast, as depicted schematically in Figure 1*d*. The observation of Love waves occurring with Rayleigh waves has, of course, been reported often, although it has never before been studied in any detail on the east coast of North America. The directional dependence of this effect will be emphasized below.

To determine the proportion of Rayleigh wave to Love wave energy from a single three-component seismograph, the following formulae (here corrected) were developed by *Darbyshire* [1954] and expanded upon by *Iyer* [1958]. With the diagram as given in Figure 2, particle motion to the east can be written as

$$x = R(t) \sin \theta - L(t) \cos \theta \tag{1}$$

with R and L representing the Rayleigh and Love wave magnitudes at any time t. (Note that the arrow for the Rayleigh wave in Figure 2 indicates direction of wave approach; with retrograde behavior the particle motion is in the opposite direction.) Similarly, particle motion to the north is

$$y = R(t) \cos \theta + L(t) \sin \theta \tag{2}$$

Particle motion upward, dependent only on Rayleigh wave energy, is

$$z = k[R(t - t_0)] \tag{3}$$

with k the Rayleigh wave constant, i.e., the ratio of the horizontal to vertical amplitude of Rayleigh waves; the phase lag

TABLE 1. Calculated and Observed Rayleigh (R) and Love (L) Wave Components of Microseisms From Different Directions

Direction	Number of Hours	$r_{xz}r_{yz}$	r_{xy} (Observed)	Calculated, % R	Calculated, % L	Observed, % R	Observed, % L
NE	200	0.18	−0.34	39	61	40–50	50–60
SE	86	−0.09	−0.55	100	0	≥90	≤10
SW	8	0.07	−0.59	23	77	~70	~30
NW	10	−0.33	−0.46	86	14	>90	<10

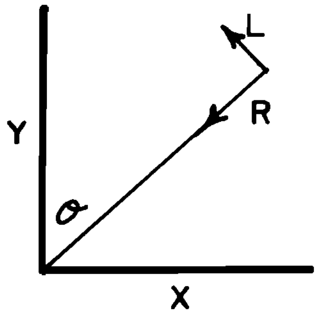

Fig. 2. Schematic of Love and Rayleigh wave arrival at angle θ to due north.

in the measurement of z, $t - t_0$, is equal to 90° phase difference between the horizontal and vertical components (which is thus $T/4$, with T the period of the wave).

Then, assuming no correlation between Rayleigh and Love wave phase arrivals,

$$\bar{x}^2 = R^2 \sin^2 \theta + L^2 \cos^2 \theta \tag{4}$$

$$\bar{y}^2 = R^2 \cos^2 \theta + L^2 \sin^2 \theta \tag{5}$$

and the correlation coefficients, averaged over a period of time, are

$$r_{xz} = \frac{xz}{(\bar{x}^2)^{1/2}(\bar{z}^2)^{1/2}} = \frac{R \sin \theta}{(R^2 \sin^2 \theta + L^2 \cos^2 \theta)^{1/2}} \tag{6}$$

$$r_{yz} = \frac{yz}{(\bar{y}^2)^{1/2}(\bar{z}^2)^{1/2}} = \frac{R(\cos \theta)}{(R^2 \cos^2 \theta + L^2 \sin^2 \theta)^{1/2}} \tag{7}$$

$$r_{xy} = \frac{xy}{(\bar{x}^2)^{1/2}(\bar{y}^2)^{1/2}}$$

$$= \frac{(R^2 - L^2)\sin \theta \cos \theta}{(R^2 \sin^2 \theta + L^2 \cos^2 \theta)^{1/2}(R^2 \cos^2 \theta + L^2 \sin^2 \theta)^{1/2}} \tag{8}$$

Then

$$\frac{r_{xy}}{r_{xz} r_{yz}} = \frac{R^2 - L^2}{R^2} \tag{9}$$

$$L^2/R^2 = 1 - r_{xy}/r_{xz} r_{yz} \tag{10}$$

The values of the correlation coefficient terms in (10) for microseisms from the northeast are given in Table 1. They were obtained from the peak value of the cross correlation, as shown schematically in Figure 1, divided by the multiple of the square roots of the autocorrelation at zero phase delay for the two components involved. The results indicate that microseisms from the northeast contain about 60% Love wave energy and 40% Rayleigh wave energy. Little difference was seen in the percentages for different source locations from the northeast: most of the sources are estimated to be on the continental shelf [see *Donn*, 1957; *Rind and Donn*, 1978, Figure 1].

The source is actually spread, providing signal from a range of directions estimated to be about 30° (from analysis of concurrently generated microbaroms which are infrasound, also generated by interfering ocean waves, and which enable more precise direction determinations). This will not greatly affect the L/R ratio [see *Darbyshire*, 1963], and signal from the northeast is generally strong enough so that widely disparate source directions do not contribute appreciably to the signal in 1 hour. However, the existence of a mixture of frequencies does affect the results. Although the formulae can be shown to produce the same end result when a mixture of frequencies is postulated, practically, the measured correlation coefficients will be adversely affected.

The peak correlation between the vertical and horizontal components, as in Figures 1*a* and 1*b*, theoretically occurs at a delay of $T/4$, with T the period of the incoming signal. With various periods the peak is found at different absolute delay times; thus with a mixture of frequencies the correlation peak is broadened, and its maximum value, used for calculating the r_{xz} and r_{yz} value, is correspondingly lowered. However, the r_{xy} component is not affected, because the amplitude at zero phase delay between the two horizontal components will be augmented by every frequency. The microseism signal recorded at Palisades has a mean Q value of 3.00 (Q = peak frequency/frequency spread at half-power points) and thus is not nearly monochromatic. The mixture of frequencies thus produces an underestimate in the values of r_{xz} and r_{yz} while leaving r_{xy} unaffected.

To verify this assumption, a correlation was performed between the r_{xz} and r_{yz} observations and a measure of the frequency content of the signal. For each of 300 hours the amplitude spectrum was obtained with the use of an analog spectrum analyzer. The frequency spread over which the amplitude dropped to one quarter of its peak value was correlated with the magnitude of $r_{xz}r_{yz}$ determined for each hour. The results showed a correlation of 0.52, significant at greater than the 99% level of significance, with lower $r_{xz}r_{yz}$ values associated with a greater mixture of frequencies. No significant correlation was found between r_{xy} and the frequency spread.

What will be the effect on the calculated L/R ratio? If $L > R$, and thus r_{xy} negative, as in this case, underestimating r_{xy} and r_{yz} will produce a greater apparent L/R ratio, so the results overestimate the Love wave energy. However, r_{xy} is negative, so there is more Love than Rayleigh wave energy present. The conclusion then is that Love wave energy makes up between 50% and 60% of the observed microseism signal from the northeast. An example of a portion of an actual record, filtered to pass 5-s waves, is shown in Figure 3. The strong vertical component is associated with in-phase north and east ground motions, with a phase lag of about 90°; the negligible vertical oscillations occur at the time of out-of-phase horizontal components, the record indicating the consecutive arrivals of groups of Rayleigh and Love waves from the northeast.

Microseisms From the Southeast

The relevant correlation coefficient statistics for 86 hours of microseisms from the southeast are given in Table 1. In contrast to the situation for northeast sources, the expected $r_{xy} = r_{xz}r_{yz}$ is negative, and the observed r_{xy} is even more negative. Reference to (10) indicates no Love waves are expected under such circumstances. Examination of the individual waves and the earlier discussion help explain much of the discrepancy.

As in the case of northeast sources, a frequency mixture from the southeast will lower the observed r_{xz} and r_{yz} correlations and thus lower the expected r_{xy}, so the expected r_{xy} correlation should be less than the observed r_{xy}. Furthermore, as signal from the southeast is generally weak [see *Rind and Donn*, 1978], signal from the northeast is often present as a background effect. This signal contains a slightly higher percentage of Love than Rayleigh waves, which increases the negative value of the observed r_{xy}, adding to already negative value of r_{xy} associated with the Rayleigh wave from the southeast. Both effects would tend to produce an $r_{xz}r_{yz}$ value less

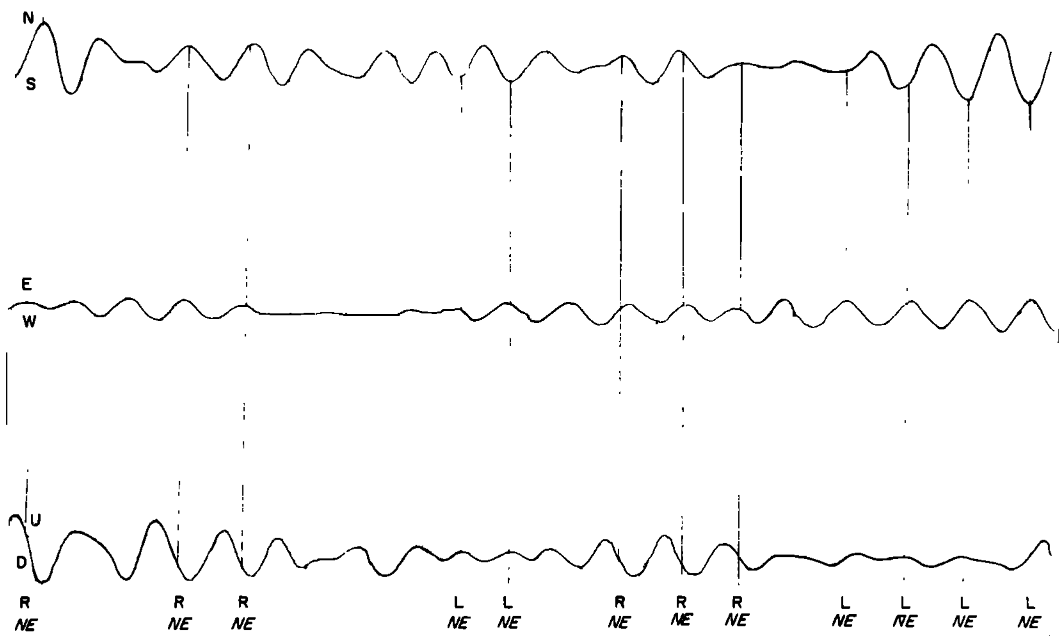

Fig. 3. The 5-s microseism ground motion from a three-component, single-station seismograph at Palisades, New York. Shown is a few minutes from the record of September 12, 1970, at 1300 EST. Visible are Rayleigh (R) and Love (L) waves from the northeast.

negative than the observed r_{xy}. One other factor is the variability of the phase lag between the vertical and horizontal for Rayleigh wave signal from the southeast mentioned previously (due to, possibly, the inclined propagation path). This will also lower the observed horizontal-vertical coherence and thus the expected r_{xy} value. Observations of individual records indicate that all these effects appear to contribute to the greater out-of-phase correlation between the horizontal components than expected.

A portion of an actual microseism record with signal from the southeast is given in Figure 4. Rayleigh waves from the southeast are clearly visible, as well as an occasional *R* or *L* wave from the northeast, but no Love waves from the southeast are apparent. Examination of a large number of records shows that an occasional Love wave does arrive from the southeast, but it is a much less common occurrence than Love waves from the northeast.

Microseisms From the Southwest

Examination of the correlation coefficients for 8 hours of data in which microseisms were almost exclusively from the southwest (Gulf of Mexico region primarily) indicates, as listed in Table 1, the presence of both Rayleigh and Love waves. Examination of the actual records does verify the presence of both types of waves, but Rayleigh waves seem more common than Love waves. The correlation coefficients are

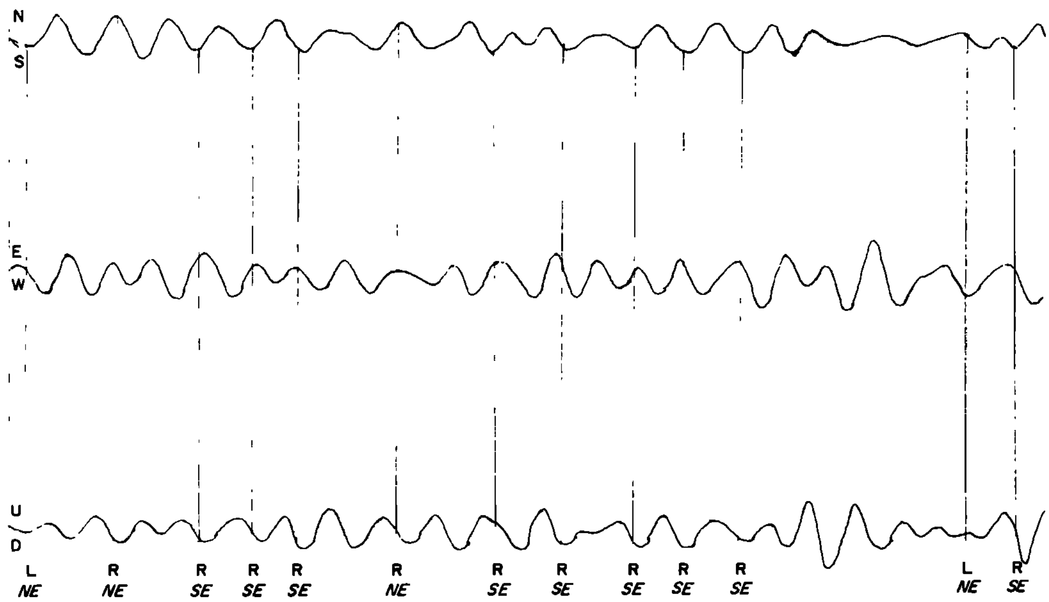

Fig. 4. Same as Figure 3 for September 19, 1970, at 1700 EST featuring, predominantly, Rayleigh waves (R) from the southeast.

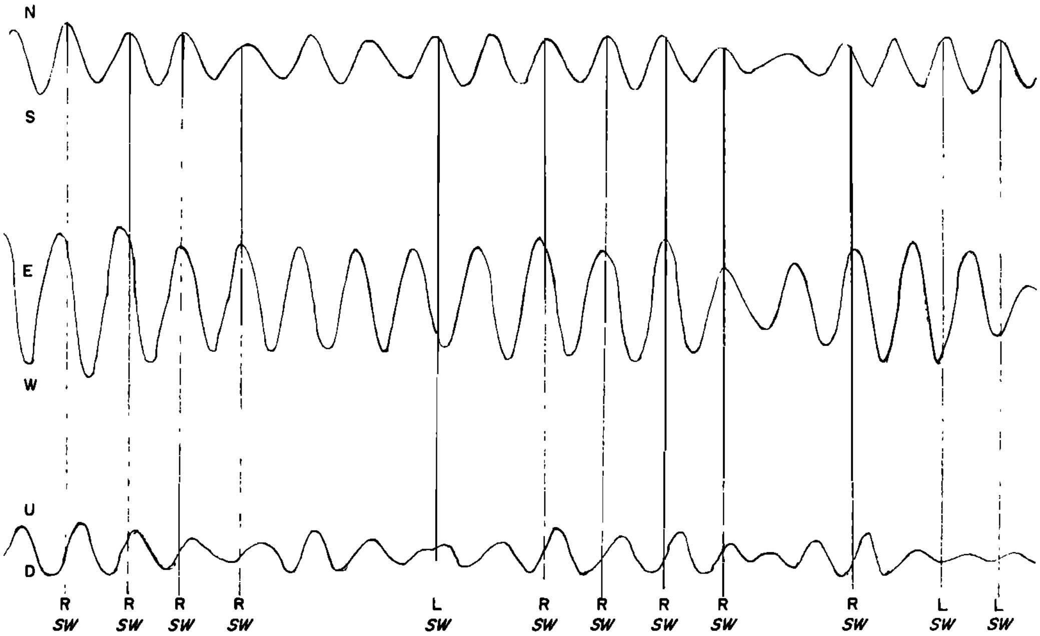

Fig. 5. Same as Figure 3 for August 19, 1970, at 1700 EST showing Rayleigh (R) and Love (L) waves from the southwest.

affected by frequency mixture as well as contamination from sources from other directions, because southwest signal is generally weak. An example of a portion of one such record is given in Figure 5.

Rayleigh Waves From the Northwest

The correlation coefficients for 10 hours of data almost totally from the northwest, given in Table 1, indicate 86% Rayleigh wave energy and 14% Love wave energy. Again, as was the case for southeast sources, the Rayleigh wave energy is underestimated, and although an occasional Love wave does appear, it is probably less than 10% of the signal. An example of a portion of a record for microseisms from the northwest is given in Figure 6, with no Love waves from the northwest present.

GENERATION OF LOVE WAVES

Previous observations of microseisms have led to the conclusion that Love waves are either present or absent at a station. No investigation has heretofore concluded that the microseism character varies with different arrival directions, either because none has been found or because little attention has been given the possibility. The questions which arise are the following: (1) How are the Love waves generated? (2) Why do Love waves come from certain directions and not others?

Love Wave Generation

The explanations offered to account for the presence of Love waves fall into the following general categories: generation in the Rayleigh wave source region by some mechanism or generation of Rayleigh waves followed by transformation during wave propagation. Supporting the first suggestion are the observations of *Haubrich and McCamy* [1969] that the Love waves seemed to come from the same directional distribution as the Rayleigh wave sources. Supporting the second contention are the observations of *Iyer* [1958] that the greater the distance of Rayleigh wave propagation (from the Atlantic Ocean to England), the greater the Love wave energy.

The observations at Palisades support the theory that both Rayleigh and Love waves are generated in the source region. Our observations show that Love waves do appear to arrive from the same direction as the well-defined Rayleigh waves. Many of the observed sources are quite close by, to the northeast and east with minimal propagational distance. These all have at least 50% Love wave energy. Microseisms from much further away, such as the southwest, do not have more observable Love waves, while observations from the far northwest and to the southeast offshore have little Love wave components. Theoretical calculations of *Strobach* [1965] show that only a small percent of Love wave energy would arise from simple Rayleigh wave propagation owing to interference effects.

It has been suggested that conversion from Rayleigh to Love wave energy may occur for Rayleigh wave propagation across the continental shelf [e.g., *Alsop et al.*, 1974]. An *SV* or *P* wave will give rise to an *SH* wave on refracting at any but normal incidence. However, calculations have been made of this effect (L. Alsop, personal communication, 1977), and only a few percent of the incident Rayleigh wave energy is lost to Love waves. If the Rayleigh wave energy is originally generated in the fundamental mode and some energy is transferred to the first higher-mode Rayleigh wave on crossing the shelf [*McGarr*, 1969], there would be even less energy available for Love wave formation (L. Alsop, personal communication, 1977). Also, our observations of offshore sources from the southeast show little Love wave energy. Thus neither simple propagation nor propagation across the continental shelf of Rayleigh waves seems to be sufficient to account for Love wave generation.

No theoretical investigation of Love wave generation in a microseism source region has ever been conducted. In order for a Love wave to be generated, what is needed is a horizontal force acting on a plane whose normal is in the vertical or, with an inclined surface, a force parallel to the local ground structure. The latter representation can actually be expected to arise in certain regions. The nonlinear interaction of surface ocean waves produces a second-order pressure force in the vertical direction which does not attenuate with depth. When this force

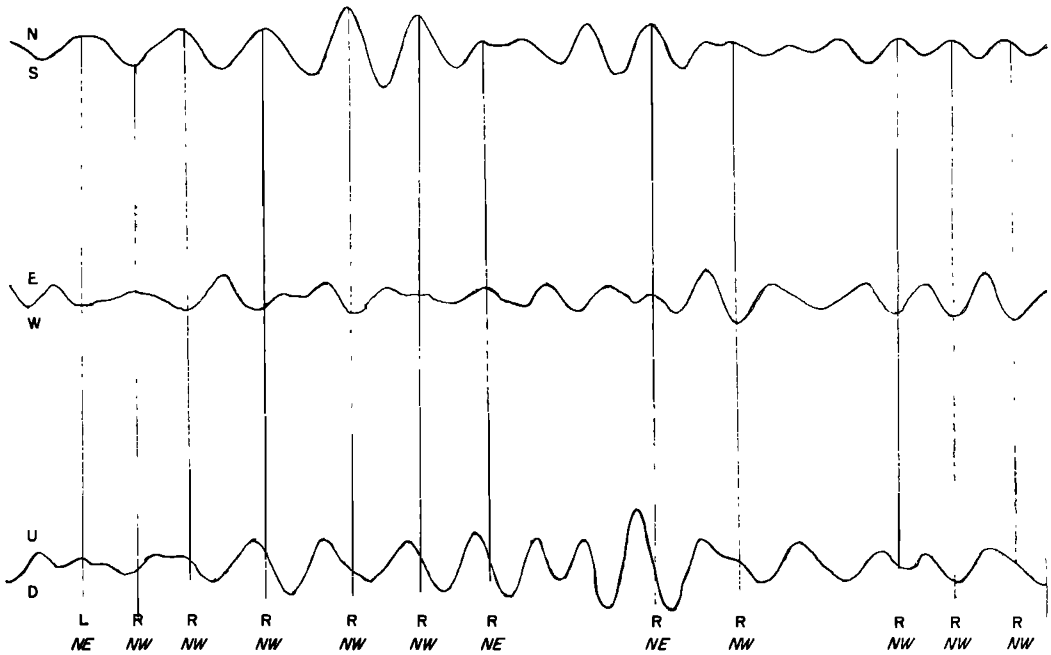

Fig. 6. Same as Figure 3 for March 21, 1968, at 0900 EST showing, predominantly, Rayleigh waves (R) from the northwest.

acts on a surface which is not perfectly horizontal, it will contain a component perpendicular to the surface, capable of generating Rayleigh waves, and a component along the surface, capable of generating Love waves. This effect is shown schematically in Figure 7. Admittedly, in the real ocean the bottom slopes are normally small.

Our observations indicate that the frequency of the Love waves does not differ appreciably from that of the concurrent Rayleigh waves because the frequency spectrum of the horizontal components which contain Love waves is generally similar to that of the vertical component which has only Rayleigh wave energy. This would be true with the proposed source mechanism, as the Love wave stress would have the same frequency as the Rayleigh wave pressure force, one-half the period of the interacting ocean waves. Yet the observed Love waves need not have precisely the same frequency as the Rayleigh waves, because the actual location of Love wave generation would be influenced more by inclined terrain surfaces than would be true for Rayleigh waves. Many previous investigations have found Rayleigh and Love waves of similar, though not identical, frequency [e.g., *Haubrich and McCamy*, 1969]. The same slight differences would then be true for source directions, again owing to the different favorable generating areas, and slight differences in direction are observed [e.g., *Strobach*, 1965].

Love Wave Propagation

The observations that now need to be explained are, Why are both Love and Rayleigh waves recorded here from the NE and SW but very few Love waves from the NW and SE? The actual reception of Love waves at a particular locale, as opposed to their generation, depends of course on propagation conditions. The questions to be investigated in this regard are the refraction effects while crossing the continental shelf or topographic irregularities, mode changes in traveling from ocean to continent, and the layered features necessary for any Love wave propagation.

The refraction condition for Love and Rayleigh waves of the same period is similar [*Capon*, 1971], and although multiple propagation affects Love wave propagation slightly more than Rayleigh wave propagation, the difference is small [*Capon*, 1971]. Refraction conditions thus do not seem to explain the appearance of Rayleigh waves and the absence of Love waves in microseisms from the SE and NW.

On crossing the continental boundary, 23-s Love waves will lose 48% of the energy in the fundamental to higher modes, while Rayleigh waves of the same period will lose only 4% [*Lysmer and Drake*, 1971]. Whether this is true for shorter periods is uncertain, but it is doubtful whether our observations can be fully explained by this mechanism, for in general, the Rayleigh waves we see may also have some energy in the higher mode (see also *McGarr* [1969]). Perhaps Love wave energy is shifted even more to higher modes and so has less energy near the surface. This effect may contribute to the paucity of Love waves from the southeast, basically offshore sources, from which we have noticed that even the Rayleigh wave energy near the surface has apparently been diminished [*Rind and Donn*, 1978].

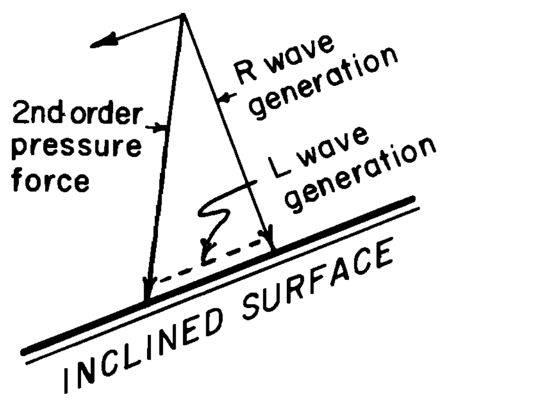

Fig. 7. Schematic of Love wave generation by the second-order pressure force from interfering ocean waves impacting on an inclinced surface.

The existence of Love waves requires the presence of a layered structure. For a simple two-layered model we can calculate the thickness of the upper layer, in which for Love waves,

$$\tan\,[kH'\cdot(C^2/\beta'^2 - 1)^{1/2}] = \frac{\mu(1 - C^2/\beta^2)^{1/2}}{\mu'(C^2/\beta'^2 - 1)^{1/2}}$$

with H', β', and μ' representing the thickness, shear velocity, and rigidity of the upper layer. If we let the phase speed for 5-s Love waves equal 3.4 km/s, we calculate for sandstone over granite a thickness for the upper layer of 1.5 km. Sharp deviations from this thickness, or discontinuities in the layers, interferes with transmission. Thus we might expect a lack of Love wave observations for microseisms whose propagation paths do not have the appropriate continuous layered structure feature for these effects.

CONTROL OF PROPAGATION BY GEOLOGIC STRUCTURE

In order to determine what particular geologic features appear to affect Love wave propagation, a study was made of previous observations of microseisms which discussed the Love and Rayleigh wave contributions. The following conclusions were reached, to be discussed more fully below: (1) Love waves are impeded during propagation from deep ocean or suboceanic basins which are devoid of a granitic layer onto sialic crust. (2) Love waves are impeded during propagation from a region with sedimentary cover or folded zones onto and across a shield region devoid of sediments.

Love Waves Impeded During Propagation From Simatic to Sialic Crust

This observation was initially discovered with regard to the '*Lg*' waves from earthquakes, with Love waves affected crossing the Black Sea depression and the Atlantic Ocean [*Waldner and Savarensky,* 1961]. The interpretation was that any interruption of the granitic layer impeded both Rayleigh and Love waves. This appears to be true, and the effect is even more noticeable for Love waves than for Rayleigh waves.

Table 2 gives a summary of some microseism observations around the world (which appear to be reliable) that pertain to the question of the Rayleigh versus Love wave component in microseisms. The observations that are most pertinent to the effect of granitic layer interruption are those made in Japan, Great Britain, Palisades, The Soviet Union, and Hawaii. In Japan, Love wave energy is appreciable only from sources to the north, on the continental shelf. For directions from the east, over the deep ocean basin, Rayleigh waves predominate. Sources to the south and west, over suboceanic basin devoid of a granitic layer, produce very few observable microseisms of either type.

In contrast to this are the observations at Great Britain, in which more Love than Rayleigh wave energy comes from sources apparently far offshore, beyond the continental shelf. The geology of the region, however, indicates that subcontinental crust extends outward to the west and northwest until the midoceanic ridge, providing a continual propagation layer for both Rayleigh and Love waves.

TABLE 2. Relative Rayleigh (R) and Love (L) Wave Composition of Microseisms Observed at Various Locations

Location	Source	R-L	References
North America			
Montana	continental shelf (Pacific Ocean) due west	$L \geq R$	*Haubrich and McCamy* [1969]
	continental shelf (Atlantic Ocean) due east	$R > L$	
California	Pacific Ocean near San Diego	$R > L$	*Gutenberg* [1958], *Haubrich and Iyer* [1962]
	Berkeley from due west	$R \simeq L$	*Wilson* [1942]
	Berkeley from the southwest	$R > L$	*Byerly and Wilson* [1938]
Central United States	Missouri from New Brunswick continental shelf	$L > R$	*Strobach* [1965]
	Indiana from New Brunswick continental shelf	$R \simeq L$	*Strobach* [1965]
	Iowa, Michigan from New Brunswick continental shelf	$R > L$	*Strobach* [1965]
New England	at Harvard, from the southeast	$R > L$	*Leet* [1947]
Greenland	on northern tip and on east coast probably from SW Greenland	$R \simeq L$	*Jensen* [1961]
Europe			
Great Britain	sources in North Atlantic	$L > R$	*Darbyshire* [1954], *Iyer* [1958]
Sweden	at Kiruna from northern coast of Norway and from New Scotland	$L \simeq R$	*Hollinderbaumer* [1959]
	at Uppsala from Norwegian coast and the North Atlantic Ocean	R	*Båth* [1962]
Denmark	continental shelf sources to the north and southeast	$L \simeq R$	*Jensen* [1961]
Germany	at Gottingen from N.A+1.* and Norway	$L > R$	*Zoeppritz* [1908]
	at Stuttgart from N.A+1.* and Norway	$R \simeq L$	*Schneider* [1959]
Soviet Union	at Yalta from North Atlantic and Black Sea	R	*Monakhov and Dolbilkina* [1958]
	at Moscow from Norwegian Sea	$R >> L$	*Monakhov and Dolbilkina* [1960]
	at Tiksi, Tashkent from northeast Norway	$L > R$	*Rykunov and Mishin* [1961]
	at Moscow, Pulkovo, Simferopol, Makhachkala from northeast Norway	$R > L$	*Rykunov and Mishin* [1961]
Asia			
Japan	from Okhotsk Sea, due north	$L = R$	*Ikegami and Kishinouye* [1951]
	from Atlantic Ocean to NE and SE	$R > L$	*Ikegami* [1962]
	from Atlantic Ocean to the east	R	*Okano* [1959]
South Africa	at Capetown from coastal sources to SW, SE	$R = L$	*Darbyshire* [1963]
Hawaii	sources from all directions	$R > L$	this paper
Ocean bottom between New Zealand and California	sources from near New Zealand and from open ocean	$R > L$	*Bradner et al.* [1965]

*N.A+1. is North Atlantic.

These results can be compared to our observation at Palisades that offshore sources to our southeast, over the deep ocean basin, provide weak Rayleigh waves and very few Love waves. From our northeast with a large continental shelf, and subcontinental crust region extending even further offshore, strong Rayleigh and Love wave energy is observed.

The Black Sea region, witha suboceanic basin devoid of granite, fails to yield Love waves at Yalta, while we observe some Love wave energy generated in the Gulf of Mexico from sources on the continental shelf region.

Finally, we looked at microseisms recorded on analogue tape from a three-component seismograph installed by Lamont-Doherty Geological Observatory at Honolulu. The purpose was to see if Love waves would be observed in a region of a deep ocean basin without a continental shelf or granitic layer appearing. Some 500 wave types were analyzed over a period of 8 days, the results indicating that a maximum of 18% of the microseisms could have been Love waves and the remainder Rayleigh waves from various directions. Thus some Love wave energy does seem to propagate on the simatic ocean crust and is observable when the recording station is not on a continental shelf (and thus there is no interruption in the simatic crustal layering). The observation of this percentage of Love waves has also been found by *Bradner et al.* [1965] with ocean bottom seismographs in the Pacific Ocean. The observation that Rayleigh waves can travel and be observed along the ocean bottom has been reported by *Latham et al.* [1967] and *Latham and Nowroozi* [1968], although the presence or absence of Love waves was not detected by their technique.

Thus we can conclude that Love wave transmission is impeded on passing from oceanic to continental crust; furthermore, it appears that Love waves can be generated on the continental shelf itself. On the west coast of North America the observations listed in Table 2 indicate that the main source of Love wave energy is the coastal region between 45° and 50°N; a lesser source is the region due west of Berkeley, California, and the least source is the region near San Diego. This relation is directly proportional to the continental shelf thickness along the west coast, which must be the generating region for the observed Love waves if offshore sources are prohibited from propagating onto the continent. Other regions with relatively large shelf extent such as the coastal areas to the northeast of Palisades, New York; of northern Norway, near Denmark and Germany; and north of Japan have been associated with large Love wave energies. Regions with small shelf areas, such as southern Africa and east of Japan, report much less Love wave energy.

Love Waves Impeded During Propagation From a Sedimentary Cover Region Across a Shield Region

Much controversy has developed over whether microseisms contain any appreciable Love wave component, because observations made in regions not widely separated often give quite disparate results. A careful analysis of this phenomenon in the United States and Europe seems to indicate that where a shield region is present along a propagation path from a nonshield region, Love wave energy is lost or greatly diminished.

The observations in Montana and at Palisades, from sources in the Pacific and Atlantic oceans, give completely opposite results. In Montana, microseisms from the west have a greater Love than Rayleigh wave component, while sources from the northeast show Rayleigh waves dominating. At Palisades, northeast sources have greater Love wave energy, while sources in the northwest have mostly Rayleigh waves. In both cases where Rayleigh waves dominated, the propagation path had to cross Canadian shield material (as well as other features), whereas the nearby sources showed dominating Love waves.

Strobach [1965] looked at the Rayleigh and Love wave energies at various midwestern stations from a source on the continental shelf near New Brunswick. Stations in Missouri showed Love wave energy greater than Rayleigh wave energy—there is no shield region for the microseisms to propagate through for these paths. Stations in Iowa and Michigan showed more Rayleigh wave energy with propagation paths through shield regions. In Indiana, with a relatively small amount of shield material to be traversed, the energies were equal. On a gross scale the presence or absence of shield material was the only difference among the various paths, i.e., all paths went through regions of acid plutonic rocks near the coast.

In Europe, various studies have been made of microseisms observed in different countries from storm situations over Norway. The results show that when the source is on the coast of northern Norway, both Love and Rayleigh waves are received in northern Sweden and at places in the Soviet Union to the east—all places which involve travel through sedimentary or folded crustal zones. In contrast, the reception to the southeast, in Norway and the Soviet Union, shows Rayleigh waves dominant, after the signal has passed through the shield region of Sweden and Finland. For sources in southern Norway the same effect is apparent—to the east, at Uppsala, Sweden, few Love waves are observed, with travel once again through the shield region of Sweden, while to the south in Denmark and Germany, with only continental shelf and sediment regions to traverse, a high percentage of Love waves is observed. The shield region appears to affect Rayleigh waves also: the transmission of microseisms from the southern coast of Norway to Uppsala is in general less efficient than that from the northern coast of Norway to Kiruno, in northern Sweden [*Santo,* 1962]. Once again, though, the Love waves are more affected.

It is possible that if the microseism source is right on the shield region, Love wave transmission is facilitated. At Palisades we observe Love waves from sources on the Labrador shield region, while Love waves are seen through Greenland from sources directly on the Greenland shield. Whether ice helps transmit seismic waves across Greenland is not known.

Love Waves From Atomic Explosions

As was first shown by *Leet* [1946], atomic explosions above the ground provide a vertical pressure pulse on the surface which generates both Love and Rayleigh waves. The Love wave generation appears to be weaker from this source in general, as has been seen by observations at Palisades from atomic explosions above and below ground in Nevada. Table 3 presents a compilation of Love and Rayleigh wave observations from nuclear explosions.

An explosion in Novaya Zemlya was recorded seismologically at several stations in Eurasia. At Uppsala, Sweden, and Agra, India, no Love waves were observed. The propagation paths to both these locations pass through shield regions. At Hong Kong, weak Love waves were observed, with a propagation path not intersecting any shield region. This suggests that whatever the source, the propagation characteristics for Love and Rayleigh waves appear to be the same. A study on the effect of ocean paths on 2- to 8-s Love and Rayleigh waves from earthquakes recorded in northeast Asia [*Waldner and*

TABLE 3. Relative Rayleigh (R) and Love (L) Wave Composition of 1- to 10-s Waves Recorded at Various Locations From Atomic Bomb Explosions

Location	Source	R-L	Reference
North America			
New Mexico	in New Mexico above alluvial sands	R;L	*Leet* [1946]
Palisades, New York	in Nevada	R	*Oliver et al.* [1960]
	Marshall Islands	R	*Oliver et al.* [1960]
	solid earth explosion in Nevada	R = L	*Oliver et al.* [1960]
Northwest Territories, Canada	at Resolute Bay, from solid earth explosion in Nevada	L > R	*Oliver et al.* [1960]
Europe, Sweden	at Uppsala from Novaya Zemlya	R	*Oliver et al.* [1960]
Asia			
India	at Agra from Novaya Zemlya	R	*Oliver et al.* [1960]
Hong Kong	from Novaya Zemlya	R > L	*Oliver et al.* [1960]

Savarensky, 1961] shows that the analysis given in the previous sections applies for waves in this period range from earthquake sources also.

CONCLUSIONS

Approximately 800 hours of microseisms recorded on magnetic tape at Palisades, New York, have been analyzed to determine their direction of approach, frequency, and character. At this location the Rayleigh wave characteristics correspond to 'ideal' Rayleigh waves from all directions except the southeast, where the phase difference between the vertical and horizontal components averages only 45°. The ratio of the horizontal to vertical particle motion suggests that we may be looking at a mixture of the fundamental and the first higher-mode Rayleigh wave, although this is uncertain statistically.

The Love wave component of the microseisms recorded at Palisades varies with the direction of arrival, and we have shown that these variations can be generalized to explain observations in different parts of the world. The majority of Love waves come from our northeast, a region with large continental shelf area; Love waves also appear from the southwest, traveling from a small shelf region in the Gulf of Mexico through coastal plain sediments to our location. Few Love waves are recorded from the northwest, apparently due to the difficulty that Love waves have in passing from a region of sediments onto and across a shield region. Love waves are also scarce from the southeast, possibly being affected by a mode change at the continental shelf but primarily owing to the difficulty in passing from oceanic to continental crust, due to an interruption in the layered structure necessary for Love wave existence. In that respect, Rayleigh waves are somewhat more successful in propagating from offshore sources to continental stations. We suggest that Love waves are generated by the same pressure force which generates Rayleigh waves acting on an inclined surface and thus imparting a stress with both vertical and horizontal components, the generation often occurring on the continental shelf.

Acknowledgments. This work was indirectly supported by National Science Foundation grants ATM 74-09449, ATM 78-06771, and ATM 78-04587. Lamont-Doherty Geological Observatory contribution 2852.

REFERENCES

Alsop, L., A. Goodman, and S. Gregersen, Reflection and transmission of inhomogeneous waves with particular application to Rayleigh waves, *Bull. Seismol. Soc. Amer., 64,* 1635–1652, 1974.

Båth, M., Direction of approach of microseisms, *Geophys. J. Roy. Astron. Soc. 6,* 450–461, 1962.

Bradner, H., J. Dodds, and R. Foulks, Investigation of microseism sources with ocean-bottom seismometers, *Geophysics, 30,* 511–526, 1965.

Byerly, P., and J. Wilson, Microseisms recorded at Berkeley, *Nat. Res. Counc. Trans. AGU,* 107–109, 1938.

Capon, J., Comparison of Love- and Rayleigh-wave multipath propagagation at Lasa, *Bull. Seismol. Soc. Amer., 61,* 1327–1344, 1971.

Cooper, R., and M. Longuet-Higgins, An experimental study of the pressure variations in standing water waves, *Proc. Roy. Soc., Ser. A, 206,* 424–435, 1951.

Darbyshire, J., Structure of microseismic waves: Estimation of direction of approach by comparison of vertical and horizontal components, *Proc. Roy. Soc., Ser. A, 223,* 96–111, 1954.

Darbyshire, J., A study of microseisms in South Africa, *Geophys. J. Roy. Astron. Soc., 8,* 165–175, 1963.

Donn, W., A case study bearing on the origin and propagation of 2- to 6-second microseisms, *Eos Trans. AGU, 38,* 354–359, 1957.

Douze, E., Rayleigh waves in short-period seismic noise, *Bull. Seismol. Soc. Amer., 54,* 1197–1212, 1964.

Gutenberg, B., Microseisms, *Advan. Geophys., 5,* 54–85, 1958.

Hasselmann, K., A statistical analysis of the generation of microseisms, *Rev. Geophys. Space Phys., 1,* 177–209, 1963.

Haubrich, R., and H. Iyer, A digital seismograph station for measuring earth noise, *Bull. Seismol. Soc. Amer., 52,* 87–93, 1962.

Haubrich, R., and K. McCamy, Microseisms: Coastal and pelagic sources, *Rev. Geophys. Space Phys., 7,* 539–571, 1969.

Hollinderbaumer, J., Uber die Ortung mikroseismischer Sturme, *Z. Geophys., 25,* 209–238, 1959.

Ikegami, R., An observational study on the propagation of microseismic waves, *Bull. Tokyo Gakugei Univ., 13,* 197–209, 1962.

Ikegami, R., and F. Kishinouye, A study on the propagation of microseismic waves, V, *Bull. Earthquake Res. Inst. Tokyo Univ., 29,* 571–576, 1951.

Iyer, H., A study on the direction of arrival of microseisms at Kew Observatory, *Geophys. J. Roy. Astron. Soc., 1,* 32–43, 1958.

Iyer, H., and B. Hinde, Microseismic research at the National Institute of Oceanography, *Nature, 183,* 1558–1560, 1959.

Jensen, H., Statistical studies on the IGY microseisms from Kobenbaun and Nord, *Geod. Inst. Medd., 39,* 67 pp., 1961.

Latham, G., and A. Nowroozi, Waves, weather and ocean bottom microseisms, *J. Geophys. Res., 73,* 3945–3956, 1968.

Latham, G., and G. Sutton, Seismic measurements on the ocean floor, *J. Geophys. Res., 71,* 2545–2574, 1966.

Latham, G., R. Anderson, and M. Ewing, Pressure variations produced at the ocean bottom by hurricanes, *J. Geophys. Res., 72,* 5693–5704, 1967.

Lee, A., The effect of geological structure upon microseismic disturbance, *Mon. Notic. Roy. Astron. Soc., Geophys. Suppl., 3,* 83–104, 1932.

Lee, A., Further investigations of the effect of geological structure upon microseismic disturbances, *Mon. Notic. Roy. Astron. Soc., Geophys. Suppl., 3,* 238–252, 1934.

Leet, L., Earth motion for the atomic bomb test, *Amer. Sci., 34,* 198–211, 1946.

Leet, L., Microseisms in New England—Case history of a storm, *Geophysics, 12,* 639–650, 1947.

Longuet-Higgins, M., A theory of the origin of microseisms, *Proc. Roy. Soc., Ser. A, 243,* 1–35, 1950.

Lysmer, J., and L. Drake, The propagation of Love waves across nonhorizontally layered structures, *Bull. Seismol. Soc. Amer., 61,* 1233–1252, 1971.

McGarr, A., Amplitude variations of Rayleigh waves—Propagation across a continental margin, *Bull. Seismol. Soc. Amer., 59,* 1281–1305, 1969.

Monakhov, F., and N. Dolbilkina, The structure of microseisms, *Bull. Acad. Sci. USSR, Geophys. Ser., 8,* 537–541, 1958.

Monakhov, F., and N. Dolbilkina, The structure of microseisms and methods of determining the direction of the source of their origination, *Bull. Acad. Sci. USSR, Geophys. Ser., 10,* 974–977, 1960.

Okano, K., Microseisms observed at Abuyami Seismological Observatory (English abstract), *Zisin, 12,* 182–190, 1959.

Oliver, J., and M. Ewing, Higher modes of continental Rayleigh waves, *Bull. Seismol. Soc. Amer., 47,* 187–204, 1957.

Oliver, J., P. Pomeroy, and M. Ewing, Long-period seismic waves from nuclear explosions in various environments, *Science, 131,* 1804–1805, 1960.

Rind, D., and W. Donn, Microseisms at Palisades, 1, Source location and propagation, *J. Geophys. Res., 83,* 3525–3534, 1978.

Rykunov, L., and S. Mishin, Some features of microseism propagation along continental paths, *Bull. Acad. Sci. USSR, Geophys. Ser., 11,* 529–533, 1961.

Santo, T., Energy sources of microseisms in Sweden, *Ann. Geofis., 15,* 335–377, 1962.

Schneider, G., Zum Wellencharakter der mikroseismischen Bodenunruhe. *Z. Geophys., 25,* 161–185, 1959.

Strobach, K., Origin and properties of microseisms from the standpoint of oscillator theory, *Bull. Seismol. Soc. Amer., 55,* 365–390, 1965.

Toksoz, M., and R. Lacois, Microseisms: Mode structure and sources, *Science, 159,* 872–873, 1968.

Waldner, N., and E. Savarensky, On the nature of the L_{gl} wave and its propagation in northeast Asia, *Bull. Acad. Sci. USSR, Geophys. Ser., 11,* 1–16, 1961.

Wilson, J., A statistical study of the periods and amplitudes of microseisms, *Nat. Res. Counc. Trans. AGU,* 228–231, 1942.

Zoeppritz, K., Mikroseismische Bewegung, Seismische Registrierungenin Gottingen im Jahre 1906, *Acad. Gottingen Nachr. Math. Phys. Kl.,* 2–10, 1908.

(Received January 25, 1979;
revised March 26, 1979;
accepted March 29, 1979.)