SEISMOGRAM ANALYSIS

TRAINING OUTLINE

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April 1960

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INTRODUCTION

The following is a detailed outline for training personnel in the analysis of seismograms from Benioff short period seismometers and in the use of the resulting data to determine locations, origin times, and magnitudes of earthquakes. It is important to remember that, unless otherwise stated, all items discussed will be for data from short period instrumentation. In reading papers and books on seismology the type of instrumentation the author has based his statements on must be considered. The reader must also be careful to separate facts from theories.

In order to understand the material to be presented the student must be familiar with the following terms and their definitions:

1. Focus or Hypocenter - The actual point at which an earthquake occurs.
2. Epicenter - The point on the surface of the earth directly above the focus.
3. Epicentral Distance - The great circle distance between the epicenter and a recording station. In degrees, it is the angle between radii through the two points.
4. Travel Time - The time it takes an elastic wave to travel from the focus to the seismometer.
5. Phase - The arrival at the seismometer of an elastic wave of a given type which has traveled a specific reflected and/or refracted path through the earth.
6. Period - The time between successive maxims or minims in a sine-type wave.
7. Amplitude - The distance, usually in mm, between successive maxims and minims in a sine-type wave.
8. Magnitude - A measure of the size of an earthquake. Magnitudes range from 0 - 8.7. Scale is logarithmic.
9. Intensity - A measure of the effect of an earthquake. Intensities range from 0 - 12. Scale is roughly linear.

1. THE EARTH

1.1 SIZE AND SHAPE

From data published in "The Geophysical Journal of the Royal Astronomical Society, Vol. 2, No. 3, Sept. 1959", pp 238:

Equatorial Radius = 6378.2 km
Ellipticity, e^{-1} = 298.2, or
Radius through Poles = 21.4 km less than the equitorial radius

The above is based on satellite observations. Data from satellites also indicates the earth is not a true ellipsoid but is somewhat tear-dropped or pear shaped.

1.2 THE LATITUDE AND LONGITUDE

The Latitude, Longitude Coordinate System (brief discussion) - Geocentric and Geographic Latitude (discuss difference). Geographic is always greater.

$\tan \lambda_c = 0.9932315 \tan \lambda_g$ for a Clarke spheroid
$\tan \lambda_c = 0.9932773 \tan \lambda_g$ for the International spheroid

(See Macelwane pp 279 and 332.)

1.3 GREAT CIRCLE ARCS

Any plane which passes through the center of the earth cuts the surface of the earth in a great circle. (Discuss and illustrate.) Useful constants:

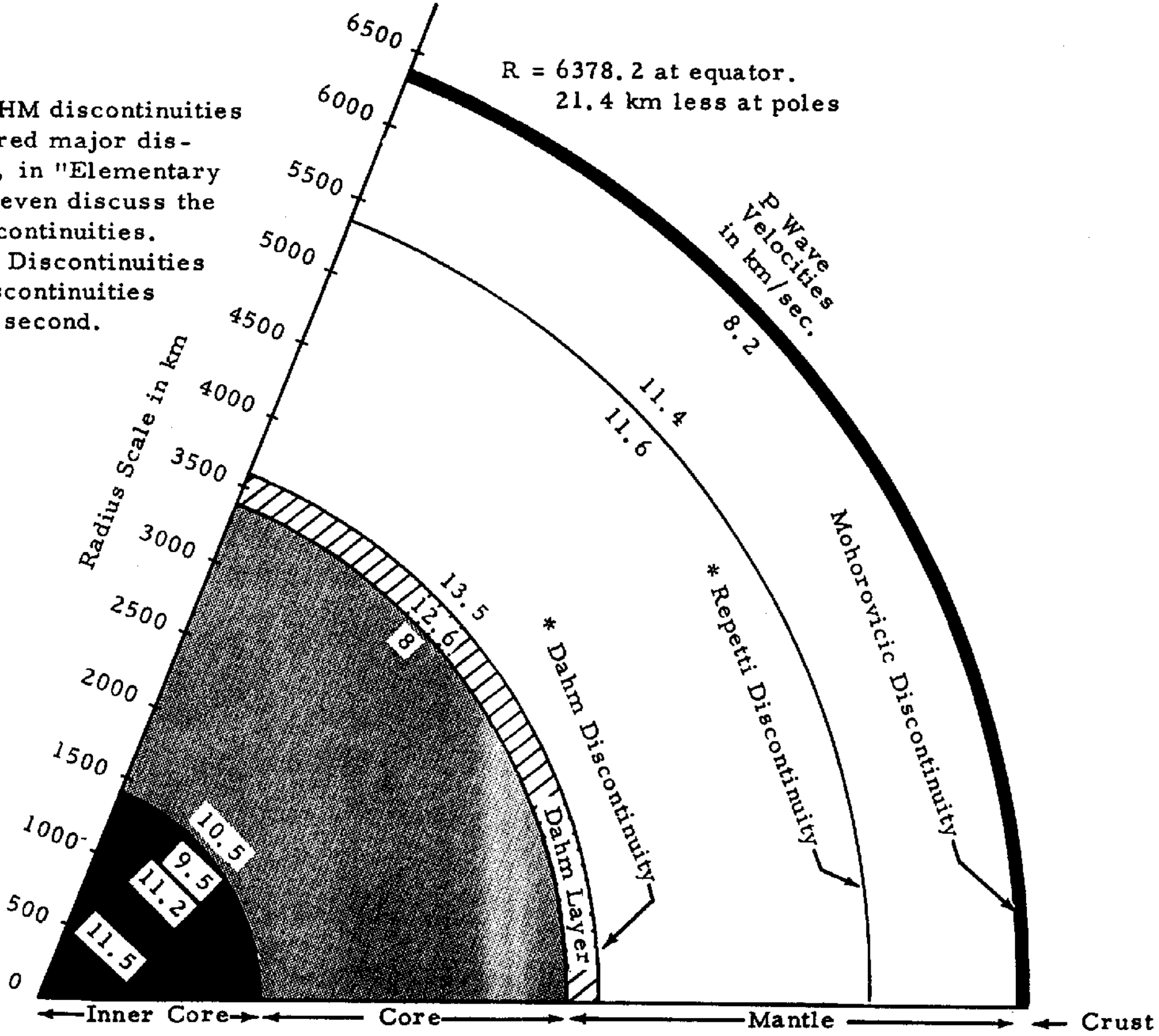
1° = 111.32 km = 69.17 statute mi.
for the equitorial great circle.

1.4 INTERNAL FEATURES OF THE EARTH

Refer to diagram. (Discuss.)

Location of major discontinuities - crust, mantle, core, inner core
Isostatic Equilibrium - thickness of crust under oceans and continents
(Macelwane and Richter)

THE INTERIOR OF THE EARTH



* The REPETTI and DAHM discontinuities are no longer considered major discontinuities. Richter, in "Elementary Seismology" does not even discuss the Repetti and Dahm Discontinuities. The Repetti and Dahm Discontinuities are not first order discontinuities and probably not even second.

The location of the boundary between the inner core and the outer core is not precisely known.

1.5 SEISMICITY OF THE EARTH

Discuss the major earthquake belts - deep sources - Refer to "Seismicity of the Earth", Gutenberg and Richter, and "Elementary Seismology", Richter.

2. EARTHQUAKES

2.1 DEFINITION

The release of elastic-strain energy at a source or "focus" to produce elastic waves which travel through the earth.

There is poor agreement among authors as to the definition of earthquakes; some restrict the use of the term to structural faulting while others apply it to almost any earth disturbance. There are about 10,000 quakes a year that are strong enough to be located. Of these, only around 10 are really big shocks.

2.2 TYPES

2.2.1 Tectonic Quakes - Caused by faulting - illustrate - Probably 95% or more of the world's earthquakes and all of the strong quakes are of this type. They may be divided into three classes:

1. Shallow or normal - focus above the Moho.
2. Intermediate - below the Moho to 300 km
3. Deep - 300 to 800 km.

Many people, including myself, do not distinguish between intermediate and deep shocks; we call anything below the Moho deep. The term "surface" is often applied to shallow or normal shocks though this is not strictly correct. Most Tectonic shocks are shallow or normal.

2.2.2 Volcanic - Earthquakes are commonly associated with volcanic action. Some may properly be called volcanic quakes, as those due to eruptions and movement of magma at depths, however, many are Tectonic quakes triggered by volcanic activity.

2.2.3 Slides - Large earth alides may produce seismic waves, however, such quakes would be very weak. The common association of slides with quakes is due to slides being triggered by quakes. This was the case in the Hobgen Dam, Montana quake of 18 August 1959.

2.2.4 Foreshocks and Aftershocks - Strong earthquakes are often preceded by preliminary tremors. These are usually much smaller than the main shocks though in some instances they may be fairly large. When a series of shocks occur, those preceding the strongest shock are termed foreshocks while those following it are called aftershocks. Work by Benioff has indicated that the magnitude and number of aftershocks tend to decrease with time in a logarithmic relationship. Frequently it is found that fore and aftershocks will not all have the same focus but will show a slight spread around the location of the main shocks. (See Richter pp. 522.)

2.2.5 Earthquake Swarms - It is not uncommon to record, over a period of time, a large number of earthquakes all from about the same place, none of which are particularly outstanding in the group. When quakes occur in such groups the group is called an earthquake swarm. There are often several strong shocks in such a group but no one shock can be picked as the main earthquake. Swarms are observed most frequently in areas of volcanic activity and may be an indication of movement of magma at depth.

2.3 SEISMIC WAVES

There are two kinds of seismic waves, body and surface waves. Body waves travel through the interior of the earth; surface waves are associated with the crust and upper part of the mantle.

2.3.1 P Wave - Fastest seismic wave - particle motion parallel to direction of propagation - sometimes called longitudinal or compressional wave or push-pull wave. This is a body wave. (Show wave path.)

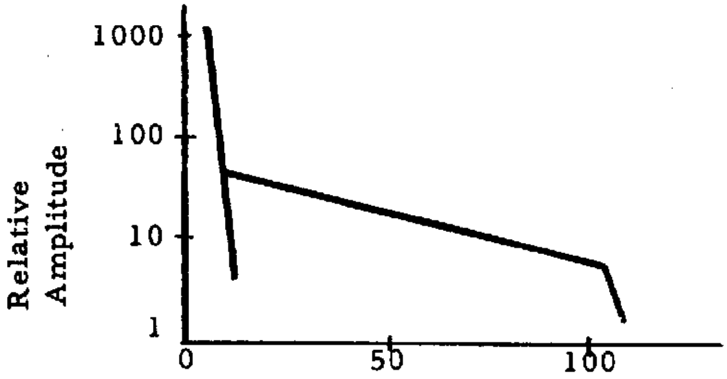
Period - The period of P may vary from less than 0.1 second up to about 2 seconds. Periods of less than 0.3 second are usually associated with events whose focus is less than 1000 km distant.

Velocity - The apparent surface velocity or travel time varies from 6 km/sec. to 25.7 km/sec. (See P wave travel time curve.) Actual velocities in the earth vary from 6 km/sec. In the crust to a maximum of 13.5 km/sec. at the inner edge of the mantle.

Discuss velocities shown in diagram and Figure 4 in J. B. Tables.

Effect on instruments - Show effect of P wave on three component system.

Amplitude vs. distance - Use figure as shown.



2.3.2 S Wave - Second fastest seismic wave - Particle motion is normal to direction of propagation - often called shear wave. This is a body wave. Almost same wave path as P.

Period - The period of S may vary from 0.1 second up to about 5 seconds. Periods of less than 0.5 second are usually associated with events whose focus is less than 1000 km distant. The period is usually slightly less than twice that of P.

Velocity - The apparent surface velocity of S is about 0.55 times that of P; the travel time is about 1.8 times that of P. (See figure 4 in J. B. Tables and pp 253 for further data on S wave velocity.)

Effect on instruments - Show effect of S wave on three component system. Cover possible polarization of S waves.

Amplitude vs. distance - S is rarely recorded at distances from 6 to 15° unless the event is deep. At less than 6° it is strong, usually being larger than P. Beyond 15° may be recorded, but it is much weaker than P, seldom being seen unless the P wave is 50 mu or more. It is usually much stronger on one horizontal than the other, depending on its polarization.

2.3.3 Surface Waves - We will cover four kinds; Love, Rayleigh, T, and Lg. Though all are called surface waves, Love and Rayleigh waves of long period actually travel in the mantle due to their long wave length. Short period instruments do not record surface waves well and they, therefore, are of little value.

2.3.3.1 Love waves - Third fastest seismic wave - Particle motion is normal to direction of propagation and in a horizontal plane. These are surface waves, often called L or G - Show wave path - Lasts many cycles.

Period - The period of Love waves varies from 2 to about 500 seconds.

Velocity - The velocity may vary from 2.5 to 4.4 km/sec., this is dependent upon the period of the wave and in which structure the wave is located. (Oceanic, Sedimentary, or Continental.) Show curve.

Effect on instruments - Show effect of Love wave on three component system.

Amplitude - This is dependent on the size of the quake and the depth of focus. Love waves are seldom seen from quakes whose depth focus is over 75 km. Beyond 20°, we seldom see Love waves except from very large quakes. At distances of less than 20°, Love waves are common and are often mistaken for S. They are difficult to see clearly due to overlying motion from S and R waves.

2.3.3.2 Rayleigh waves - Slowest seismic wave - Particle motion is retrograde elliptical in a vertical plane parallel to direction of propagation. These are surface waves called R - last many cycles. Show wave path.

Period - The period of Rayleigh waves may vary from 2 to about 500 seconds.

Velocity - This may vary from 1.0 to 4.3 km/sec., depending on the period of the wave and the structure of the earth the wave is in (Oceanic, Sedimentary, Continental, or Mantle). Show curve.

Effect on instruments - Show effect of Rayleigh wave on three component system. The Two horizontals will always be either in phase or 180° out, and will lag the vertical by 90°.

Amplitude - As was the case for Love waves, this is dependent on the size of the quake and its depth. Rayleigh waves are seldom seen from quakes whose depth of focus is over 75 km. Beyond 20° Rayleigh waves are common but are difficult to see clearly due to overlying L wave motion.

2.3.3.3 The T wave - This is a wave of fairly recent discovery (1940) and one that is not yet "necessarily" thoroughly explained. Ewing, Press, and Tolstoy showed it is in effect a sound wave in the sea; Gutenberg believed it is transmitted in the Solar channel as a guided wave which, when impinging on the continent gives rise to P, S, and surface waves which are recorded as a complex and irregular short period phase. The mechanics of its origin are even less well understood though it seems to be produced only by quakes occurring in oceanic structure.

2.3.3.4 The Lg wave - A guided wave in the continental crust. Compared to Love and Rayleigh waves it is small and short period. It is occasionally seen superimposed on the longer surface waves. It is cut off if its path has to cross even a small section of oceanic crust.

2.3.4 Microseisms

The more or less continuous movement of the ground due to both cultural and natural causes. They are generally a mixture of Love and Rayleigh waves.

Cultural mics are usually short period (1.0" and down) and are often "cigar" shaped (gradual build-up and decay). A few of the many possible sources are:

road work
traffic
trains
quarry work
power plants
heavy machinery
mining
etc.

Natural mics are normally thought of as having long periods (5" and over), however, at least two types are short period. The first type is due to running water, surf, or water falls. The second and more important, since the first can easily be avoided, are mics due to strong local winds. These are unpredictable, difficult to avoid, and can make a record useless.

Natural mics of long period, often peaking around 6", have been shown to be associated with cyclonic storms over water. The mechanism by which the storm's energy is transferred to the ground remains uncertain. These waves lose much of their energy when crossing major structural boundaries.

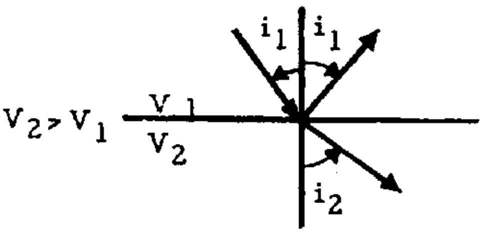
Some authors apply the term microseism only to the long period waves, preferring to call the short period waves "noise". (See Richter, pp 375 - 378).

2.4 REFLECTION AND REFRACTION OF SEISMIC WAVES

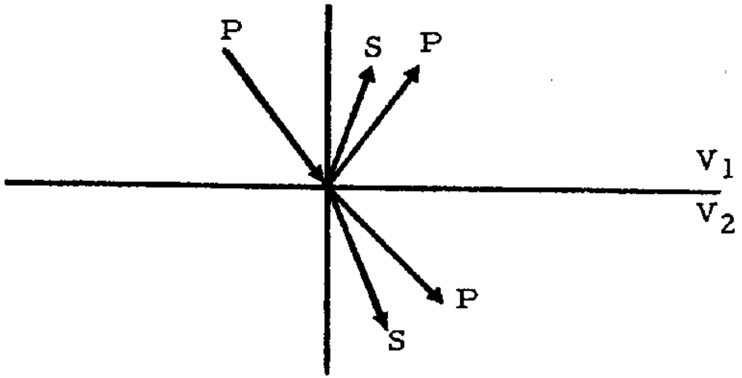
Based on laws of optics, there are two main laws:

1. Huygens Principle - If a wave front strikes a surface, each point on the surface acts as a new energy source.

2. Snell's Law - $\frac{\sin i_1}{\sin i_2} = \frac{V_1}{V_2}$



(See Richter pp 251).



3. ANALYSIS

Define envelope. Earthquakes are usually divided into four types, each type corresponding to an approximate distance range. The classification of a quake as one of these types is decided, however, by its recorded character. There is a transition zone between each range where a quake may be one type by character but a different type on the basis of distance. In such instances the type indicated by the character should be used.

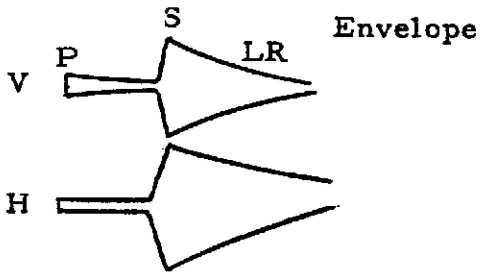
The four types are: Local, near regional, regional, and teleseism.

Characteristics of each type are discussed below. Equal gain on the vertical and horizontals is assumed.

3.1 LOCALS

Locals - $\Delta = 0 - 1.4^{\circ}$, S-P = 0 - 20".

Period - P and S 0.3" or less
L and R 0.5" or less



Amplitude - P usually larger on V
S usually larger on H

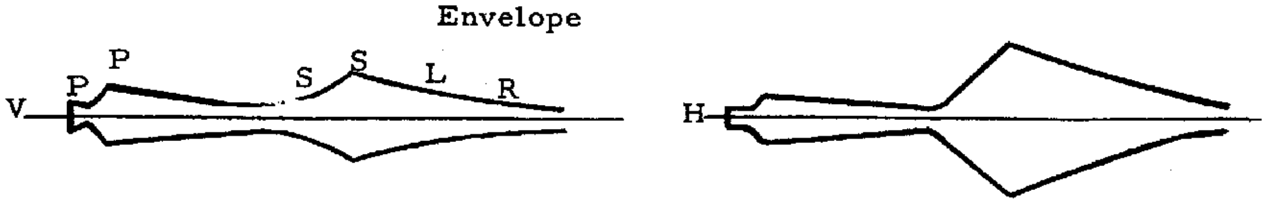
These amplitudes may be reversed due to a horizontal direction of approach by the waves. The maximum amplitude usually occurs in the S group. Rayleigh waves may be 20 times as strong as the P group. Thus, if the P is weak enough you may see only the Rayleigh waves and mistake them for a teleseism. The vertical and one of the horizontals should show about the same amplitude in the case of Rayleigh waves.

3.2 NEAR REGIONALS

Near regionals - $\Delta = 1.4 - 6^{\circ}$, S-P = 20 - 70".

Period - P and S 0.5" or less though longer periods are sometimes observed.

Define - Coda - .5 - 2".



Amplitude - P usually larger on V
S usually larger on H

As in the case of locals, these may be reversed due to a horizontal direction of approach by the wave. The maximum amplitude normally occurs in the S group. Initial S is difficult to pick due to continuing P motion.

Note that both P and S show multiplicity. This is generally believed to be due to refraction of the wave fronts along layers in the earth's crust.

3.3 SEISMIC WAVES AT SHORT DISTANCES

See Richter 282 - 296. In the preceding paragraphs we discussed the character of local and near regional shocks to the extent that little difficulty should be encountered in recognizing them on a seismogram. Various arrivals were simply called P, S, L, and R. This is correct as far as the types of elastic waves composing the signal are concerned, however, the body waves recorded for local and near-regional shocks are greatly affected by crustal layers so their paths through the earth bear little resemblance to those for true P and S. In order to explain the complex arrivals observed in local and near-regional quakes, seismologists have proposed many different types of crustal layering and wave propagation. These have resulted in a multitude of possible phases, each having a different notation. The student of seismology trying to gain an understanding of near earthquakes is thus beset with a number of different P types; some are outdated, others represent only one seismologist's opinion, which may never have been generally accepted. Since all of the different P types are simply the result of different theories about the earth's structure we shall discuss only the ideas most generally accepted at this time and then discuss the resulting P waves. There would be a corresponding S for each P type.

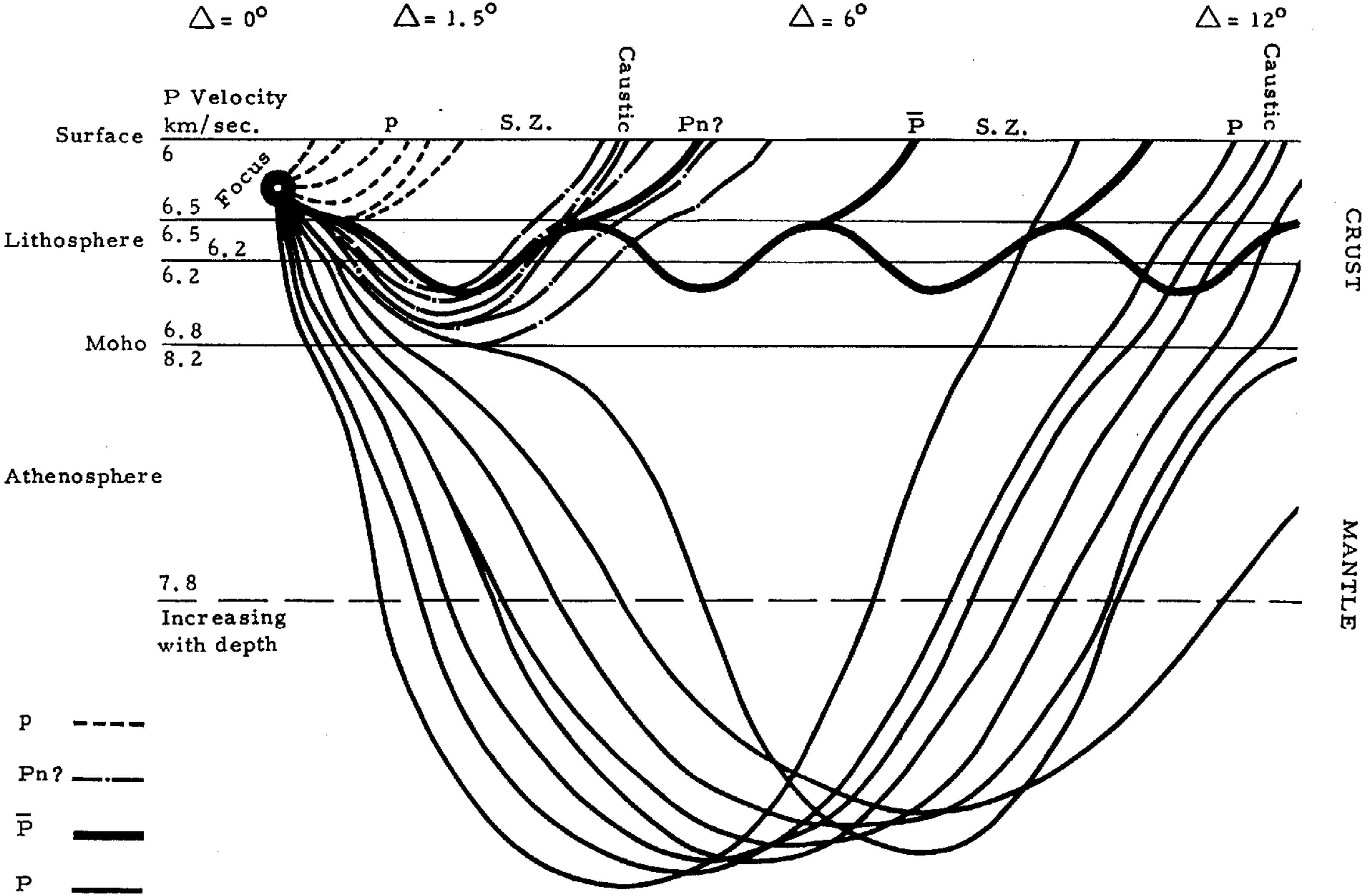
The Moho discontinuity was discovered by A. Mohorovicic near the turn of the century. Little reinterpretation of it has been required through the years. The sharp change in velocity as an elastic wave crosses it is well established.

In 1926, B. Gutenberg found indications of a low-velocity layer at a depth of about 50 miles. He called this the "athenosphere" layer. His belief in this layer was a solitary one until recent work by Press and Ewing with surface waves confirmed its existence. It is the region immediately below the Moho.

When viewed as a whole, the earth's crust appears to be hopelessly heterogeneous. It may, however, be divided into two general classifications: Oceanic structure and Continental structure. In the first, the Moho is about 10 km below the surface with the crust being composed of three major layers: (a) water, (b) sediments, (c) basaltic material. The depth to the Moho on continents is about 35 km with at least 4 main layers: (a) sediments, (b) a mixed and folded tectonic layer, (c) a granitic layer, (d) a basaltic layer. Keep in mind that these are very general descriptions and that the crust may be radically different at any given point.

Gutenberg has proposed that in portions of at least two of the crustal layers velocity may decrease with depth. Work by Press and Ewing, Miss Lehmann, and M. Bath have tended to confirm this. Gutenberg terms these layers "lithosphere" channels.

WAVEPATHS AT SHORT DISTANCES



From analysis of seismograms there appears to be at least 5 different P arrivals at short distances:

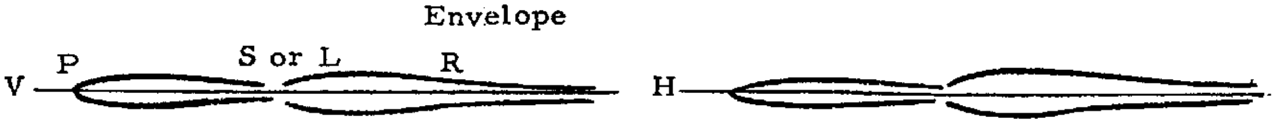
1. $\bar{P}$ - velocity = 5.5 km/sec. A channel wave in the lithosphere channel. Commonly seen following Pn where Δ exceeds 150 km.
2. p - velocity = 6.34 km/sec. The direct wave from focus to station. First arrival out to about 120 km.
3. Pn - velocity = 3.1 km/sec. First arrival from 120 km to about 12°. Travel time curve ties into that for true P. Old theory said this wave was horizontally diffracted just below the Moho, however, belief in the athenosphere channel almost precludes this type of path. There is mounting evidence that velocities of first arrivals from surface focus quakes in this distance range are nearer 6.8 - 7 km/sec. corresponding to a wave that does not penetrate the Moho.
4. P - velocity varies with epicentral distance. First arrival from about 12 - 105°. Travels in the mantle.
5. Not yet well defined. A wave reflected from the Moho. Its travel time will be highly dependent on the depth of the Moho.

The illustration on the following page shows the path of each of these phases except No. 5. I have used only one lithosphere channel in order to simplify the wave paths. Wave velocities and layer thicknesses shown are generalizations. Note the shadow zone and caustic regions caused by the lithosphere and athenosphere channels. These are highly sensitive to focal depth. The figure is greatly shortened in length.

3 4 REGIONALS

Regionals - $\Delta = 6 - 16^{\circ}$; S or L-P = 1 - 5'.

Period - P = 0.3 - 1.0" occasionally greater.
L and R = 1 - 5".



Amplitude - P, L, and R - Commonly have about the same amplitude on V and H though the surface group is often larger on the H. The maximum amplitude occurs in the surface group.

True S is seldom recorded in this distance range. A very common error is to call the surface wave arrival S. When S is observed, the quake is usally deep and S may be seen preceding the surface arrival, if there are surface waves.

3.5 TELESEISMS

Teleseisms - $\Delta = 16 - 180^\circ$; S-P = 3° - 10:33 ± 5.

Events in this distance range do not have a common envelope. (Illustrate with several possible ways P might look).

Period - P = 0.4 - 2.0", usually 0.6 - 0.9
S = slightly less than twice the period of P.

Amplitude - P - Always larger on the vertical.
S - Usually larger on one horizontal.

Note that one H may show it stronger than the other. (It is conceivable that S might be stronger on the V due to polarization. I have never observed this).

3.6 PHASES AND TRAVEL TIME CURVES

Phases and travel time curves - define terminology used:

1. Reflections from surface as PP
2. Reflections from core as PcP
3. Refractions through the core as PKP = P'

Develop travel time curves for the following phases:

	P	0	103°	
diff	P	103	140°	
	P'_1	180	142°	long period
	P'_2	142	190°	long period
	P'	108	142°	short period (Richter calls this P'') pp 258
	S	0	103°	
	L	0		
	R	0		
	PP	0	206°	
	PKS	103	180°	

PcP	0	90°
PcS	0	70°
ScS	0	83°
SKS	83	180°
PKKP	0	162°
P'P'	0	140°

3.7 COMMONLY RECORDED PHASES

The recorded character of quakes whose epicentral distance exceeds 16° (teleseisms) is extremely varied. The following discussion will cover only quakes in that distance range. The strength and character of the initial arrival and subsequent phases depends primarily upon four variables: (a) Magnitude of the quake, (b) Epicentral distance, (c) Depth of focus, and (d) Natural period of the phase.

The term "focus" has two meanings in seismology. It may mean the actual point at which the quake occurred, or, it may refer to an epicentral distance at which a given phase tends to be strong in relation to its amplitude at other distances.

The first of these, size of the quake, is probably the most important. We see only the P phase for the vast majority of quakes in this distance range. As the size of the quake increases, the shorter period phases begin to be recorded at their focal distances. If the quake is near magnitude 6, the longer period phases may be recorded at their focal distances. If the quake is exceptionally large (say mag. 7 and up), phases may be recorded at many distances.

The chances of recording phases are greatly enhanced if the quake is deep, except for surface waves which, as was mentioned before, are rarely seen from deep quakes.

The character of some phases is briefly summarized in the table on the following page.

Phase	Period range	Common period	Stronger on	Focal distance	Remarks
P	0.3-2	0.6-0.9	V		Observed from 0-103°
diff P	0.5-2	0.7-0.9	V		Observed from 103-140°
P'	0.5-2	0.7-1.2	V	142°	Richter calls this P", 108-142°
P'_1	0.8-5	1-2	V	142°	Observed from 142-180°
P'_2	0.8-5	1-2	V	142 & 180°	Observed from 142-190°
S	1-5	2-3	H		Never lasts over 2 or 3 cycles Observed from 0-103°
L	2-500	20	H		Lasts for many cycles, show dispersion.
R	2-500	20	V		Last for many cycles, show dispersion.
PP	0.6-4	1.0-2.5	V	20-25° 34-51° 61-84° 120° 180°	Longer period than P
SP	1-4	2-3	V	120°	Seldom seen unless quake is deep
SKP	0.6-4	1.5-2.5	V & H_L	131°	Observed from 103-180°
PcP	0.4-2	0.5-1.0	V	30-40°	Observed from 0-90°
ScP	0.6-2	0.8-1.2	V & H_L	30-40°	Observed from 0-70°
ScS	0.5-3	1-2	V & H_L	30-40°	Observed from 0-83°
SKS	2-6	2-3	V & H_L	93-105°	Precedes S from 83° out
PKKP	0.5-2	0.8-1.2	V	121°	Often mistaken for new quake
P'P'	1-4	1.5-2.5	V	76°	Often mistaken for new quake
SKPP'	2-4	1.5-2.5	V	87°	Seldom seen unless quake is deep
pP	0.6-3	0.8-1.2	V		Depth phase
PcPP'	1-4	1.5-2.5	V	175°	May be mistaken for new quake

The phase PcP is the only phase that commonly exhibits a period as short as or slightly shorter than P.

Several phases that usually have periods only slightly longer (0.1 to 0.4") than P are: PP, ScP, SKP, PKKP, P'P', and pP.

The period of S is usually a little less than twice that of P.

The period of P' is short (0.5-2") at distances less than 142° but is normally longer at distances beyond 142°.

At about 83° S begins to be preceded by SKS. It is not uncommon to observe both SKS and S at about 84 - 85°.

Due to polarization on some phases whose last leg of travel is as an S are recorded well on the vertical and the longitudinal horizontal components and poorly on the transverse horizontal.

If the quake is deep, all phases, including P, seem to exhibit slightly shorter periods than for a comparable surface quake; phases also tend to build up and decay rapidly. This is probably due to the elimination of one path through the crustal layers in the case of phases from deep quakes.

3.8 DIRECTION DETERMINATION

The direction of approach may be determined for P waves through the use of the following criteria:

1. If the ground moves up, the V trace moves up;
2. If the ground moves North, the N-S trace moves up;
3. If the ground moves East, the E-W trace moves up.

Thus, the relation of the vertical trace to the horizontal traces will establish the direction of approach. A common method of determining this relationship is the in-phase, out-of-phase method. Thus:

1. V and N-S in; direction toward focus is S;
2. V and N-S out; direction toward focus is N;
3. V and E-W out; direction toward focus is E.

If one horizontal shows twice or more amplitude than the other, the direction is more nearly in line with that horizontal exhibiting the greater amplitude.

4. TIMING

(Discuss the importance of accurate timing.)

4.1 WWV AND WWVH

The National Bureau of Standards broadcasts time signals at 2.5, 5, 10, 15, 20, and 25 megacycles from Beltsville, Maryland (near Washington, D. C.) and at 5, 10, and 15 megacycles from the island of Maui, Hawaiian Islands. The first is called WWV and the second WWVH. Their standard carrier frequencies are modulated with various standard audio tones and time signals to provide timing references.

During the first three minutes of each five-minute interval, starting on the hours, the carriers are modulated by tone signals, 600 cps during the first three-minute period, 440 cps during the second, etc. These are interrupted for 40 milliseconds each second except at the beginning and end of each 3-minute period. Starting 10 milliseconds after the beginning of the 40 millisecond interruption, second pulses are superimposed on the carrier every second except the 39th. An additional pulse is sent 0.1 second after each minute. You can hear this double click.

WWV second pulses are 5 cycles of a 1000 cycle tone, those of WWVH are 6 cycles of a 1200 cycle tone.

Just before each 5 minute, station identification is given in voice from WWV and International Morse Code from WWVH. Also, at this time Eastern Standard Time is announced from WWV and both stations code Greenwich Time.

Radio propagation forecasts for the North Atlantic are broadcast at 19-1/2 and 49-1/2 minutes past the hour by WWV and at 9 and 39 minutes for the North Pacific by WWVH.

WWV is off the air about 4 minutes each hour starting at 45 minutes plus 0 to 15 seconds.

The accuracy of information broadcast is as great as the present state of engineering art will permit. Frequencies are accurate to within one part in 10^8.

4.2 TIME CORRECTIONS

Superimpose WWV on the program from the timer in use. If WWV puts a time mark on before the clock, clock is slow and the correction is +; if WWV puts the time mark on after the clock has, the clock is fast, and the correction is —.

4.3 CHRONOMETERS

Hamilton; skips the minute mark. Ulysses-Nardin; skips the 50-second mark.

With chronometers you must key on your own reference marks and code what they are.

```
- - - - -  =  0
. - - - -  =  1
. . . . .  =  5
- . . . .  =  6
- - - - .  =  9
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5. INSTRUMENTATION

This section could cover many items, however, we shall plan on only calibrations.

5.1 GAIN

Equations for obtaining the gain using weight lifts and sine wave calibrator are given.

Weight Lift

$$\text{V - Gain} = \frac{800\ (\text{mm})}{\text{Wt. in grams}}$$

$$\text{H - Gain} = \frac{1600\ (\text{mm})}{\text{Wt. in grams}}$$

Ball Lift Calibrator

$$\text{V - Gain} = \frac{800\ (\text{mm})}{\text{Wt. in grams}}$$

$$\text{H - Gain} = \frac{8000\ (\text{mm})}{\text{Wt. in grams}}$$

Sine Wave Calibrator

$$\text{V \& H - Gain} = \frac{1000000\ (\text{mm})}{\text{Driving force in mu}}$$

5.2 FREE PERIOD

Initial set-up free period should be 60 cpm ± 1%. This is then allowed to vary from 55 - 65 before adjustment is required.

5.3 DAMPING

Initial set-up damping ratio should be 15:1. This may then vary from 5:1 to 50:1 before adjustment is required.

6. MAGNITUDE

Because short period instrumentation often records only the P wave, Gutenberg's "Unified Magnitude" is used.

6.1 GROUND MOTION

If the period and amplitude of a P wave are known, the corresponding ground motion may be found from the following equation:

$$\text{mu/sec.} = \frac{(\text{mm})\ (10^6)\ \frac{1}{G_t\ T}}{\text{Gain}}$$

where mm = peak-to-peak amplitude and $\frac{1}{G_t\ T}$ = f (T); see following table:

PERIOD CORRECTION FACTORS

T	$\frac{1}{G_t\ T}$
0.4	.833
0.5	.752
0.6	.722
0.7	.752
0.8	.823
0.9	.902
1.0	1.000
1.1	1.213
1.2	1.384
1.3	1.572
1.4	1.820
1.5	2.030

6.2 UNIFIED MAGNITUDE

The unified magnitude is defined as:

$$m = \log_{10} \frac{\Delta}{T} + Q + S$$

where $\frac{\Delta}{T}$ = microns of ground movement from G with a period of T seconds,

$Q = f(\Delta, h)$ already in log form, and
S = station correction factor.

Richter on pp 688, Fig. VIII-6, has called Q, A.

Since we use peak-to-trough amplitude and normally obtain amplitude in mu, we uniformly reduced the factor Q (or A) by $\log_{10} 2000 = 3.3$.

We do not use the station correction factor.

The unified magnitude may be related to that obtained from surface waves (M) by the following equations:

$$m = 2.5 + 0.63M \text{ or } M = 1.59m - 3.97 \text{ (see Richter pp 348)}$$

7. EPICENTER DETERMINATION

The location, depth, and origin time of an earthquake may be determined by analysis of the following factors: Direction of approach, phase minus P time intervals, and time intervals between recording stations. Direction determination has been discussed previously. The use of phases and time intervals between stations in conjunction with P wave travel time charts will now be covered.

7.1 USE OF PHASES TO DETERMINE DISTANCE

S-P. The time interval between P and S is a valuable indication of distance from 0 - 6° and 16 - 83°. Beyond 83° it is difficult to identify S among SKS, ScS, and PS.

The S-P interval decreases as focal depth increases so the depth of the event must be known before the S-P interval can be used to obtain a close distance estimate.

PcP-P. If PcP can be positively identified it may be used to estimate distance in the range 10 - 50°. The PcP-P interval is not greatly affected by focal depth.

PKKP-P and P'P'-P. These time intervals may give a good estimate of distance. They are virtually unaffected by focal depth.

Surface Waves - P. These will sometimes give a rough estimate of distance.

7.2 USE OF PHASES TO DETERMINE DEPTH

pP-P. This is the most valuable aid to analysts in determining depth. pP-P varies with both depth and distance but is much more sensitive to changes in depth so that focal depth may be obtained for quakes whose distance is not known (see Table in J-8 Tables).

S-P. If distance is known, the S-P interval will give a fair estimate of depth.

PcS-ScP. Though rarely observed, this interval will give an excellent indication of depth and is only slightly changed by distance. The difference is 10 seconds for each 100 km of depth.

(Discuss the use of the various tables in the J-B Tables.)

7.3 THE USE OF STEREOGRAPHIC PROJECTIONS

The methods of construction and use of stereographic projection in epicenter determination are discussed in Macelwane, pp 266-278. The charts to be used are polar stereographic projections. There are two types.

The first are termed "P-O" charts and show travel times from various stations to any point, (and, therefore, travel times from any point to each station). The coordinates of any point on these charts may be obtained from the "base map" chart. Note that all charts have an identical reference grid.

The second type of charts are called "ΔP" charts and show arcs of constant time difference between stations. Thus, if three stations record an event, the time differences between them may be calculated and the corresponding time difference arcs drawn. The resulting intersection is the location.

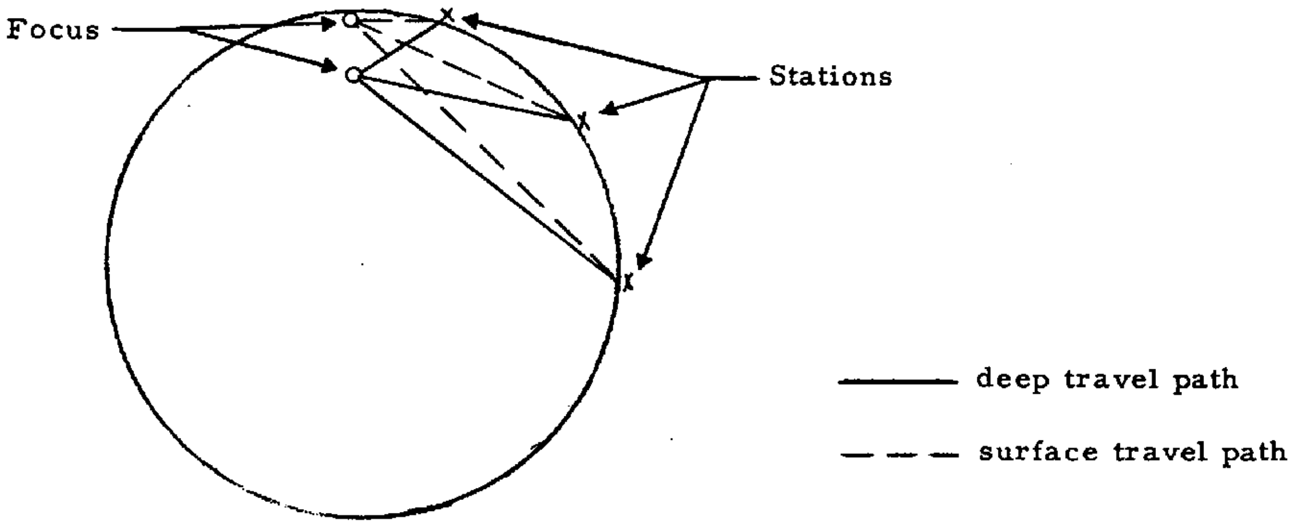
Coordinates may be obtained from the base map. The origin may be found by noting, on a P-O chart for any recording station, the travel time and then subtracting this time from the arrival time at the station used.

Depending upon the *control given by the recording stations it may be desirable to locate an event using ΔP charts or by using P-O charts directly. The P-O charts are more accurately drawn than ΔP charts since they are based on calculations and ΔP charts are drawn by over-laying P-O charts.

*Define.

Where data from only three stations is available there is always at least two possible locations. Often phases, character, direction, etc., may be used to eliminate one of these but in some instances the ambiguity remains.

In general, focal depth shortens the travel path of P at any given epicentral distance, and, therefore, the travel time of P is also shortened. The only exceptions occur at very small epicentral distances and fairly great depths. A second general rule is; the greater the epicentral distance, the greater the effect on P wave travel time. Again there are exceptions at very short epicentral distances. The reasoning behind these general rules may be illustrated by the following figure. (Note - depth is exaggerated.)



Travel times of P at various distances and depths are given in the Jeffrey's and Bullen Seismological Tables.

7.4 ELLIPTICITY CORRECTION

The travel times for P, given by Jeffreys and Bullen, are for a spherical earth, that is distances are geocentric. In work where a high degree of accuracy is required, travel times obtained from distance calculations must be corrected for the earth's ellipticity since it can affect P wave travel times by as much as about 1.5 seconds. The calculated times are for a reference sphere of radius 6366.2 km. The corrections are based on the International Spheroid which has an equatorial radius of 6378.4 km and a polar radius of 6356.9 km. Thus, at any given latitude the surface of the spheroid is above or below the surface of the reference sphere by some distance usually called H which is usually given in km. This distance varies from + 12.2 km at $\lambda = 0^\circ$ to -9.3 km at $\lambda = 90^\circ$. (See Macelwane pp 332.)

In considering the general effect of ellipticity, *Jeffreys defined a standard sphere of reference such that each internal surface of equal velocity for any pulse was spherical and enclosed the same volume as the corresponding surface of equal velocity within the actual earth. In subsequent papers Bullen considered the effect of ellipticity on P and S waves and came up with a simple method of obtaining ellipticity corrections which though not exact, is easily accurate enough for present work. He defines the ellipticity correction as = $f(\Delta)\,(h_0 + h_1)$ where $f(\Delta)$ is a distance factor, and h_0 and h_1 are the heights of the station and epicenter in relation to the reference sphere. Values of h are given in Macelwane pp 332, (he calls them H), and values of $f(\Delta)$ are given below.

Δ°	10	20	30	40	50	60	70	80
$f(\Delta)$	0.010	0.028	0.035	0.042	0.047	0.050	0.060	0.066

Δ°	90	100
$f(\Delta)$	0.064	0.066

* M.N.R.A.S., Geophys., Suppl. 3, 271 - 274, 1935.

8. NOISE STUDIES

8.1 NOISE LEVELS

It is often desirable to know the background level of noise at a station. This is commonly found through random measurements from which noise distribution curves may be plotted. These show noise level vs. probability of occurrence. A station's noise level usually refers to the 50% level on this type of curve rather than just the average noise level.

8.2 TRIPARTITE NOISE STUDIES

A small tripartite array is often used to study the predominate direction, velocity, and wave length of noise. A primary assumption is that most noise consists primarily of Rayleigh Waves.

9. RECORD ANALYSIS

This section will consist of supervised record reading.

READING AND REFERENCES

SECTION	SUBJECT	AUTHOR	PAGES	SUBJECT
	Introduction	Richter	3 - 9	Introduction
			16 - 19	Definitions
			135 - 139	Intensity
			210 - 213	Seismographs
			221 - 230	Seismographs
1.2	Geocentric-Geographic Latitude	Macelwane	279 & 332	Ellipticity
1.4	Internal Features	Macelwane	227 (fig.)	Internal Features
1.5	Seismicity	Gutenberg	Maps	Seismicity
		Richter	395 - 409	Seismicity
			412 - 436	Seismicity
2.1	Definition of Quakes	Richter	22 - 29	Earthquake Motion
2.2	Earthquake Types	Richter	151 - 163	Causes of Quakes
			168 - 185	Faulting
			189 - 209	Tectonic Quakes
			300 - 311	Deep Focus Quakes
			66 - 78	Foreshocks, Aftershocks Swarms
			522 (fig.)	Aftershock scatter
2.3	Seismic Waves	Richter	247 - 277	Seismic Waves
2.3.1	P Wave	Jeffrey's & Bullen	7 (fig. 4)	P Velocity
2.3.2	S Wave	Jeffrey's & Bullen	7 (fig. 4)	S Velocity
2.3.3	Surface Waves	Richter	241 - 245	Surface Waves
2.3.4	Microseisms	Richter	375 - 378	Microseisms
3.3	Close Shocks	Richter	282 - 296	Close Shocks
		Gutenberg (Science)	959 - 965	Low Velocity Layers
3.6	Travel Time Curves	Richter	674 - 687	Transit Time Tables
		Jeffrey's & Bullen	Tables	Seismological Tables

READING AND REFERENCES
(continued)

SECTION	SUBJECT	AUTHOR	PAGES	SUBJECT
6.	Magnitude	Richter	338 - 371	Magnitude
			688 - 690	Magnitude Charts
7.	Epicenter Determination	Richter	314 - 323	Locating Earthquakes
7.3	Stereographic Projections	Macelwane	266 - 278	Stereographic Projections
7.3.6	Effect of Depth	Jeffrey's & Bullen	Tables	Deep Travel Times
7.4	Ellipticity Correction	Macelwane	332	Ellipticity

REFERENCE LIST

AUTHOR	REFERENCE
Gutenberg	Gutenberg, Beno and Richter, C. F., Seismicity of The Earth; 1949; Princeton University Press; Princeton, New Jersey, U. S. A.
Gutenberg (Science)	Gutenberg, Beno, Low-Velocity Layers In The Earth, Ocean, and Atmosphere; Science; 1 April 1960, Volume 131, Number 3405; National Publishing Company; Washington, D. C., U. S. A.
Jeffrey's and Bullen	Jeffrey's, Harold and Bullen, K. E., Seismological Tables; 1948; Office of the British Association; Burlington House W.I., London, U. K.
Macelwane	Macelwane, J. B. and Schon, F. W., Introduction to Theoretical Seismology; Part 1, Geodynamics; 1932; St. Louis University; Saint Louis, Missouri, U. S. A.
Richter	Richter, Charles F., Elementary Seismology; 1958; N. H. Freeman and Company; San Francisco, California, U. S. A.

In the list of reading and references given on Page 26 and 27, only the Author's names have been listed. The specific articles and books referred to are as given above.