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HAWAII INSTITUTE OF GEOPHYSICS
UNIVERSITY OF HAWAII

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ABSTRACT

Two distinct types of signals have been identified from studies of T-phase spectra and source locations. One, with its source at a shoaling slope of the ocean bottom and with dominant frequencies near 4 cps, is the previously recognized and described classic T phase. The other, with its source in deep water and with dominant frequencies near 30 cps, is newly identified and is here termed the abyssally generated, or abyssal, T phase. Scattering from the sea surface is proposed as a mechanism for producing rays which propagate through the ocean with an apparent velocity equal to sofar velocity. The sea surface roughness is hypothesized as shaping the spectrum of the abyssal T phase. A synthesis of the power-level record is derived which relates the degree of sharpness of the abyssal T-phase peak with focal depth.

INTRODUCTION

The classic T phase is believed to be refracted into the ocean at a sloping bottom and to enter the ocean sound channel after undergoing downslope propagation. It is characterized by frequencies peaking at about 4 cycles per second. Recent evidence indicates that an additional mechanism operates which favors higher frequencies and is not restricted to a sloping bottom. The resulting signal, characteristic of earthquakes which occur under the deep ocean bottom, is here termed abyssally generated, in distinction to the classic slope-generated T phase.

BACKGROUND

Tolstoy and Ewing [1950] discussed conditions at the source which are favorable to the production of a T phase. They pointed out that where an earthquake occurs under a flat ocean bottom, the sound energy can enter the ocean sound channel only by diffraction or some closely analogous process. The location of an epicenter on a slope was recognized as a more favorable source condition. Milne [1959] specified downslope propagation as the mechanism for projecting acoustic rays from a nuclear explosion, occurring in a land-locked area, into the sound channel. Johnson et al. [1963] compared the intensities of T phases from the Andreanof Islands for a variety of source situations. It was observed that T phases from earthquakes with 'epicenters at the lower end, and to seaward, of the continental slope are typically weak or not received'. This pattern was considered to support downslope propagation as the mechanism for projecting acoustic energy into the ocean sound channel.

The development and operation of a program for routine location of T-phase sources [Johnson, 1966] allowed the sites of T-phase generation to be computed from arrival times at a hydrophone network. A study of the aftershock sequence of the Rat Islands earthquake of February 1965 [Johnson and Norris, 1966] showed that, although the preponderance of T phases were generated at distinct radiators along the Aleutian Ridge, a significant number of them had sources in abyssal regions. The corresponding earthquake epicenters, as reported by the U. S. Coast and Geodetic Survey, (C&GS), nearly coincided with the computed T-phase sources. The strength of these abyssally generated T phases was found to be about 10 decibels lower than that for T phases generated at the ridge by an earthquake of the same magnitude.

NEW EVIDENCE

On 29 July 1965 an earthquake of magnitude 6.4 occurred under the Aleutian Trench off Amukta Pass. The C&GS reported the origin at 51.2N, 171.3W, 23 km, 08h 29m 22.1s. The resulting T phase, recorded at California, Oahu, Midway, Wake, and Eniwetok, was of exceptionally long

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duration with two peaks in the power level (See Figure 1).

Magnetic tape recordings of this _T_ phase were also available from the stations at Eniwetok, Wake, Midway, and Oahu. A distinct difference in the spectral composition of the two peaks was noted on aural examination of these recordings. While the later peak sounded practically the same as all other _T_ phases which we had encountered, the frequencies for the earlier peak were noticeably higher.

The _T_-phase sources were computed for both peaks using sofar velocities and arrival times read from the magnetic tapes. The California station was not used in the computations however, since, lacking a magnetic tape recording, the high- and low-frequency peaks could not be identified. For the high-frequency peak, computations showed a source at 51.1N, 171.6W, 08h 29m 26s, and for the low-frequency peak, a source at 52.1N, 172.4W, 08h 29m 40s. As plotted in Figure 2, the source location for the high-frequency peak was in the Aleutian Trench, about 24 km from the epicenter; that for the low-frequency peak was on the Aleutian Ridge, about 126 km from the epicenter.

The Oahu magnetic tape record was processed by a Northrop Nortronics ST-701 Spectral Contour Plotter. The result, shown in Figure 3, illustrates the separation in time and frequency of the two peaks. The earlier peak is centered at about 30 cps while the later peak is centered at about 10 cps. No correction was made to this figure for the response of the hydrophone system. Such a correction would shift the peak power to lower frequencies.

The spectral contour plot of a classic _T_ phase, with its source at the Aleutian slope, is shown in Figure 4. The C&GS listed this event as originating at 52.1N, 173.1E, 05h 43m 31s, 33 km, 1 November 1966. Note that the spectrum of this signal is quite similar to that of the later phase in Figure 3.

We conclude that the low-frequency peak shown in Figure 3 is the classic _T_ phase, projected into the sound channel by downslope propagation, whereas the high-frequency peak is a _T_ phase generated at the epicenter by an as yet unexplained mechanism. Figure 5 illustrates the spatial relationships of this model. In a vertical section typical of the Aleutian Ridge, rays are directed from an earthquake focus into alternate paths leading to long-distance propagation though the ocean.

It should be noted that the use of sofar velocity in the source calculation for the abyssal _T_ phase gave an origin time which agreed closely with that of the earthquake. Also, the standard deviation of residuals was about one second. This agreement restricts the possible modes of propagation of the abyssal _T_ phase to modes whose apparent velocity is very nearly equal to sofar velocity.

Although we have discussed in some detail only one double-peaked event, we have recognized numerous similar events in the hydrophone records. A partial list of these is given in Table 1. They were obtained by scanning

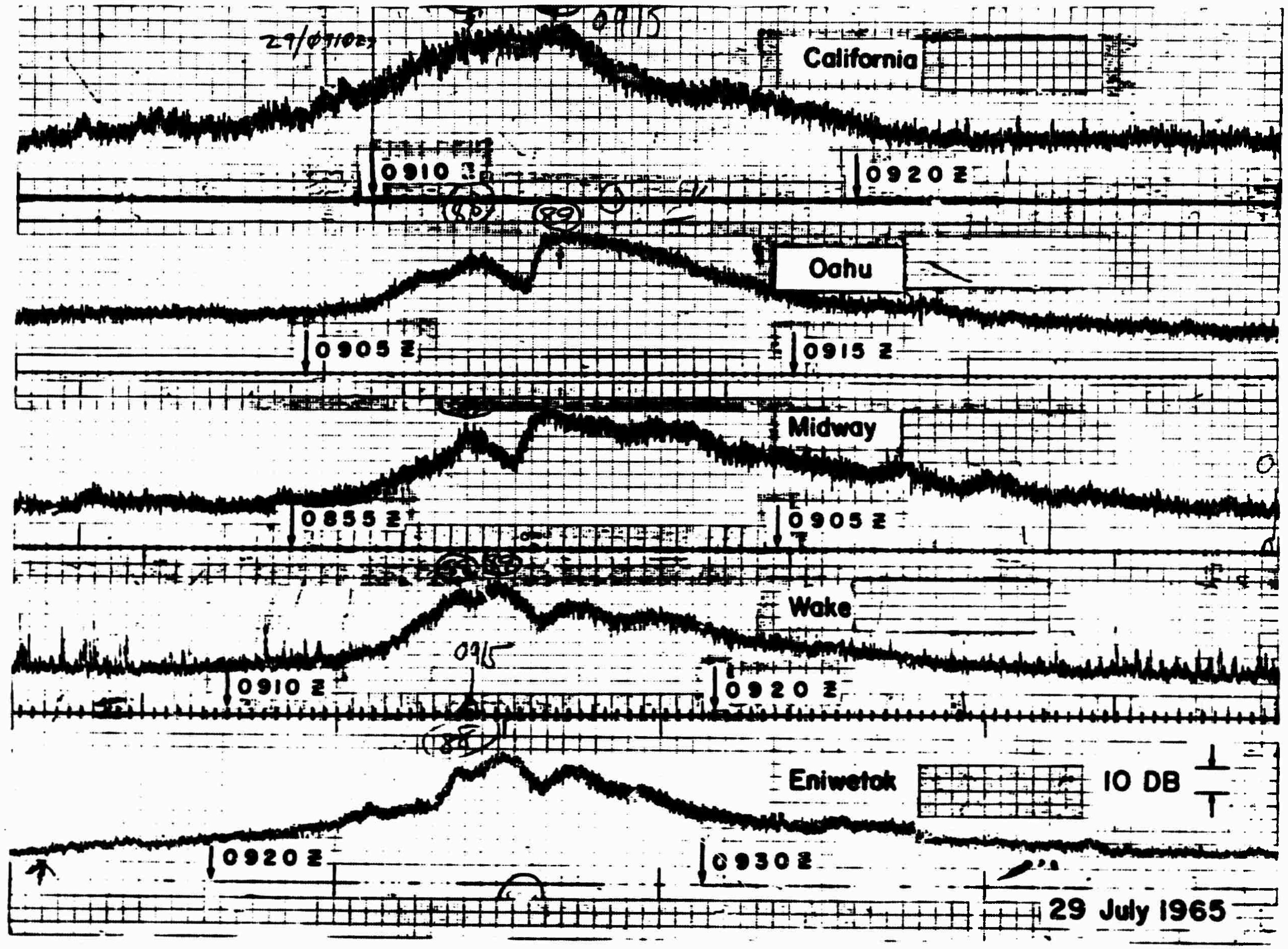


Fig. 1. Sound power level records from five hydrophone stations of the magnitude 6.4 earthquake which originated under the Aleutian Trench on 29 July 1965. Th· earlier peak is of higher frequency.

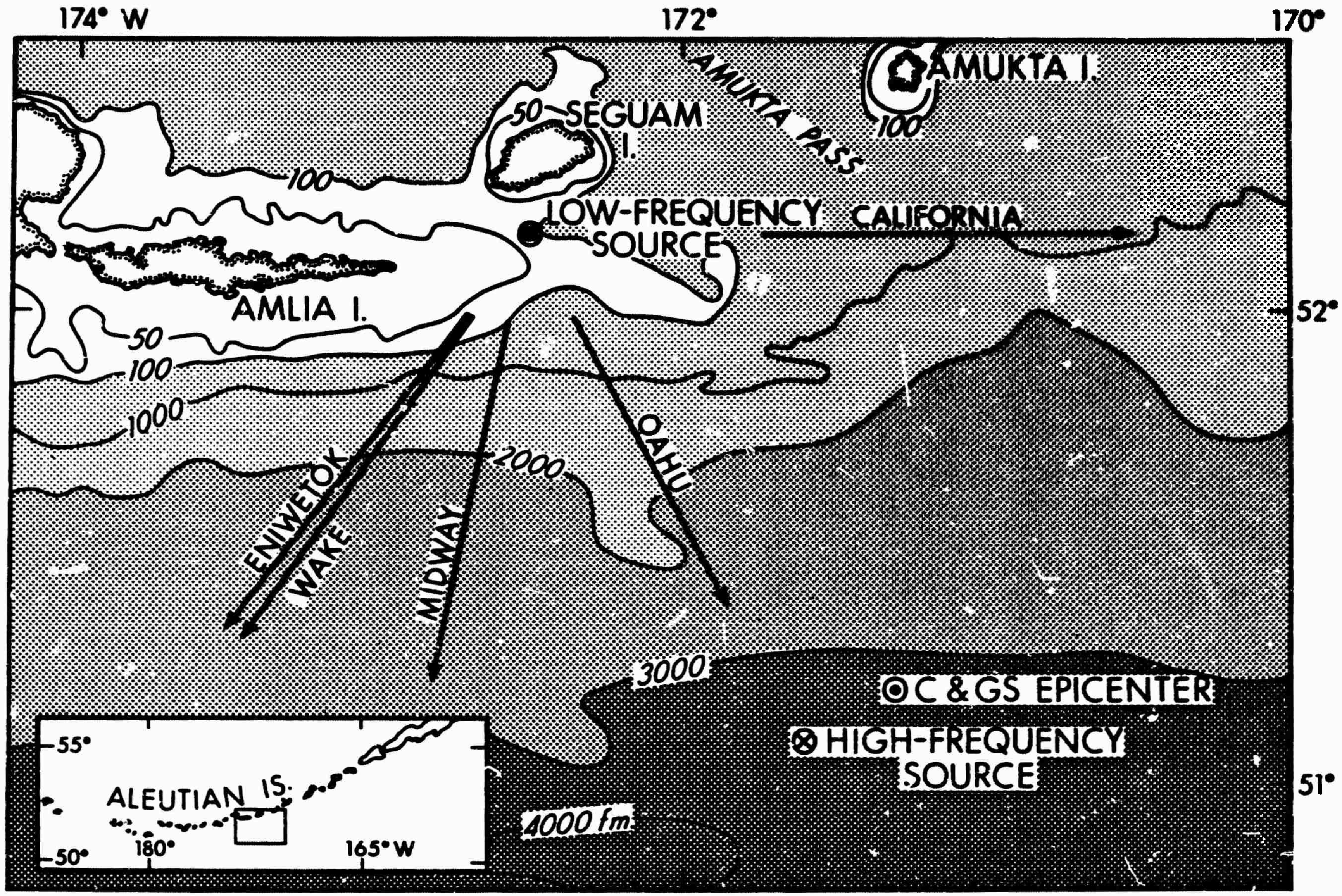


Fig. 2. Epicentral region for the magnitude 6.4 earthquake of 29 July 1965. T-phase source locations and azimuths to recording stations are shown.

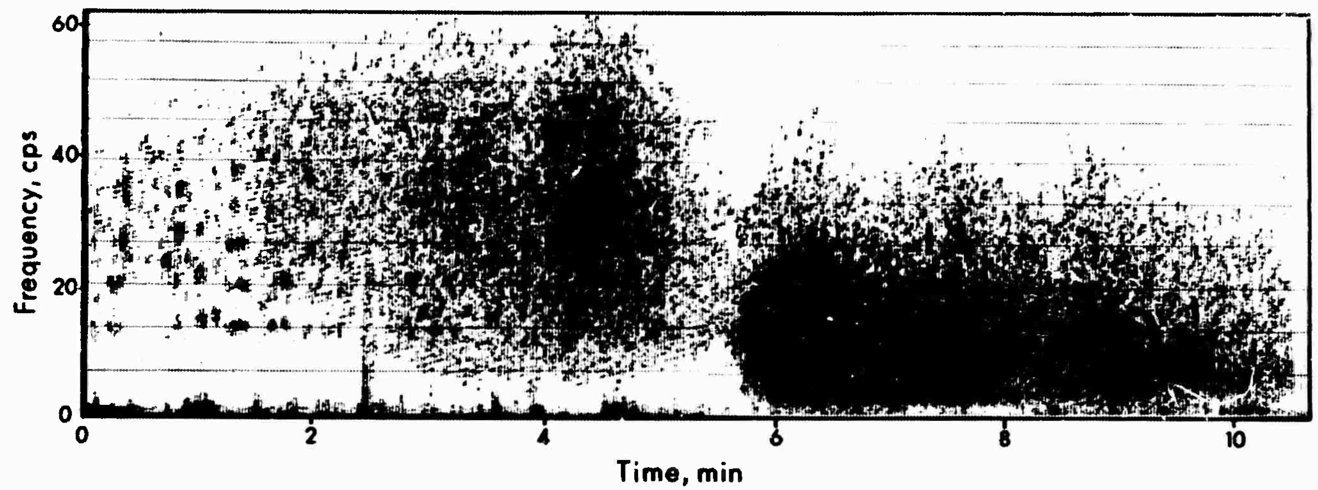
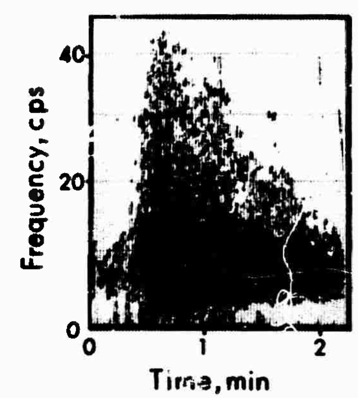


FIG. 3. *(above)* Spectral contour plot of the Oahu record of the Aleutian Trench earthquake of 29 July 1965. The contour interval is 6 decibels. The high frequency peak is abyssally generated.

FIG. 4. *(right)* Spectral contour plot of an Aleutian slope *T* phase. Earthquake origin is 52.1N, 173.1E, 33 km, 05h 43m 31s, 1 November 1966.



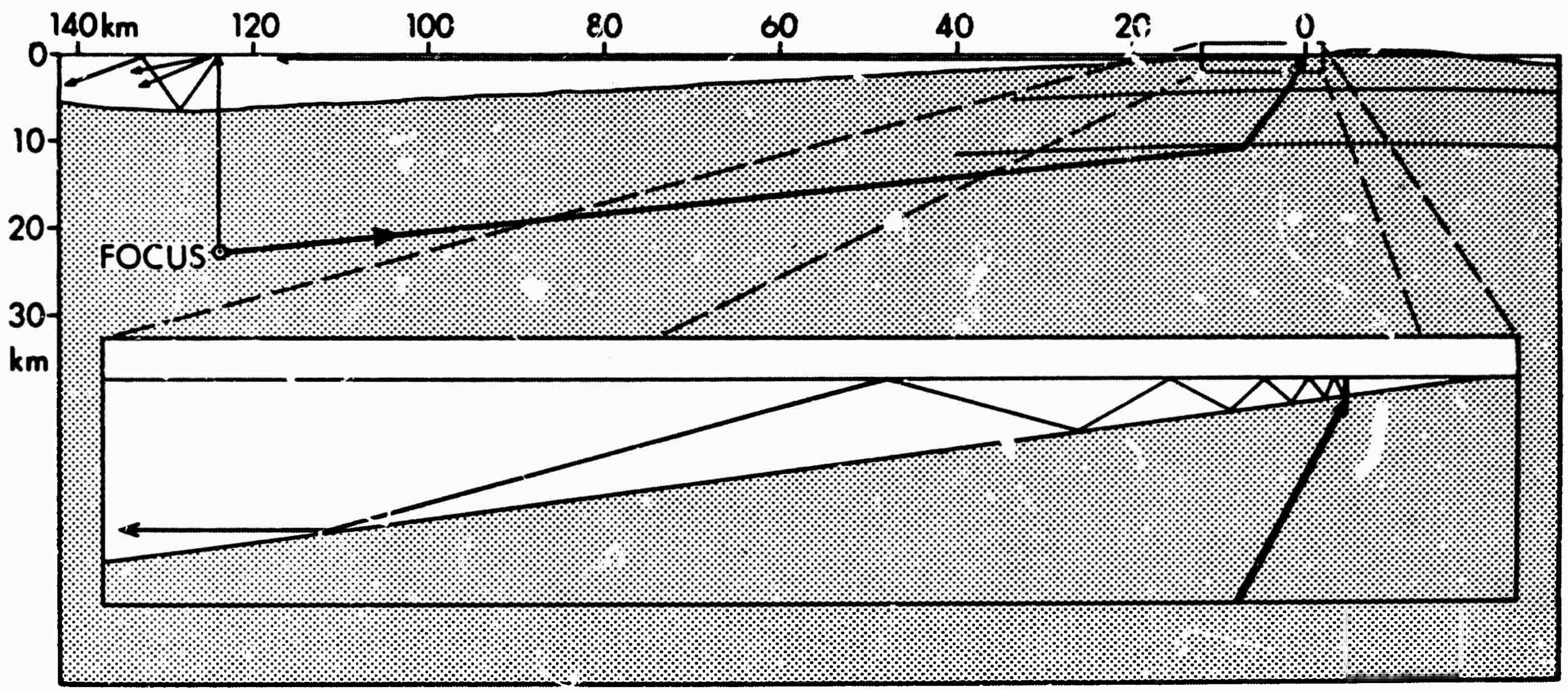


Fig. 5. Vertical section typical of the Aleutian Ridge. Rays are directed from an earthquake focus into alternate paths leading to long distance propagation through the ocean. Downslope propagation is shown in the enlarged section. (Vertical and horizontal scale are equal.)

the C&GS epicenter cards for abyssal epicenters. Events listed are those for which the hydrophone record shows a double-peaked T phase with a gradual increase in the rate of onset extending over several minutes before the first peak of power level. (By contrast, slope-generated T phases rise somewhat abruptly out of the background.) For many low-magnitude earthquakes both peaks could not be detected, presumably due to poor coupling at the slope [Johnson et al., 1963]. Figure 6 shows four of the double-peaked events listed in Table 1.

TIME BETWEEN PEAKS

In support of our findings which specify the regions of generation of the high- and low-frequency T phases, the observed time between peaks varies directly with the reported distance offshore (more correctly offslope) of the epicenter. In Figure 7 these measurements are plotted for the 10 events listed in Table 1. (The solid circles indicate the events for which magnetic tapes were obtained and the characteristic high and low frequencies were observed.)

In interpreting Figure 7, we approximate the time between peaks, Δt, as the travel time for P waves from the focus to the 50-fathom contour plus the travel time for T waves from the 50-fathom contour back to the epicenter. We assume a shallow focus and take the mean horizontal component of velocity to be 6 km/sec in the earth and 1.5 km/sec in the water. We then have

$$\Delta t = s\left(\frac{1}{6} + \frac{1}{1.5}\right) = \frac{5}{6}\, s$$

where s is the distance between the epicenter and the 50-fathom contour. This line is plotted in Figure 7 and is a reasonably good fit to the data. A computation in which travel time is more carefully accounted for does not yield significantly different results.

A portion of the scatter of the data in Figure 7 should be ascribed to the uncertainty of epicenter location by the seismograph network. For example, the epicenter computed for the Longshot nuclear explosion was 25 km to the northwest of its location on Amchitka Island [Herrin and Taggart, 1966]. Preliminary results suggest that the abyssal T-phase source computations locate the epicenter more accurately than do computations from P-wave arrivals.

Although P-wave velocity was used in the foregoing discussion, there is no reason to exclude S waves as contributing to the energy of the slope-generated T phase. At the distances under consideration, the S-P interval is about 10 seconds. Our interpretation is that the contribution of the S phase is contained in that portion of the T phase which follows the peak, along with reverberation and arrivals from parts of the ridge more distant from the focus.

MECHANISM

Any hypothesis for the mechanism of generation and propagation of abyssal _T_ phases must be consistent with the higher frequency content of this phase, the lack of a ray path between the _P_ waves and the sofar channel, and an apparent velocity which is very nearly equal to sofar velocity.

Let us first consider a mechanism employing scattering, which, in the ocean, may be categorized as surface scattering, volume scattering, or bottom scattering. Volume scatter could produce sofar rays directly; however such scattering would require the existence of velocity inhomogeneities with dimensions on the order of the wavelengths involved (i.e., 35 to 75 meters). Although _Piip_ [1964] demonstrated that such large-scale inhomogeneities existed in the water column near Bermuda, the velocity contrasts do not seem sufficiently great to sustain significant volume scattering.

On the other hand, scattering from gravity waves at the sea surface, offers stronger possibilities. _Rayleigh_ [1945] treated reflection from a corrugated surface for the case of normal incidence. He showed that corrugations have no effect on sound with wavelength greater than the wavelength of the corrugated surface. Diffracted spectra exist, however, for shorter wavelengths.

An indication of the scale of roughness of the sea surface is given by _Moskowitz_ [1964] who presents power spectra of gravity waves at various wind speeds. For fully developed seas under 20- and 25-knot winds, spectral peaks occur at about 7 and 10 seconds, respectively; the corresponding wavelengths would be about 80 to 160 meters. To the wave lengths which predominate in the slope-generated _T_ phase, such surfaces would appear smooth. The shorter wavelengths observed in the abyssal _T_ phase may be just those which are scattered into nearly horizontal directions by the ocean surface. As illustrated in Figure 5, the requisite scattering may be accumulated during multiple reflections from the ocean surface and floor.

Such a generation mechanism would require that the signal be initially channelled by paths reflecting at the surface and that the signal be either reflected at the bottom or refracted clear of the bottom by the velocity gradient. These paths contain the range of apparent velocity spanned by the sofar rays. For sources in high latitudes, a portion of the initially surface-reflected rays become sofar rays as the sound channel becomes deeper toward the equator. However the ray which would arrive at the same time as the sofar axis ray would still be one which had been reflected at both the surface and the bottom.

Another mechanism was suggested by _Biot_ [1952], i.e., the coupling of energy between Stoneley waves and the sofar channel. Such a mechanism,

Table 1. Source Data for Earthquakes Which Generated Abyssal *T* Phases

Date	Time (UT) h m s	Latitude	Longitude	Place	Mag.	Depth (km)
07 29 65	08 29 22.1	51.2N	171.3W	Andreanof Is.	6.4	23 R
10 01 65	08 52 05.8	50.1N	178.3E	Rat Is.	6.3	32
11 18 65	22 08 45.7	53.1N	161.9W	S. of Alaska	5.3	8
01 05 66	17 21 27	51.2N	171.2W	Andreanof Is.	4.5	33
01 17 66	18 56 16.6	52.0N	171.2W	Andreanof Is.	4.8	46
01 28 66	22 38 12.2	51.6N	157.0E	Kamchatka	5.6	107 R
04 15 66	04 58 06	51.1N	174.3E	Near Is.	4.7	33 R
04 29 66	01 46 43	53.8N	157.8W	Alaska	5.2	33 R
05 11 66	21 39 35.3	48.8N	156.3E	Kuril Is.	5.7	28
06 02 66	03 27 53.3	51.1N	176.0E	Rat Is.	6.0	41 R

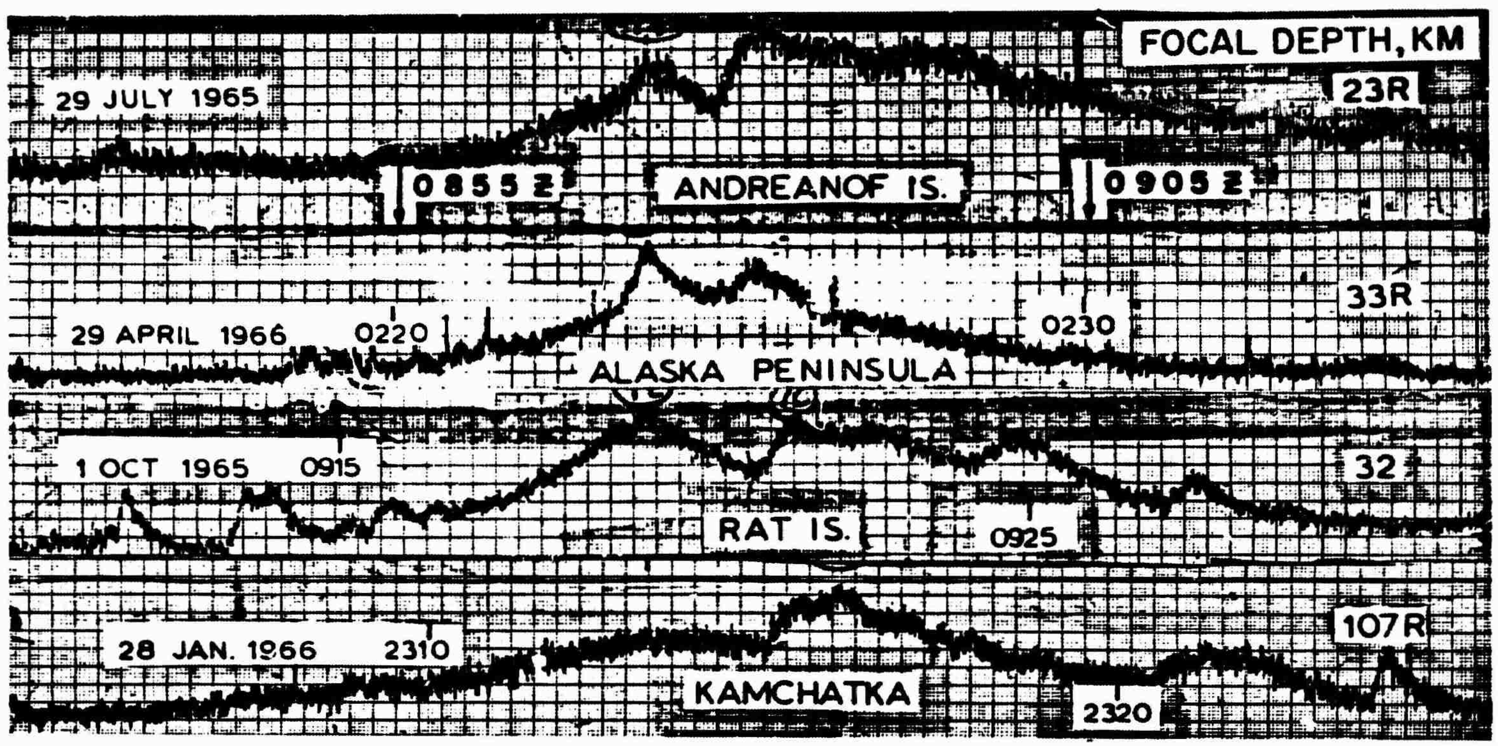


Fig. 6. T phases with both abyssal and slope arrivals selected from the Midway record. Additional earthquake source data are in Table 1.

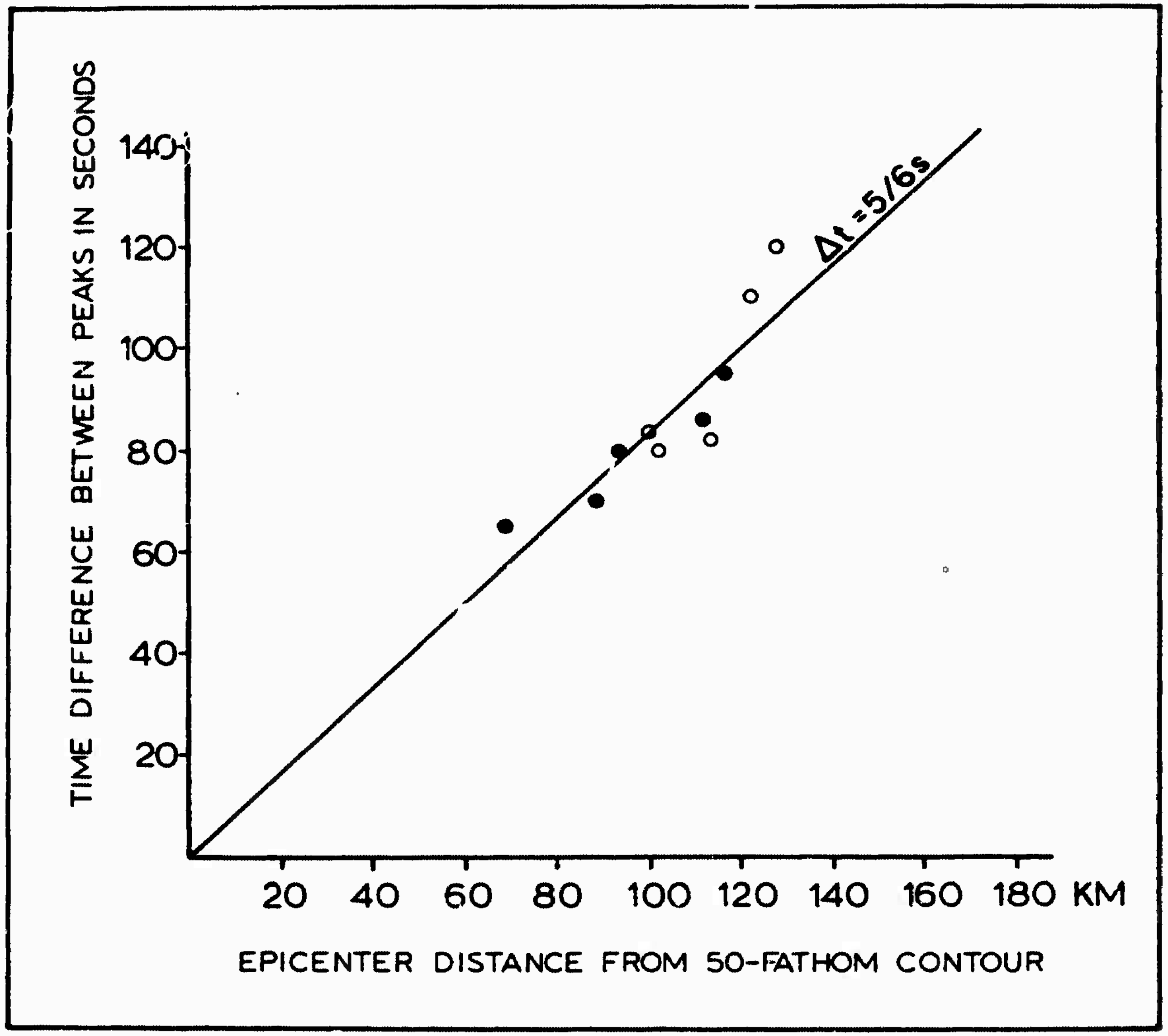


Fig. 7. Time separation of high- and low-frequency peaks versus the distance of the epicenter from the 50-fathom contour. Solid circles indicate the events for which magnetic tapes were obtained and the characteristic frequencies observed. Open circles indicate that the magnetic tape was not studied. The slope of the line is theoretical.

however, does not account for the absence of low frequencies from the abyssal T-phase spectrum. Also, as shown in the next section, the power-level variation of the abyssal T-phase record is appropriate to a diffuse source such as a scattering horizon; one would expect a signal of much shorter duration from a velocity-coupled mechanism.

SYNTHESIS OF POWER-LEVEL VARIATION

A conspicuous feature of abyssal T phases is the previously described gradually increasing onset rate. We will now draw a theoretical interpretation of this featu e and show how it is related to focal depth.

In Figure 8, a conventional cartesian coordinate system has its origin at the epicenter for a point source at depth $z = h$. The positive x-axis passes through a receiver dS at distance Δ. Under the assumption of spherical spreading in the crust, the intensity of P-wave radiation, incident at the level ocean floor, is described as

$$I \propto h(x^2 + y^2 + h^2)^{-\frac{3}{2}}$$

We assume that, to some layer in the ocean, the insonification of the ocean floor imparts a diffuse energy density which is proportional to I. This assumption does not take account of the variation with the angle of incidence of energy transmitted through the ocean floor. However, this error is partially compensated by neglecting the contribution of S waves at higher angles of incidence [Ergin, 1952].

We wish to obtain an expression for the sound power level at surface elements dS. Let dE' be the energy transmitted to dS from volume element dV which transects the excited layer. For large Δ, dE' is practically a constant fraction of the total energy radiation from dV.

$$dE' \propto I \, dV \, dS \propto h(x^2 + y^2 + h^2)^{-\frac{3}{2}} \, dV \, dS$$

All volume elements from which dS receives energy during the same inter l dt form a hyperbolic strip which is symmetrical about the x-axis. Such strip is indicated by AA' in Figure 8. The major contribution to the integral of dE' along this strip is from the portion near the epicenter (near the x-axis). In order to facilitate integration we will approximate the hyperbola by the straight line tangent to it at the x-axis, i.e., x independent of y. For $dV \propto dx\, dy$

$$dE = \int dE' \propto \int_{y=0}^{y=\infty} h(x^2 + y^2 + h^2)^{-\frac{3}{2}} \, dS \, dx \, dy$$

$$dE \propto h \, dS \, dx \left[\frac{y}{(x^2 + h^2)\ (x^2 + y^2 + h^2)^{\frac{1}{2}}} \right]_{y=0}^{y=\infty} = \frac{h \, dS \, dx}{x^2 + h^2} \ .$$

Since this energy arrives during the interval $dt = dx/\gamma$, where γ is T-wave velocity, the intensity at the receiver is

$$\frac{dE}{dt \, dS} \propto \frac{h \, \gamma}{x^2 + h^2} \ .$$

The power level with arbitrary reference is

$$L = 10 \log \frac{h}{x^2 + h^2} \ . \tag{1}$$

The travel time from the epicenter to the receiver is

$$t' = \frac{(x^2 + h^2)^{\frac{1}{2}}}{\alpha} + \frac{\Delta - x}{\gamma}$$

where α is P-wave velocity.

Expressed independently of Δ

$$t = t' - \frac{\Delta}{\gamma} = \frac{(x^2 + h^2)^{\frac{1}{2}}}{\alpha} - \frac{x}{\gamma} \ . \tag{2}$$

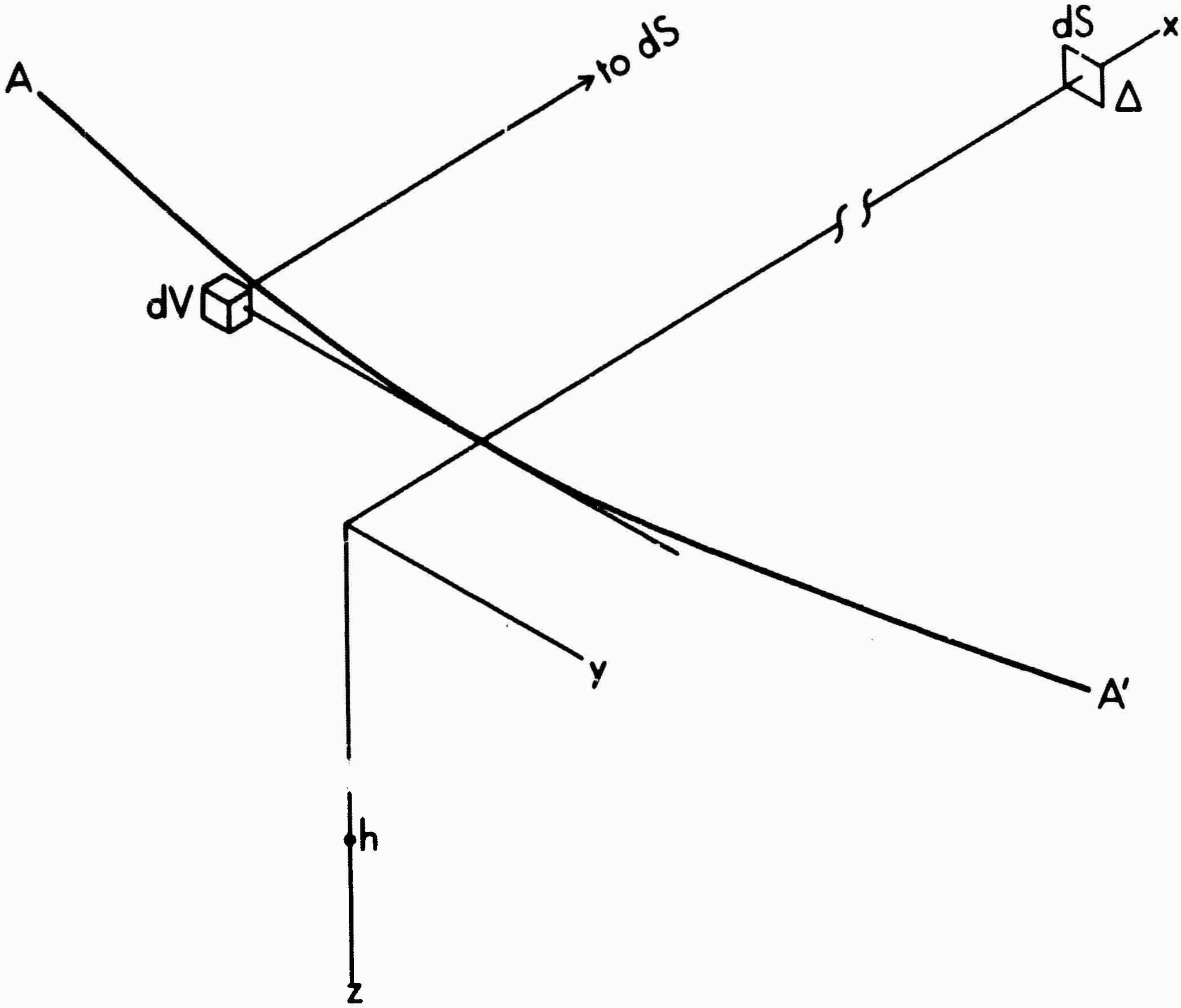


Fig. 8. Geometry for synthesizing abyssal T-phase power level.

From parametric equations (1) and (2) abyssal T-phase records can be synthesized.

Synthetic T phases, where $\alpha = 6$ and $\gamma = 1.5$ km/sec, are shown in Figure 9 for three focal depths. The arbitrary reference level for each synthesized curve has been adjusted so that they have a common asymptote. Two actual T-phase records are also shown for comparison. Despite the extensive simplifications in the foregoing derivation, the characteristic features of the abyssal T phase have been retained, as shown by comparison with the actual recorded events. The degree of sharpness of the abyssal T-phase peak appears to be a valid indicator of focal depth. This indicator appears more sensitive for shallower depth earthquakes.

DIRECTIONS FOR FURTHER STUDY

Abyssal T phases, as here described, have been positively identified only from sources in that sector of the Pacific rim which lies between Japan and Alaska. Throughout this region the sound channel is quite near the surface with the result that refracted surface-reflected (RSR) rays become sofar rays in the lower latitudes of the hydrophones. Is this transformation from RSR to sofar rays a necessary condition for observing abyssal T phases? Other regions where earthquakes occur under a deep ocean floor are off northern California and Oregon and the East Pacific Ridge. However, T phases observed from these regions have the classic low-frequency spectrum. Although the ocean floor in these regions may not be smooth it does not intersect the sound channel axis as is required by the downslope propagation mechanism for producing sofar rays. This anomalous situation must be resolved before our current models of T-phase generation can be completely acceptable.

Further study of the mode of propagation of abyssal T phases may be made by comparing the signal recorded from a sound-channel hydrophone with that from a hydrophone on the deep ocean floor. Such instruments have been installed by the Pacific Missile Range Facility at Wake Island and recording is now in progress.

Under the model proposed there it would be possible to demonstrate a continuously varying superposition of abyssal and slope-generated T phases as the epicenter is moved toward the slope; however, we have not as yet found intervals of less than 65 seconds between high- and low-frequency peaks. Although strong earthquakes with epicenters in non-abyssal regions often generate classic T phases with low-level forerunners, the forerunners appear to be of low frequency. An exception to this is the Kamchatka event shown in Figure 6.

Interest in sound scattering in the ocean has been practically confined to much higher frequencies and to the cases of back-scattering and forward-scattering [Chapman and Scott, 1964]. Some laboratory studies have been conducted with more variable geometry [Moore and Parkins, 1966], but the case of normal incidence was not included and the relation of laboratory surfaces to the ocean surface is uncertain. More appropriate experimental work is needed to determine the energy reradiated at low grazing angles for normally incident sound at frequencies of less than 100 cps.

ACKNOWLEDGMENTS

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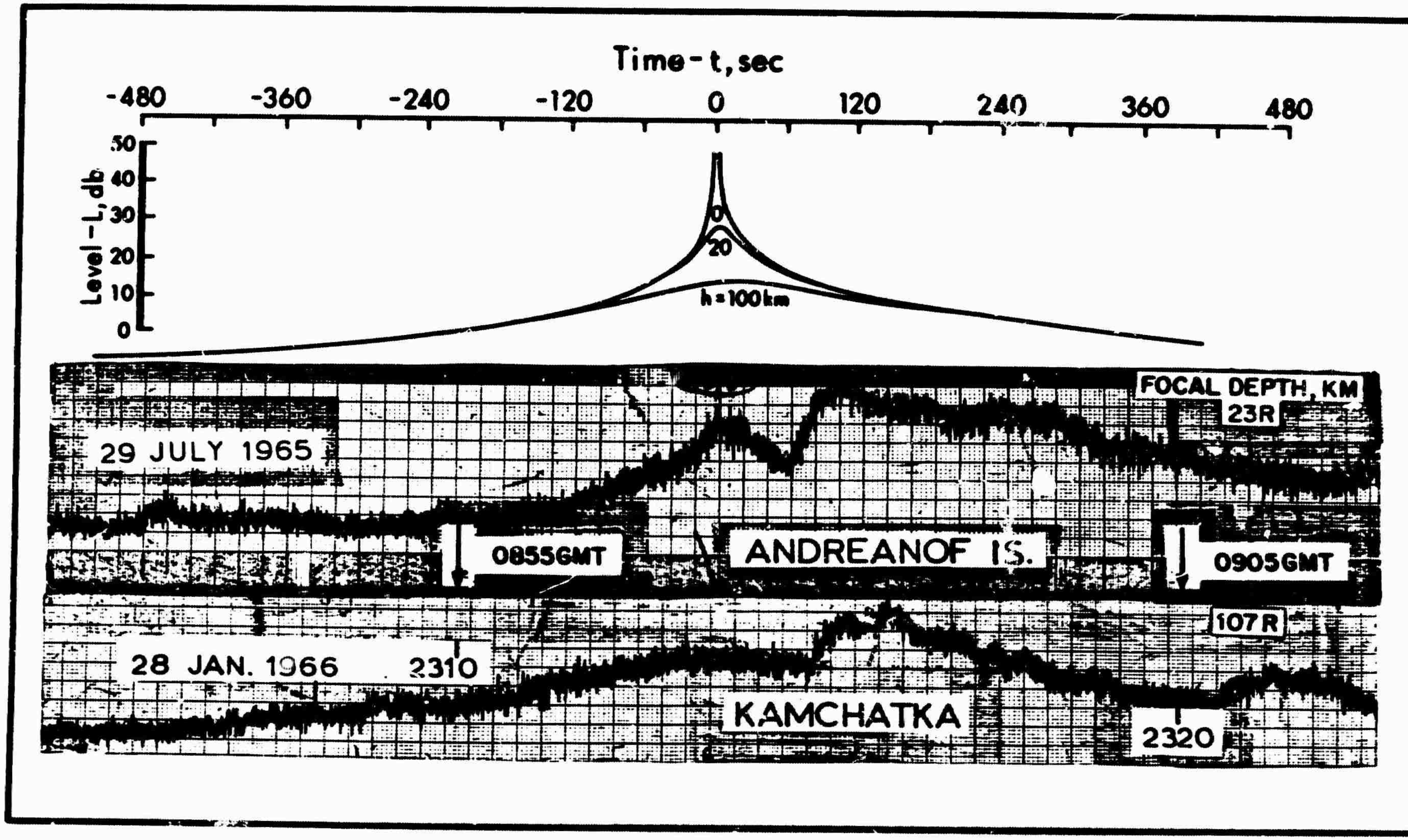

Fig. 9. Synthe . abyssal T phases for two focal depths. Two actual T-phase records are shown for comparison The level scale is the same for both synthesized and actual records.

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Two distinct types of signals have been identified from studies of T-phase spectra and source locations. One, with its source at a shoaling slope of the ocean bottom and with dominant frequencies near 4 cps, is the previously recognized and described classic T phase. The other, with its source in deep water and with dominant frequencies near 30 cps, is newly identified and is here termed the abyssally generated, or abyssal, T phase. Scattering from the sea surface is proposed as a mechanism for producing rays which propagate through the ocean with an apparent velocity equal to sofar velocity. The sea surface roughness is hypothesized as shaping the spectrum of the abyssal T phase. A synthesis of the power-level record is derived which relates the degree of sharpness of the abyssal T-phase peak with focal depth.

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