

THE RELATION OF AMPLITUDES OF CONVENTIONAL SEISMIC
REFLECTION RECORDS TO THE STRATIGRAPHY OF THE
SHAUNAVON FORMATION OF SOUTHWESTERN SASKATCHEWAN

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A THESIS
PRESENTED TO
THE FACULTY OF GRADUATE STUDIES AND RESEARCH
THE UNIVERSITY OF MANITOBA

.

IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE
MASTER OF SCIENCE, GEOPHYSICS

.

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SEPTEMBER, 1967



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ABSTRACT

A study of the absolute amplitudes from seismic reflection records revealed that lithologic variations may be traced by observing absolute amplitude variations. The amplitude information was obtained by considering the effects of energy injection, propagation and instrument response. By evaluating these effects the total system is defined within the limits of the accuracy with which its components have been determined and any variable or group of variables may then be calculated from a variation in the amplitude response.

CONTENTS

I

	Page
INTRODUCTION	
Scope of Study	1
Acknowledgements	2
Geographic Setting	2
Geologic Setting	4
Previous Work in the Area	6

II

EXPERIMENTAL CONDITIONS	
Field Conditions	8
Measurement of Amplitude Data	10
Preliminary Laboratory Amplitude Study	10

III

AMPLITUDES OF REFLECTED WAVES	
Factors Affecting the Amplitudes of the Reflections	19
Energy Injection	20
Propagation of the Energy	21
Instrument Response	31

IV

INTERPRETATION OF THE AMPLITUDE DATA	
Application of Corrections to the Amplitude Data	44

IV (Continued)	Page
Conclusions Reached in the Study	44
SUGGESTIONS FOR FUTURE WORK	46
REFERENCES	50

V

APPENDIX A - SEISMOGRAM SYNTHESIS.	52
APPENDIX B - INSTRUMENT RESPONSE	59

Figures:	Page
17. Combined System Power Response Contoured in db	39
18. The Response of a Spatial Array to an Advancing Wave Front (For Equal Amplitude Continuous Waves)	40
19. Calculation of the Combined System Amplitude Attenuation and Correction Factor . . .	43
20. Relation of the Corrected Amplitudes and the Position of the Reflection Point for the Reflection M.	45
21. Upper Shaunavon Formation Lithofacies Map	47

LIST OF TABLES

Tables:	Page
1. Measured Amplitudes from Monitor Seismic Records	13
2. Amplifier Gain Reduction for Reflection M . .	42
3. The Calculated Value of the Coefficient Alpha for the Preparation of the Synthetic Seismograms	55

INTRODUCTION

Scope of Study

A reflection seismogram is a complex record of the response of the earth and the recording equipment to an energy injection. In order to obtain more information than that required to construct the conventional structural model of the earth, high resolution methods should be applied. "High resolution" may be defined as the high fidelity recording and analytic procedures required to produce the best resolving power of the seismic exploration method applicable to stratigraphic studies and special structural problems. In this study "high resolution techniques" imply the recovery of absolute amplitudes from reflection seismograms to determine any correlation between the magnitude of the amplitudes and lithologic variations.

To recover the amplitude information the effects of energy injection, propagation, and instrument response must be evaluated. Once such an evaluation has been achieved and related to the amplitudes in a type area, then a change in amplitude in an adjacent area would indicate a variation in one or more of the factors in this system. The reliability of any conclusions obtained, when a variation of one or more of the factors contributing to the amplitude response occurs, is dependent on the accuracy with which these factors have been determined. In this thesis the emphasis is placed on the effects of lithologic variations upon the amplitude response.

Acknowledgements

The author wishes to express his appreciation for the generous assistance given by Dr. D. H. Hall, the Department of Geology, the University of Manitoba, and the British American Oil Company Limited which provided the data and the use of their facilities for this study.

Any problems arising from the preparation of computer programs were overcome with the collaboration of Mr. D. Richards of the Geology Department, Geophysics Section, the University of Manitoba.





Geographic Location

The study area lies between longitudes $108^{\circ}40'$ (Range 21 west of the Third Meridian) and $108^{\circ}50'$, and between township-lines 3 and 4 (Figure 1). In the entire area extending from township 21 in the north, the Canada-United States border in the south, and longitudes 108° and 110° in the east and west, respectively, the reservoirs of the Shaunavon Formation, combined with those of the Upper Jurassic Vanguard and Lower Cretaceous Blairmore Formations, form Saskatchewan's second largest oil-producing district. The oil fields of the Shaunavon formation follow a roughly linear north-south distribution about longitude $108^{\circ}30'$, and are distributed in an ascending stratigraphic position and northerly direction as follows: Rapdan, Eastend, Dollard, Leon Lake, Leitchville-Shaunavon, Bone Creek-Instow, Gull Lake and Delta-Premier.

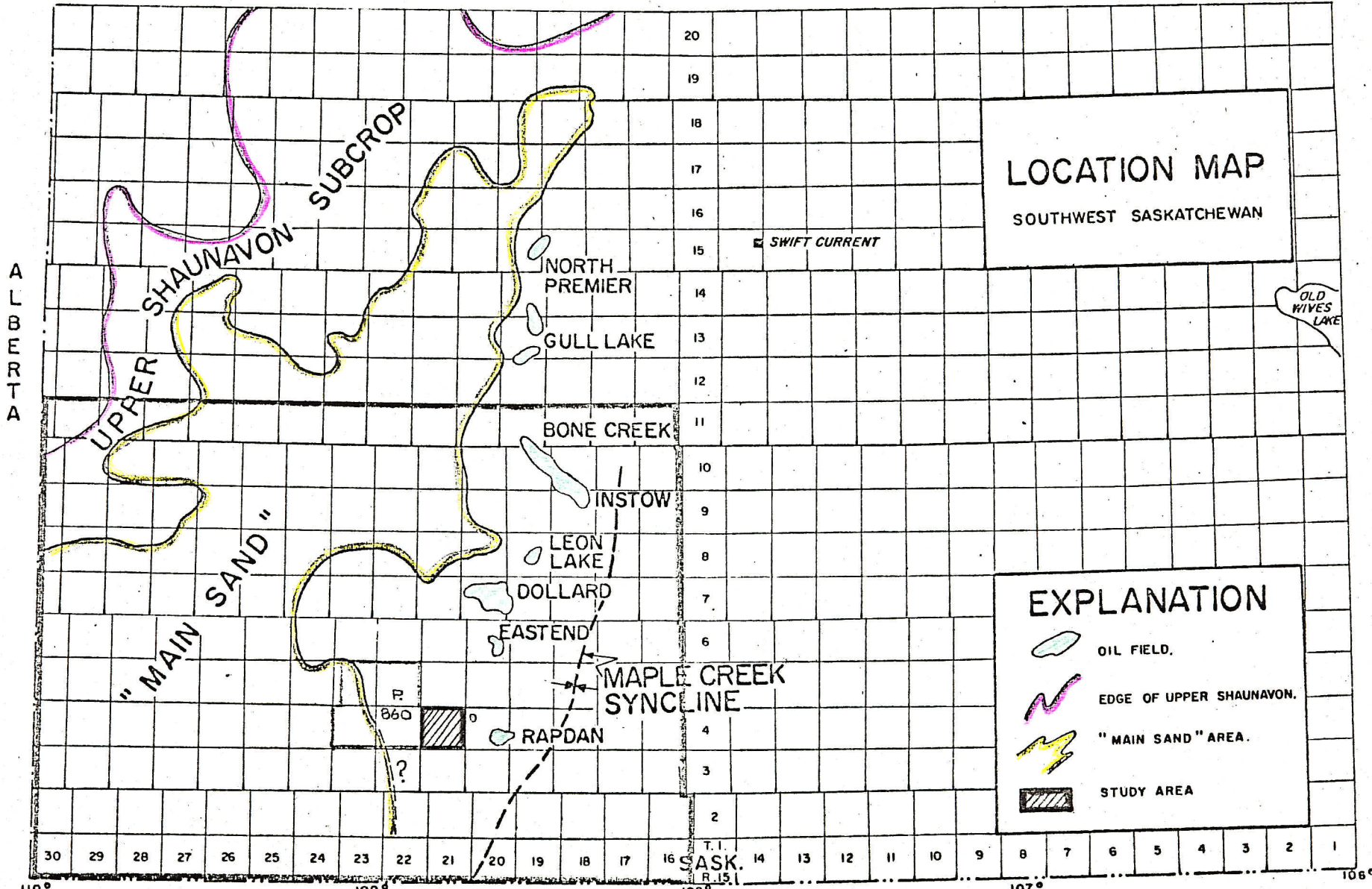
LOCATION MAP

SOUTHWEST SASKATCHEWAN

EXPLANATION

-  OIL FIELD.
-  EDGE OF UPPER SHAUNAVON.
-  "MAIN SAND" AREA.
-  STUDY AREA

SWIFT CURRENT



ALBERTA

3

110° 109° 108° 107° 106°

U. S. A.

FIGURE N° 1.

Geologic Setting

The Shaunavon Formation, situated in the subsurface in the entire area, lies at depths ranging from 2700 feet along its northern edge to 4500 and 5000 feet in the southern extremity. In the study area the average depth to the Shaunavon Formation is 4600 feet. The formation dips south-east 13 to 16 feet per mile as an irregular, steplike or terraced monocline in the western and northern two-thirds of the area (Christopher, 1964). In the south-east it forms a nearly flat-bottomed syncline with an eastern limb rising at a rate of 30 feet per mile. The tectonic strike is northeast with local departures.

In Saskatchewan the Shaunavon Formation lies at the top of the Middle Jurassic Section. It is overlain by the Upper Jurassic Vanguard Formation and underlain by the Middle Jurassic Gravelbourg and Watrous Formations (Figure 2). The Jurassic Formations were deposited disconformably on the Mississippian Mission Canyon marine limestone, and are disconformably overlapped by the Lower Cretaceous Blairmore Formation of shale, mudstone and sandstone.

The Shaunavon-Gravelbourg contact is conformable throughout the area but becomes difficult to identify towards the northwestern edge of the Shaunavon Formation.

The Shaunavon Formation is subdivided into two members. The Lower Member, characterized by cream "lithographic" limestone with a thin bed of oolite near the top over the northern two-thirds of the area, is separated from the Upper Member by a widespread discontinuity. The Upper Member consists of a complex interfingering of quartz sandstone, marlstone, shale, oolite, argillaceous dolomite and bioclastic limestone, generally 45 to 75 feet in thickness.

SCHEMATIC CROSS SECTION ILLUSTRATING PRESENT DAY STRUCTURE

WEST.

EAST.

← SWEETGRASS ARCH

MAPLE CREEK
SYNCLINE →

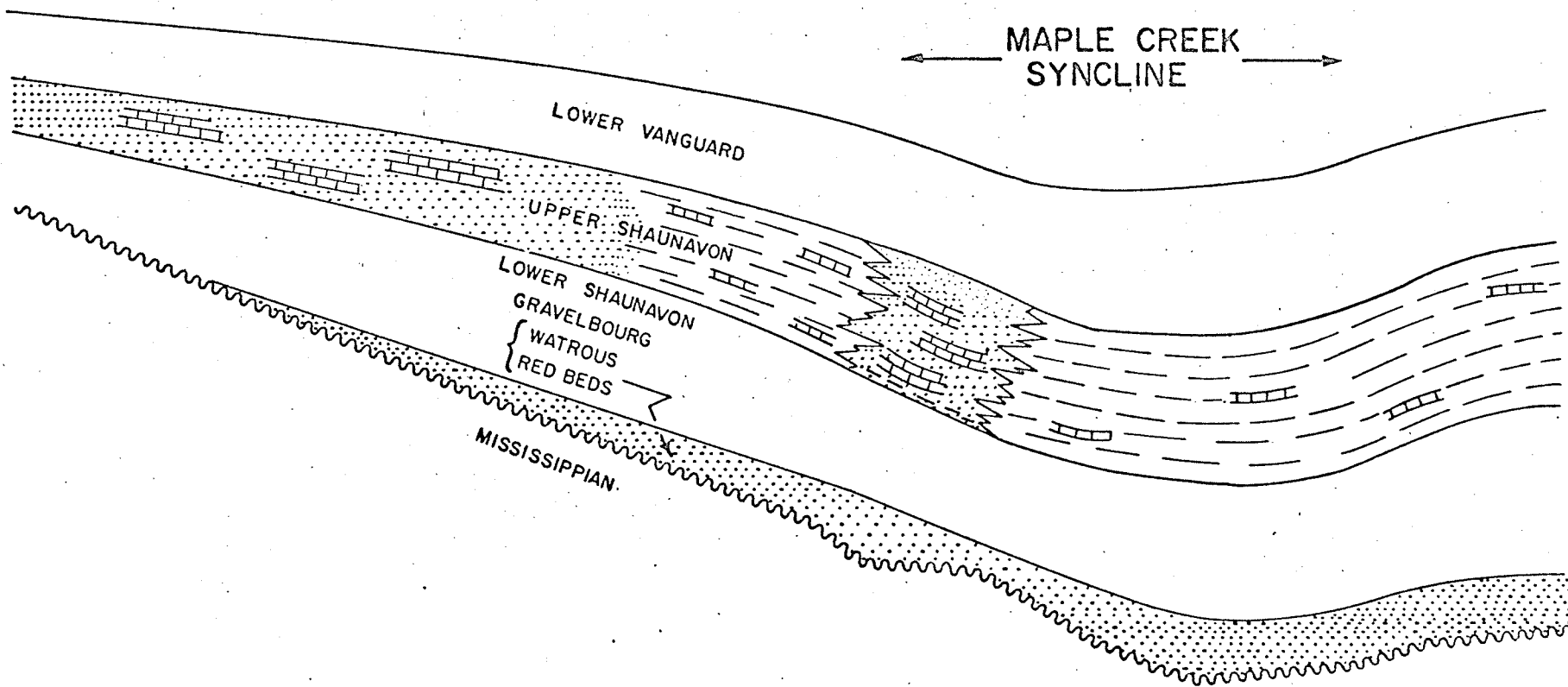


FIGURE 2

Previous Work in the Area

During an earlier project, The British American Oil Company Limited prepared a number of synthetic seismograms using continuous velocity logs obtained from wells located near the Rapdan field immediately to the east of the present study area (Fig. 1). By varying the thickness of the high speed material (HSM) in these velocity models of the Upper Shaunavon Formation a number of character changes for the Shaunavon reflection were obtained on the synthetic seismograms. These results were compared to field records in the present area of study and an estimate of the distribution of HSM was then made (Fig. 3). Although this map was proven by subsequent drilling to give a fair indication of the distribution of HSM it provided no consistent correlation to the rock types. It was found that the lithology in areas of HSM could vary from limestone to sandstone and that the lithology at locations thought to have only a fair prospect for HSM varied from shale to argillaceous sandstone or limestone. These variations made the interpretation of offshore bars extremely difficult and emphasized the limitations of the use of synthetic seismograms as a sole means for studying stratigraphic variations. This provided the impetus for a continued search for other methods of delineating stratigraphic changes in a favorable horizon.

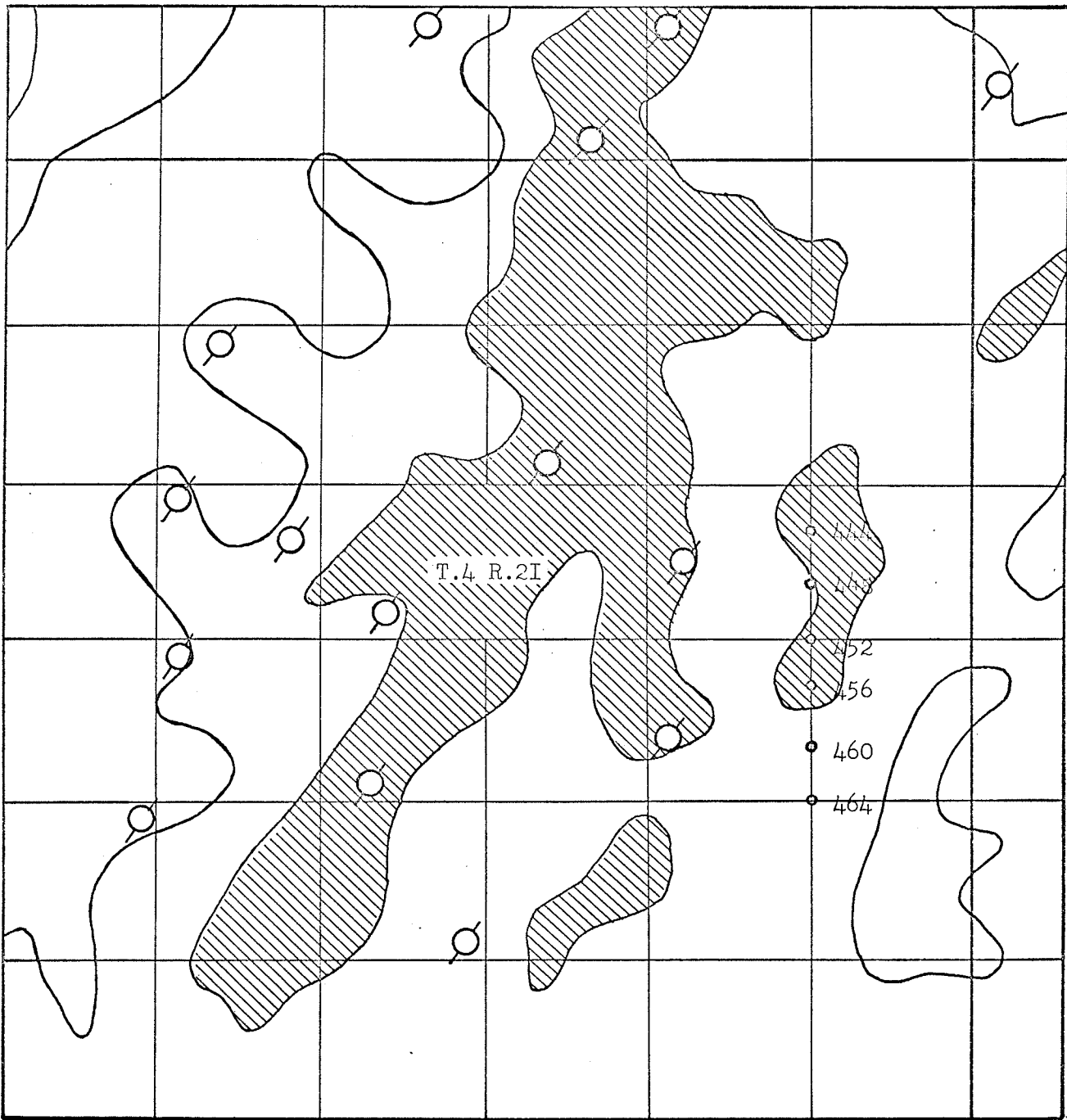


FIGURE 3 Outline of high speed material by synthetic seismogram character study

- Well
- Seismic line
- ▨ High speed material (HSM.)
- Fair prospect HSM.

II

EXPERIMENTAL CONDITIONS

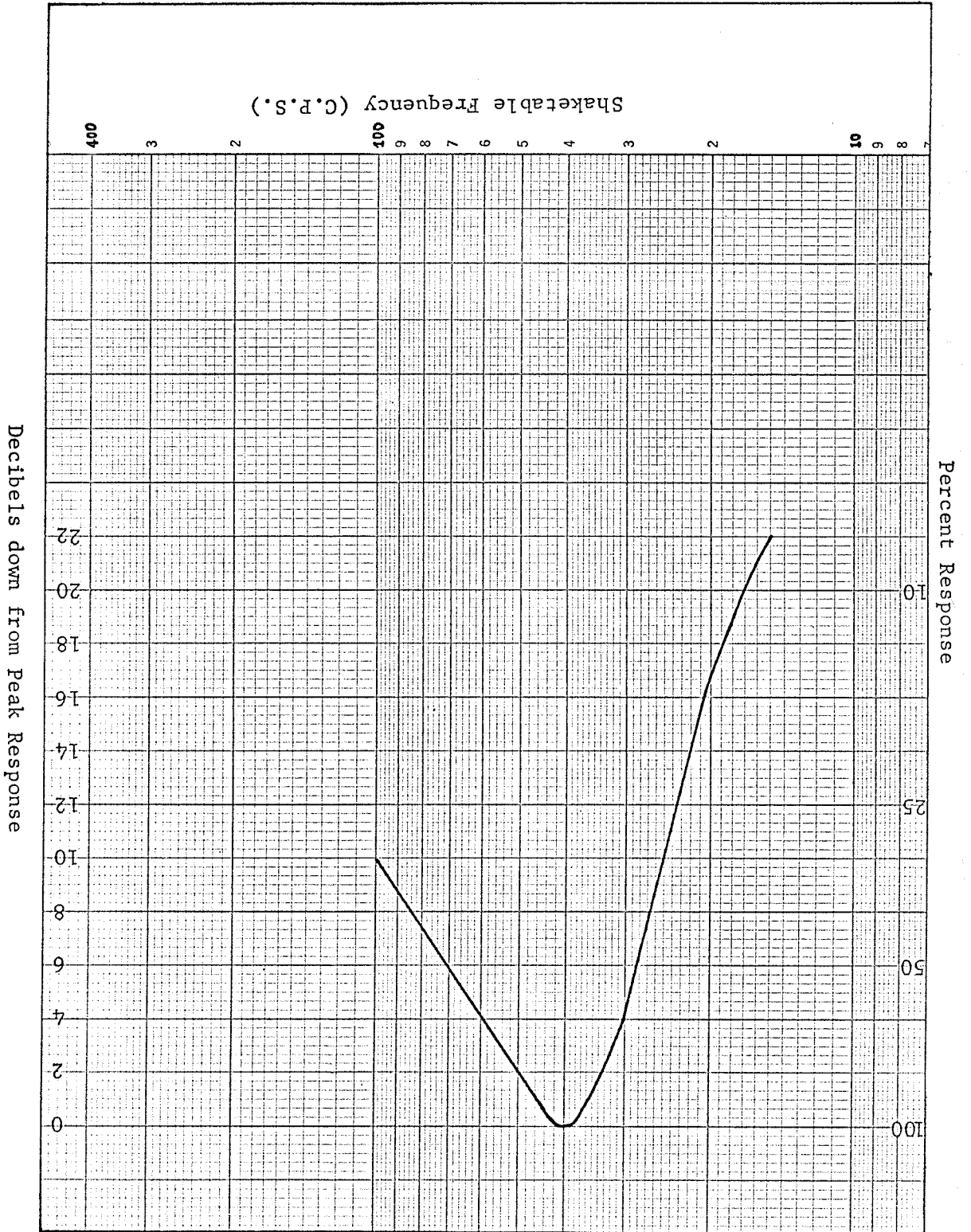
Field Conditions

The data used for the study were obtained from standard split-spread reflection seismograms. The line was shot from north to south with shot points located every one-third of a mile (Fig. 3). The instrument lines extended 1800 ft. on both sides of the shot point with 12 groups of four geophones on each side. Geophone spacing was 40 ft. with the nearest geophones of the central groups, 12 and 13, a distance of 20 ft. from the shot point. The charges were buried at a depth of 75 ft. and this depth remained constant throughout the survey. Surface elevations in the area varied less than 20 feet.

The amplitude characteristics of the geophones used are shown in Figure 4. The frequencies at 50% response are 28 and 70 cps and the low and high cut slopes are 18 and 8 db/octave, respectively. The peak response is estimated at 40 cps. The recording equipment was designed for magnetic tape recording and playback. It consisted of 24 seismic signal channels with simultaneous control of each major function for all channels from a master control unit. System interlocks provided the means of single-knob adjustments of record and playback parameters.

The amplifiers used produced a linear phase shift of 10° /octave at full gain and a total harmonic distortion of less than 0.1 per cent for 3 mv input at 30 cps or higher. Gain regulation of all channels was alike to within ± 1 db and was recorded on the tape as a function of time. The master control provided simultaneous single-knob control of all channels for filters, gain, automatic volume control (AVC), and suppression.

FIGURE 4. Detector response curve.



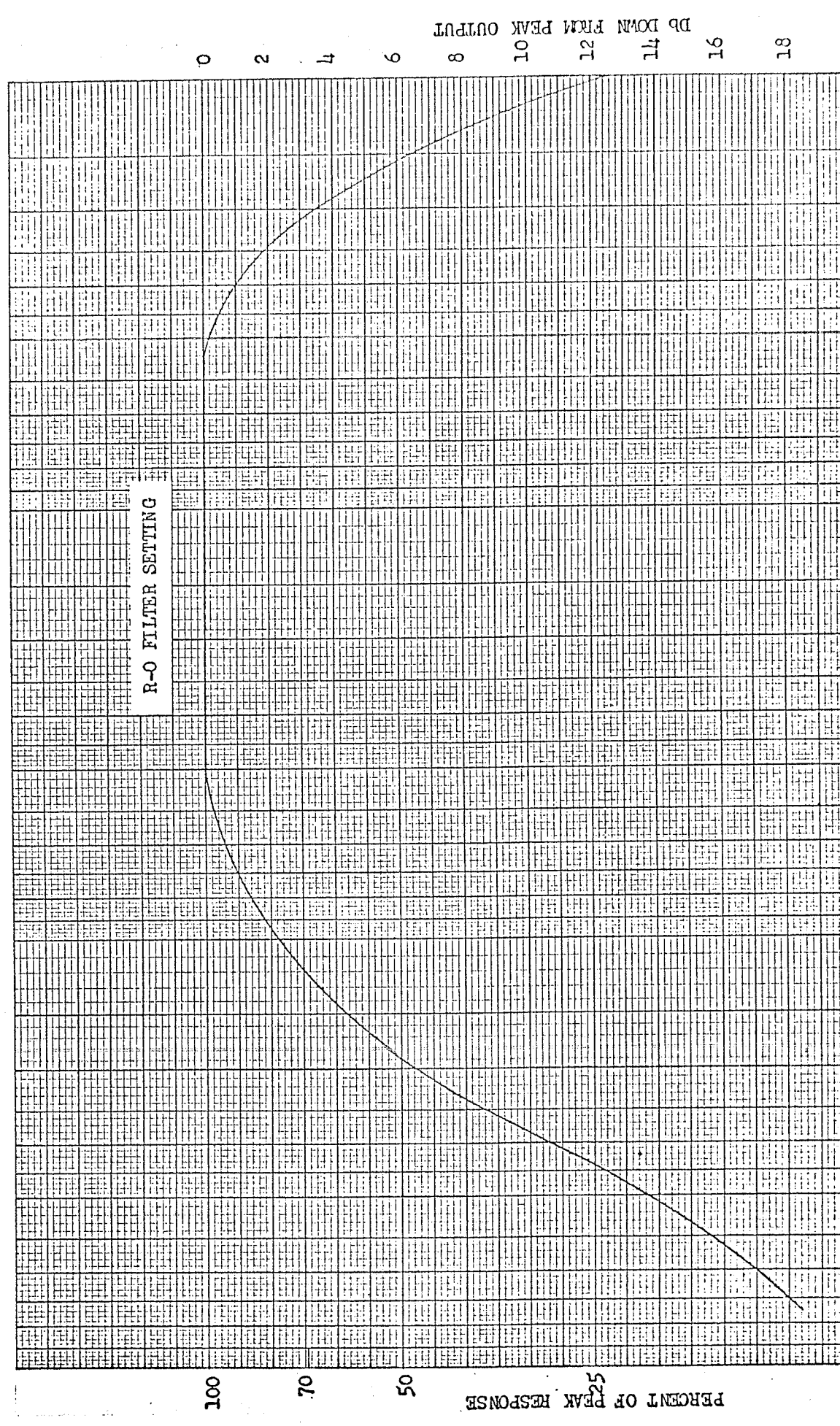
The filter used throughout this survey was an open filter characterized by a bandpass ($F_2 - F_1$) of 958 cps. F_1 and F_2 frequencies measured at 50 per cent amplitude response were 2 and 960 cps, and low and high cut slopes were 5 and 10 db/octave, respectively (Fig. 5). Figure 6 shows a portion of a typical record from the area of study.

Measurement of Amplitude Data

The reflections from the Upper and Lower Shaunavon Formation and the Mississippian Limestone were identified by the use of Continuous Velocity Logs (C.V.L.) and from reports of previous work in the area. The peak to peak amplitude was measured and recorded as shown on Table 1 with its accompanying illustration. The amplitudes were then plotted as functions of shot point to seismometer group distance, Figures 7 and 8, and as functions of the reflection point (Fig. 9).

Preliminary Laboratory Amplitude Study

Amplitude studies, in general, follow two approaches. One technique employed is based on the relative amplitude of two reflection events. Subsurface changes may be indicated by variations in the relative amplitudes from these two horizons. The second type of amplitude study is the one considered in this thesis and utilizes the variations in the absolute amplitudes of a prominent reflection as a criterion for the recognition of stratigraphic changes.



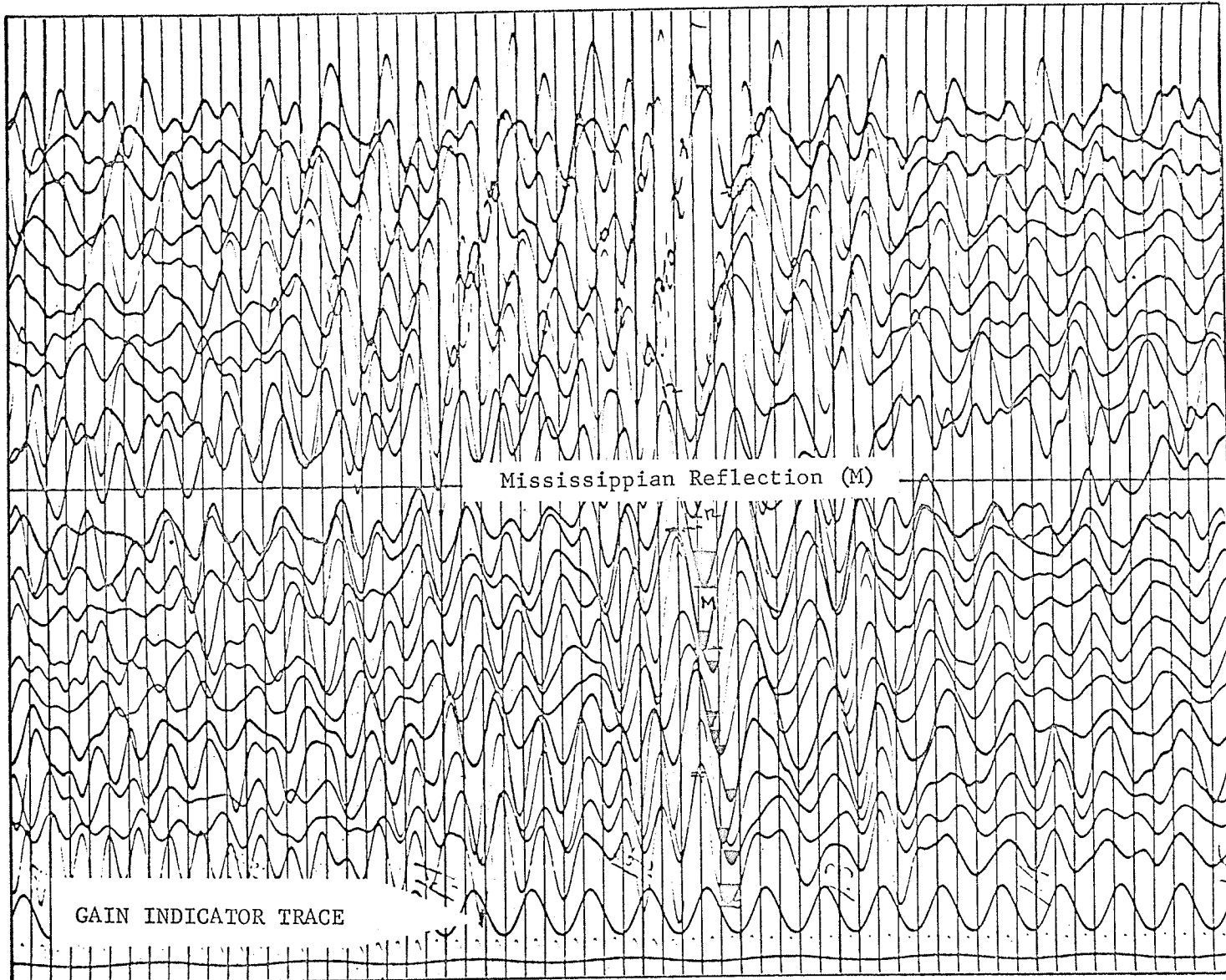


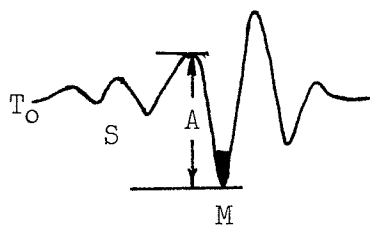
FIGURE 6. Portion of a typical reflection seismogram

TABLE 1. Measured Amplitudes from Monitor Seismic Records

Record	444	448	452	456	460	464
Gain Step	21	20.9	20.5	20.5	20.5	20.5
Trace	Amp.	Amp.	Amp.	Amp.	Amp.	Amp.
1		0.97	1.39	0.90	0.76	0.77
2	0.48	0.70	0.60*	0.80	0.90*	0.81*
3	0.98	1.05	1.38	1.30	1.57	0.70**
4	1.21	0.75*	1.76	1.07	1.52*	1.60**
5	1.06*	0.85	1.24	0.99	1.15	1.36**
6	.86	0.78	1.46	1.15	0.86*	1.20**
7	1.10	1.25	1.55	1.33	1.08	1.40
8	0.65	0.92	1.15	1.16	0.85	1.15*
9	0.98	1.20*	1.41	1.60	1.20	1.70
10	0.86	0.82	0.97	1.43	0.97*	1.00
11	1.28	1.20*	1.40*	1.48*	1.50	1.59*
12	1.15**	0.94*	0.80**	1.19*	1.16	1.55*
13	1.10	0.91*	0.90	0.95	1.00*	1.30*
14	1.15	1.15	1.00	1.44*	0.75	1.24**
15	.99*	1.30	0.75	1.55*	1.54*	1.22*
16	1.15	0.98	0.81	1.40	1.54	1.10
17	.62	0.80	0.69	0.67	0.83	0.87
18	1.34	0.75	0.95	1.20	1.40	1.30
19	1.20	0.77	0.75	0.90	1.43	1.17
20	.95	1.00	0.85	0.95	1.27	1.11
21	1.38	1.46	1.35*	1.20*	1.08	0.98*
22	1.13	0.78	1.00	1.20	1.36	0.95
23	0.70	0.90	0.40	0.70	1.10	1.10*
24	0.64	0.83	0.90	1.01	1.00	0.60*

* indicates noisy trace

** very noisy



T_o = Two way time

S = Shaunavon

A = Amplitude

M = Mississippian

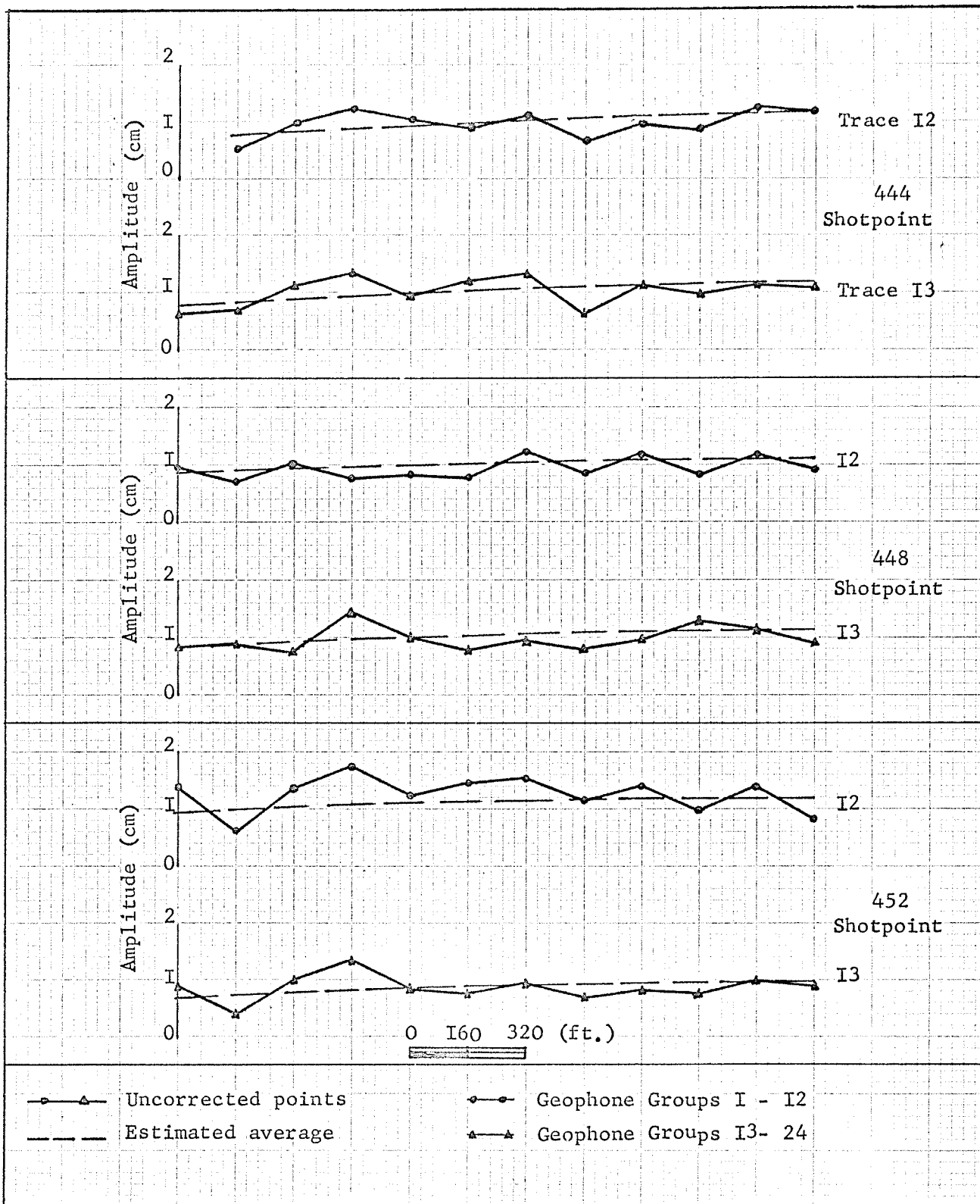


FIGURE 7. Relation between amplitude and shotpoint-seismometer distance for reflection M.

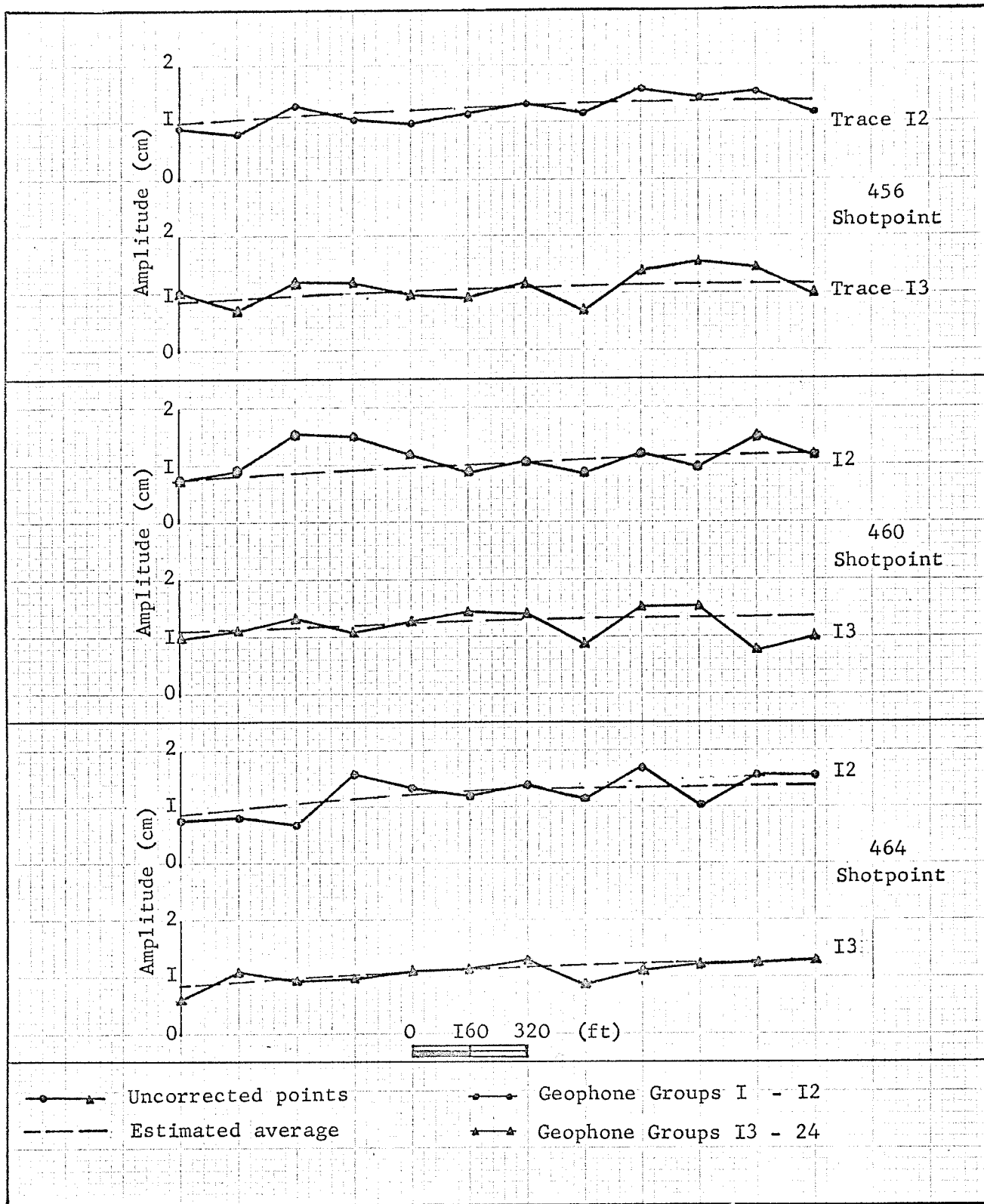


FIGURE 8. Relation between amplitude and shotpoint-seismometer distance for reflection M.

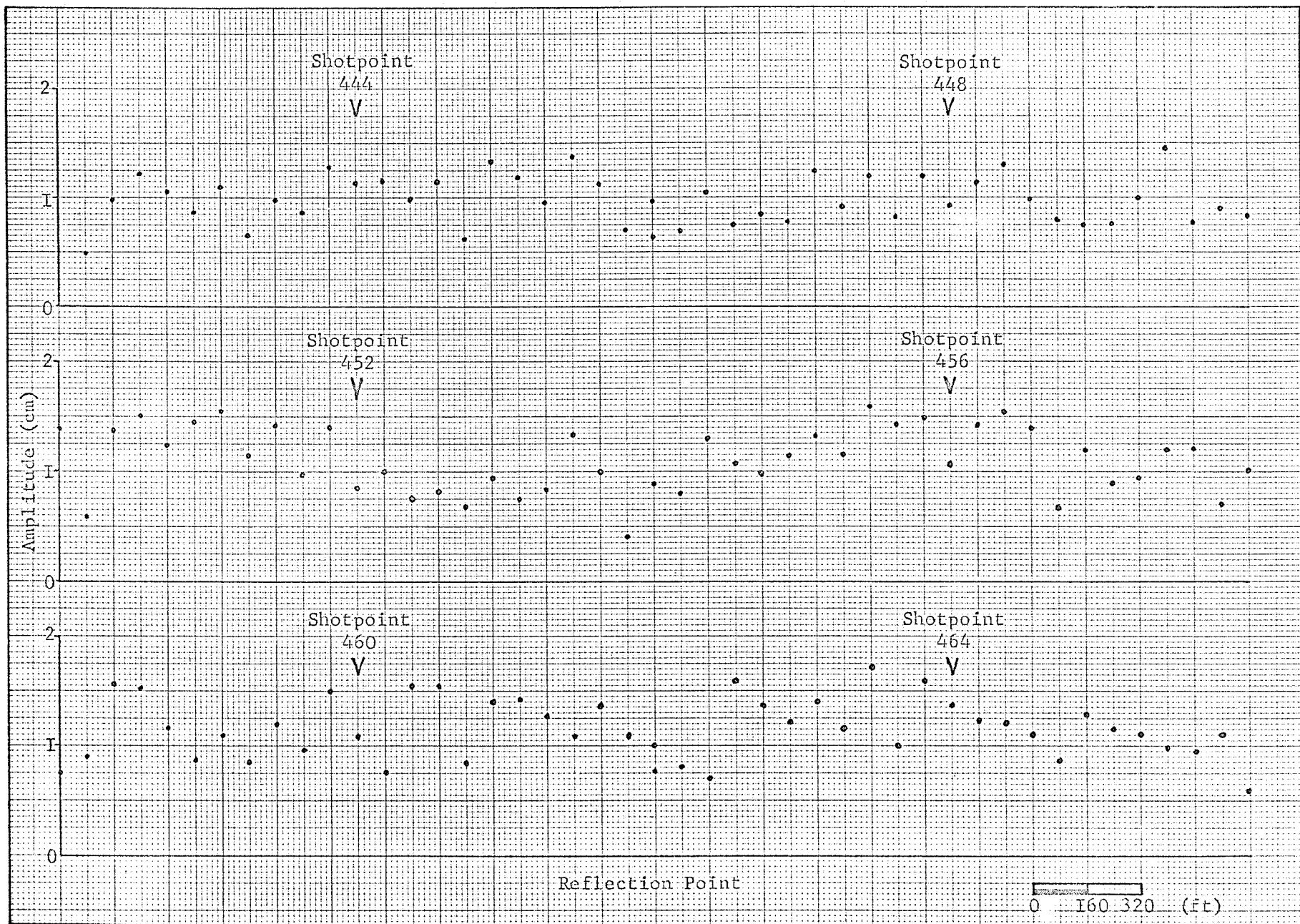


FIGURE 9. Relation between amplitude and the position of the reflection point for reflection M.

Koefoed (1960) presented an interesting report on absolute amplitude measurements. He inferred that such a study could provide useful information about the lithology of the earth model. To test whether a similar method might be applicable in the study area, synthetic records were prepared for three models with varying amounts of H.S.M. (Fig. 10). A more thorough discussion of the preparation of the synthetic seismograms is given in Appendix A. Results from this experiment indicated that variations in the Upper Shaunavon could cause measurable effects on the amplitude of the Mississippian reflections and hence an absolute amplitude study might find application as an improvement of the resolution of seismic data.

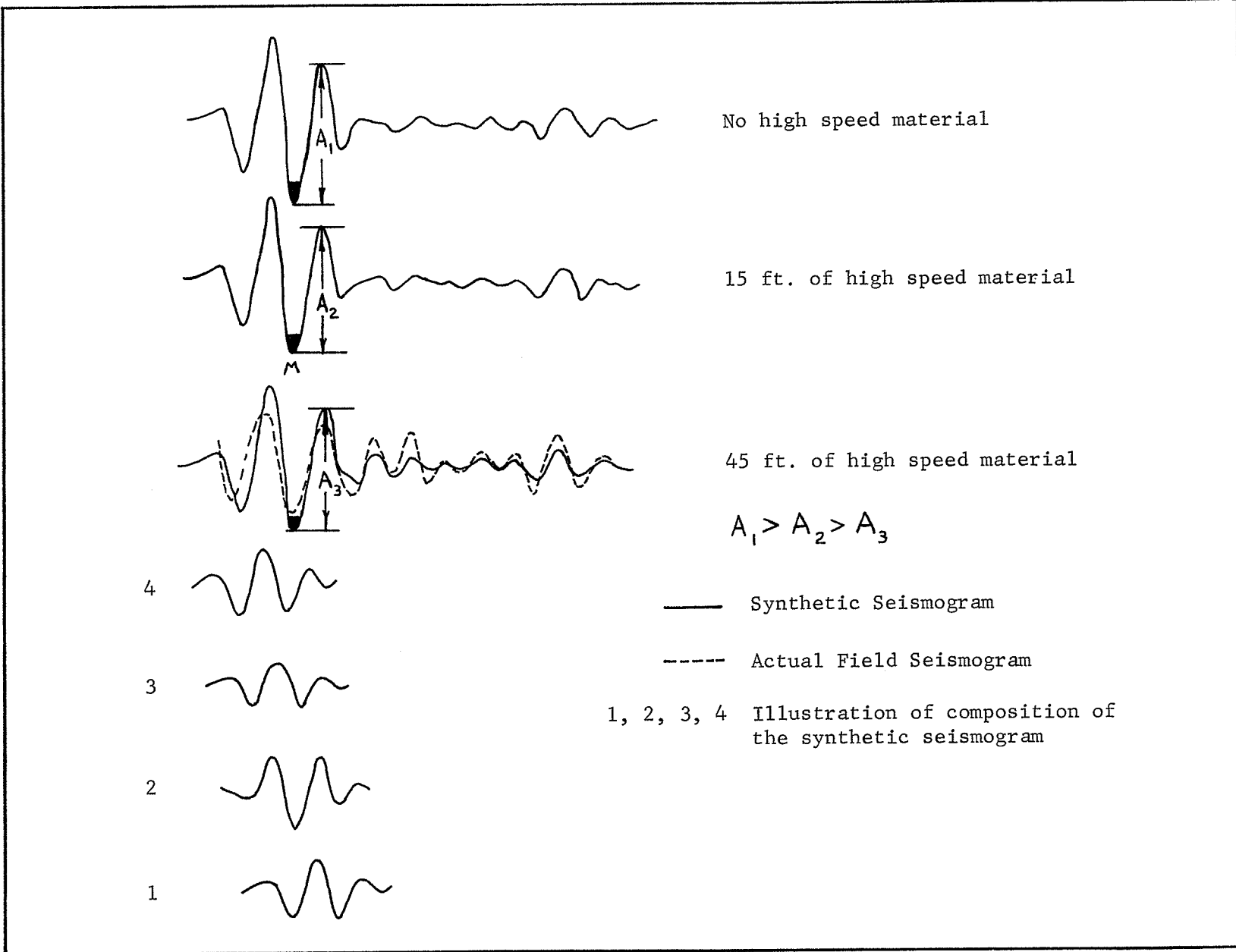


FIGURE 10. Synthetic seismogram amplitude study.

III

AMPLITUDES OF REFLECTED WAVES

Factors Affecting the Amplitudes of the Reflections

The amplitudes obtained from reflection seismograms are affected by a number of factors, all of which must be considered in the type of study proposed here. Their effects are then evaluated, the reliability of the evaluation depending on previous research, and corrections applied to produce uniform conditions from one shotpoint to another. Basically these factors are grouped into three categories: energy injection, the propagation of the energy through the earth, and the instrument response to the energy arriving at the surface. The factors considered in this study are listed below:

A. Energy injection.

1. Weight and type of explosive charges.
2. Lithological composition of the rocks in the explosion area.

B. Propagation of the energy through the earth.

1. The energy partition at each reflecting boundary.
2. Wave attenuation due to absorption.
3. Dispersion, diffraction and scattering.
4. Curvature of the reflecting boundary near the reflection point.
5. The near surface layer.
6. The surface elevation.

C. Instrument response.

1. The geophone response.

2. The effects of the geophone array.
3. The amplifier response.
4. Filtering, mixing and shot point arrays.

Energy Injection

To make an amplitude study meaningful, corrections have to be applied to reduce the amplitudes of the waves to a constant charge weight and to the excitation conditions of one shot point. Although the energy released by an explosive charge may be estimated fairly reliably, the effective energy giving rise to the amplitudes recorded is difficult to estimate and is, in general, unknown. Quantitative relationships that have been obtained are of an empirical nature because of the difficulty in describing mathematically the accompanying processes which affect the formation of an elastic wave. The dependence of wave amplitude on charge weight for a fixed explosion-to-instrument distance may be expressed by the formula:

$$A = CW^{n(f,W)}$$

where C is a proportionality factor influenced by the type of explosive, the nature of the waves recorded, and the properties of the medium in which the explosion occurred; n is an exponent, that is a function of the charge weight W and the frequency f of the waves recorded. The value of n varies widely during explosions in reservoir (0.3 to 1.9) and boreholes (0.5 to 1.4). Also, the exponent n decreases with an increase in charge weight.

During this survey the charge type, weight, and depth of burial were kept constant. However, no record was kept of any lithologic variations in the shot medium and no information is

available about shot hole loading procedures. Judging from the fairly constant amplitude of the uphole break, and due to the lack of information suitable for calculating the effective energy, the conditions at each shot point were considered to be uniform.

Propagation of the Energy

A study of observed amplitudes in seismic work depends upon the partition of the amplitude of an incident wave front at an interface. The equations to be used were suggested by K. Zoeppritz in 1908 and describe this partition for a plane wave. The following is an application of this method in the study of amplitudes of longitudinal waves from seismic reflection records, and follows the development presented by Gutenberg (1936). The emphasis of this study is placed on longitudinal waves, since the transverse waves that are created as reflection and refraction waves by oblique incidence of a longitudinal wave at an interface are polarized. They have therefore no energy if the longitudinal wave is incident perpendicular or nearly perpendicular to the interface, and contain appreciable energy only for large angles of incidence. Muskat and Meres (1940) calculated the intensities of the longitudinal and transverse waves created at an elastic interface after incidence of a longitudinal wave, and more recently, McCamy et al (1962) calculated solutions of Zoeppritz' amplitude equations.

The following discussion of the amplitudes of longitudinal waves was quoted, with minor changes only, from Gutenberg (1936).

It is repeated here because of the concise nature of that report and its relevance to the amplitude study attempted in this thesis.

Suppose that the energy is produced at a point A (Fig. 11) at the surface of the earth, that the energy radiation is uniform in all directions, and that the media are isotropic horizontally. No assumptions are made concerning the vertical direction since the following argument is valid regardless of the vertical velocity distribution. The two rays leaving the point A with angles of incidence i_1 and i_2 differing by the small amount di arrive after refractions and reflections at the points K and L separated by the small distance dx .

To satisfy the assumptions, the same amount of energy, e , must pass through each unit area of a sphere about A with the very small radius, r . The zone, Z , on the sphere due to the cones of rays between angles i_1 and i_2 is:

$$Z = 2\pi rh = 2\pi r^2 di \sin i$$

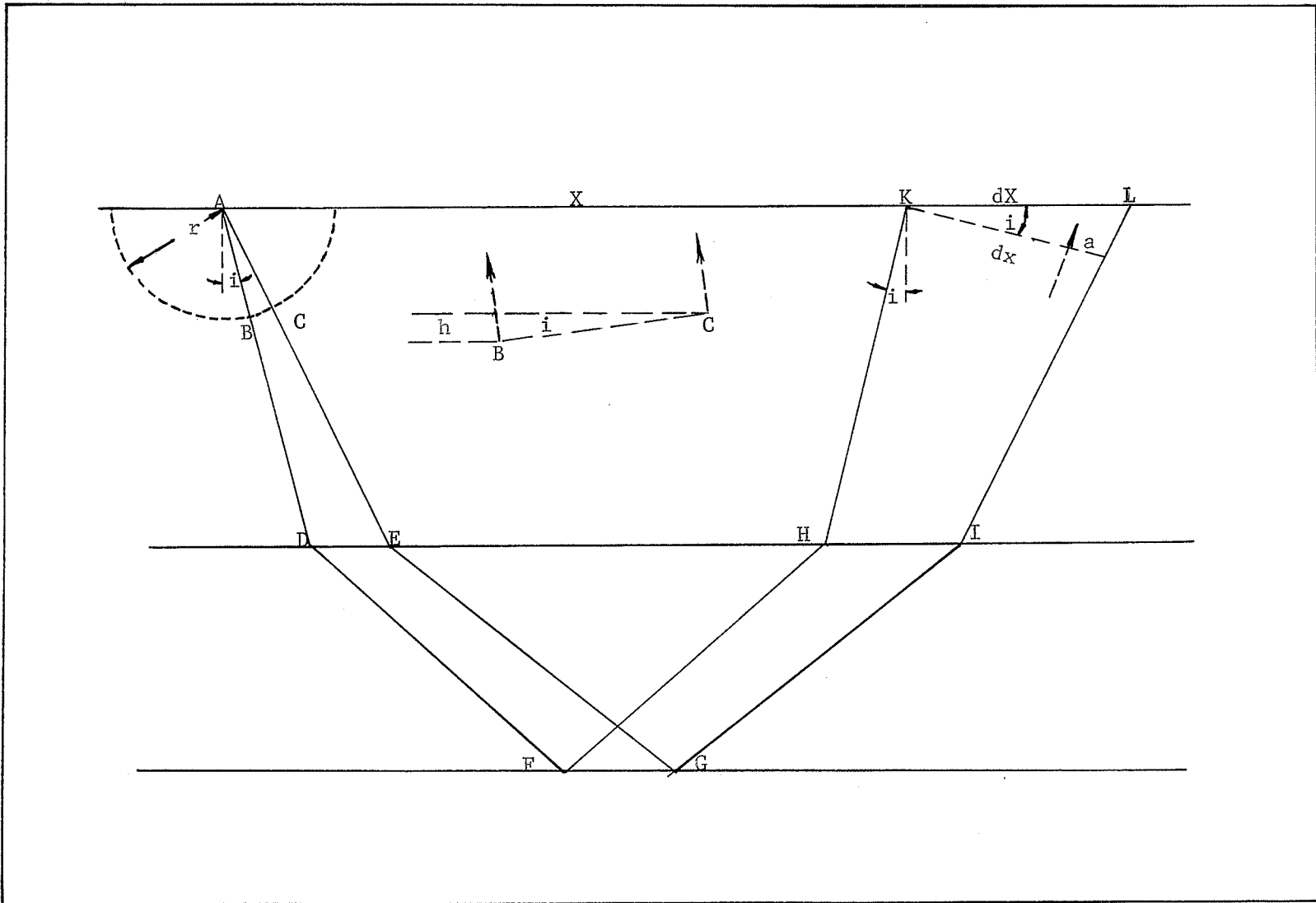


FIGURE II. Energy radiation in a layered medium (From Gutenberg, 1936).

The total energy between the two cones is eZ . The energy is split into the longitudinal and transverse reflected and refracted waves at each reflection and refraction of the rays. Let F be the factor giving the ratio of the energy flux along the path under consideration, influenced by the refractions at DE and HI and the reflection at FG. FeZ becomes the total energy arriving at the surface. At a distance X from A it is spread over a zone of width dx , with area $2\pi X dx = 2\pi X dx \cos i$ perpendicular to the energy flux. The energy per unit of area is:

$$E = \frac{FeZ}{2\pi X dx \cos i} = r^2 e \frac{F di \sin i}{X dx \cos i} = C \frac{F di}{X dx} \tan i$$

where: C is a constant for each explosion and is a function of the effective energy.

The amplitude of the ground motion is proportional to $(E)^{\frac{1}{2}}$ for a given period of the approaching wave. The displacement of a particle at the surface is due, not only to the amplitude of the arriving wave, but also to the movement of the two waves reflected at the surface. The angle of emergence and Poisson's ratio must therefore also be considered. Letting B equal the factor by which E must be multiplied to obtain the amplitude A of the ground in a given component, the following equation is obtained:

$$A = cB \left(F \left| \frac{di}{dx} \right| \frac{\tan i}{X} \right)^{\frac{1}{2}}$$

where: C is a function of the original energy and the period of the wave i is the angle of emergence at the distance X .

To approximate the corrections that must be applied to the amplitude data obtained in this study values for C, B and F must be obtained. From the previous section on energy injection C may be considered constant. B may be calculated as a function of i and Poisson's ratio.¹ When this ratio is equal to 0.272, a good approximation in most cases, the values of B for the vertical component of ground movement and for $i = 0, 5,$ and 10 degrees are 2.00, 1.99 and 1.97 respectively.

The energy ratio between the reflected or refracted longitudinal wave and the arriving wave at each point of reflection must be known to calculate the factor F. For vertical incidence the energy ratio of the reflected energy E_r to the arriving energy is

$$\frac{E_r}{E_a} = \frac{(\rho_2 V_2 - \rho_1 V_1)^2}{(\rho_2 V_2 + \rho_1 V_1)^2}$$

where ρ = density in the medium

V = longitudinal velocity in the medium.

Neglecting the effects of density, the factor F for this case is therefore equal to the values of alpha calculated for the impulsive synthetic seismogram with attenuation. McCamy et al (1962) showed that the density effect may be neglected without introducing serious errors.

¹ For details see for example: B. Gutenberg, Handbuch der Geophysik, Vol. 4, pp. 42-48.

For the case of waves reflected from the base of a homogeneous layer it can easily be seen from a diagram that

$$\tan i = \frac{x}{2d}, \text{ and } \frac{di}{dx} = \frac{\cos^2 i}{2d}$$

Substituting these values into the equation for A the following expression is obtained:

$$A = cB \frac{\cos i}{2d} (F)^{1/2}$$

Near the shot point $B = 2.00$, $\cos i = 1$ and $C = 1$. The amplitudes in this region will therefore be approximately proportional to $1/d(F)^{1/2}$. The factor F will decrease slightly with increasing i , reach a minimum, and then increase slowly. (At this point the development deviates from that presented by Gutenberg (1936)). An empirical formula that gives F exactly for $i = 0$, and approximately when i is less than 0.7 times the critical angle, may be expressed as follows:

$$F_i = [F_{i=0}] \cdot (1 - .0007 i^2)^1$$

where: i must be less than 0.7 times the critical angle.

Applying this formula for the value of $F = 0.20113$ obtained for the Mississippian reflection from the high speed model synthetic seismogram, the calculated amplitude response was approximately 0.922 and 0.982 for i equal to 10 and 5 degrees, respectively. The values agree fairly closely with those published by McCamy et al (1962), curves 8 to 10, when the medium above the Mississippian reflection is considered to have an average velocity of 12 to 14000 fps., while the Mississippian interval velocity is 20,000 fps. For a more precise approximation of the amplitude

¹ From The British American Oil Company Limited technical file.

response the Thomson or Haskell matrices, which approximate the amplitude response of a layered earth model, might have been employed. However, for the accuracy requirements of the present study, the amplitude response developed in this section was considered to be adequate.

To determine the attenuation (a) a correction was computed using data from the report by Attewell and Ramana (1966). The report was a summary of all published and unpublished data on attenuation and interval friction in rocks. The results were presented as a graph of attenuation in db per cm. and frequency (Fig. 13). The analysis of data lead to the following conclusions:

1. Attenuation is directly proportional to frequency.

$$b^* \approx 5 \times 10^{-7} \text{ (db/cm)} \quad \text{for } 10^{-3} < f < 10^0 \text{ (R-waves)}$$

2. Attenuation is approximately proportional to frequency ($f^{0.911}$)

$$b \approx 10^{-5} \text{ (db/cm)} \quad \text{for } 10^0 < f < 10^8 \text{ (P-waves)}$$

3. Attenuation is directly proportional to frequency.

$$b \approx 2 \times 10^{-6} \text{ (db/cm)} \quad \text{for } 10^{-3} < f < 10^8 \text{ (R and P waves)}$$

* b is the constant of proportionality.

4. Internal friction (Q) is independent of frequency, a mean value being 4.7×10^{-3} over the frequency range

$10^{-3} < f < 10^7$ (P,S,R,L). Attenuation is related to internal friction by the expression:

$$a = \omega / 2c, Q$$

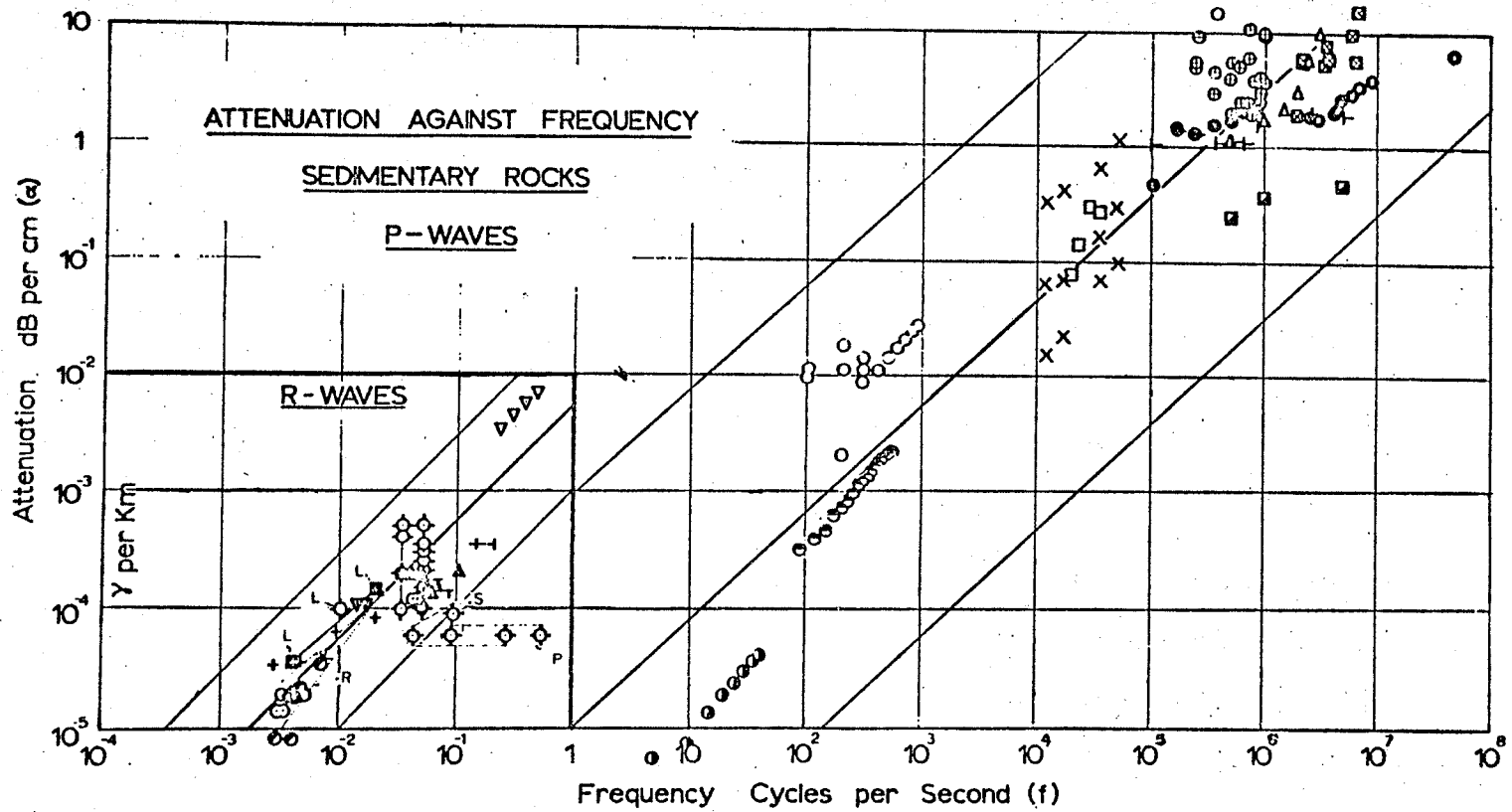


FIGURE 12. Attenuation as a function of frequency for P waves in sedimentary rocks (from Attewell and Ramana, 1966)

where ω = angular frequency

C_1 = phase velocity.

Using a value of 50 cps. as the dominant frequency component the spatial attenuation factor $a = b(f)^{0.911} = 10^{-5} (50)^{0.911}$ db/cm. Assuming straight line paths, the energy reaching the surface at the furthest point from the shot point location, from a reflector at a depth of 4700 feet (the Mississippian event), should have travelled approximately 200 feet (6096 cm) further than the energy arriving at the nearest geophone group. The attenuation resulting from these conditions equals 1.06 db. or a ratio of 1.13. Hence the amplitudes observed at the furthest geophone group must be increased by a factor of 1.13. A graph of the variation of attenuation with distance travelled is given in Figure 19b. As the angle of incidence increases the travel paths will become curved, and the actual distance the energy pulse must travel will be somewhat larger than that used in the straight line approximation above. However, the accuracy of the computed attenuation relations as given in Attewell and Ramana (1966) does not warrant a more thorough investigation in this study.

The effects of attenuation due to absorption as discussed above may be selective as to frequency, that is, larger fractions of the wave energy of particular frequencies may be absorbed than that of others. In a perfectly elastic medium, all frequencies would be transmitted without absorption. However, in the earth high frequency seismic waves are absorbed to a much greater extent than low frequency waves.

Dispersion is the effect of variation of the velocity of a wave with a variation in frequency. For an imperfectly elastic medium such as the earth some dispersion is to be expected. Since the earth sharply limits the range of frequencies that is transmitted, only limited opportunity exists for the observation of dispersion. No appreciable effects of dispersion have been noted by other authors and hence the effects of this phenomenon are not considered here.

Similarly the effects of diffraction and scattering, defined as the creation of small energy waves produced when an advancing wave front strikes free particles which are small compared with the wave length, are neglected.

The curvature of the reflecting boundary near the reflection point may have either a converging or diverging effect on the waves. Generally, the magnitude of the curvature can be determined from the reflection times. However, depth variations too small to detect from the time values may be large enough to affect the amplitudes of the seismic reflections. Such amplitude variations may appear as anomalies in an absolute amplitude study.

The conditions in the near surface layer were found to be fairly constant in the survey area and no corrections to compensate for variations in this layer were made.

Similarly surface elevation variations were considered too small to be taken into account.

Instrument Response

In seismograph work most of the waves dealt with are due to transitory disturbances, so that the wave motion may be a wave pulse. The behaviour of waves, as found from experiments with continuous waves, can often be applied to wave pulses; however, the theory of continuous waves cannot be used indiscriminately and every application must be tested. A standard use of the theory of continuous waves is its application to linear arrays of multiple geophones. This type of analytical treatment gives the geophone response in a form that resembles multiple antenna theory of radio waves.

Several other assumptions must be made for the application of this technique:

1. The time increment (Δt) from geophone to geophone in each group remains constant.
2. The geophones are equally spaced and uniformly planted.
3. The impedance matching must be correct (resonance is minimized).
4. The output of the multiple group is the vector sum of the output of each geophone.

Following the method outlined by Hales and Edwards (1955) it can be shown that if a wave $A \sin(\omega t)$ travels along a line of "n" equally spaced geophones the resultant output can be expressed by:

$$O_R = A \left[\frac{\sin(n\omega\Delta t/2)}{\sin(\omega\Delta t/2)} \right] \sin(\omega t)$$

The original amplitude A is modified by the term in square brackets, and from this modification the important criteria of linear multiple groups may be derived. If q is the term in brackets and the stepout

time Δt is expressed in terms of geophone spacing, $x = V \Delta t / \sin i$, then q may be more conveniently given by:

$$q = \frac{\sin(\pi n D \sin i)}{\sin(\pi D \sin i)}$$

where $D = \frac{f \Delta x}{V}$

f = the frequency of the received disturbance

V = the velocity involved.

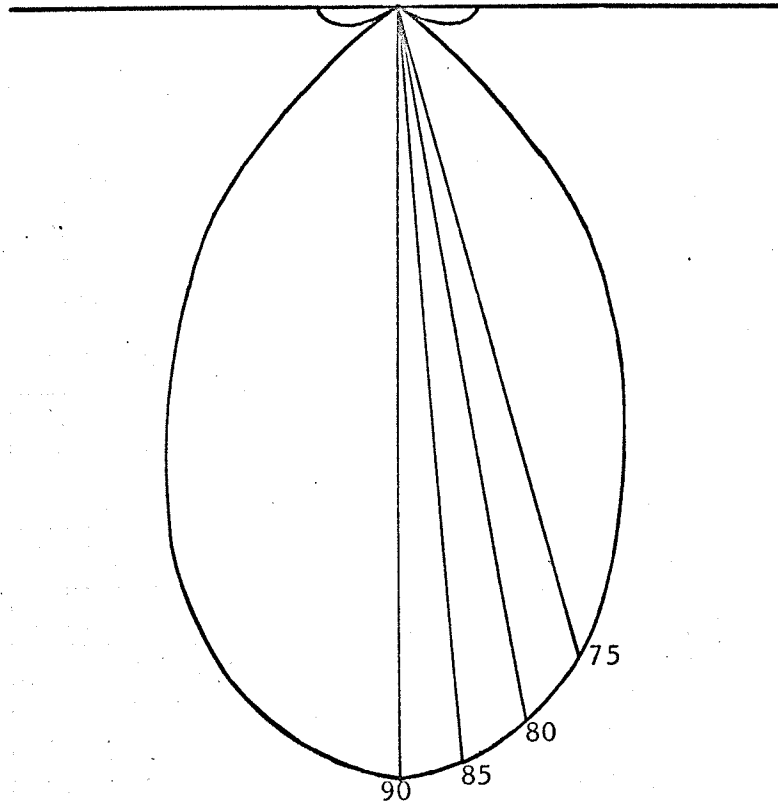
For values of $\sin i = m/nD$ ($m = 1, 2, 3 \dots$) the response q will equal zero. In the special case where $m = 0$, q will have the limiting values of $\pm n$. For intermediate values of i , q will oscillate with values between $+n$ and $-n$ with rapid phase reversals as zero values are passed through. Figure 13 shows the response q as a polar diagram similar to that derived for a multiple antenna array for radio waves. The values, $x = 40'$, $f = 40$ cps and $V = 5800$ fps, as estimated from The British American Oil Company Limited data, were used to construct this diagram. The emerging rays for i equal to $75, 80, 85$ and 90° are indicated. The responses of the geophone array for these values of i are $.877, .944, .985$, and 1.00 , respectively.

To examine the response of the multiple group to disturbances of different frequencies the equation for q may be rewritten as:

$$q = \frac{\sin(nCf)}{\sin(Cf)}$$

where $C = \pi \Delta x \sin i / V$

The value of C is considered a constant for disturbances arriving



$D = 1.104/n$; Zero Response when $i = 64^{\circ}56'$

FIGURE 13. Directional sensitivity of a linear array of geophones

from a particular direction i . Figure 14 shows the response as a function of frequency for values of $i = 76, 80, \text{ and } 84^\circ$. A dashed line indicates the effect of the response, q , for $i = 76^\circ$ on the resultant response curve obtained by the combination of the geophone and amplifier curves. It can be seen that the position of the peak frequency response has been decreased to 90% and has been shifted to 38.5 cps from 40 cps. This effect will become more important as the angle of incidence increases. The program used for the computation of the effects of the arrival of the energy at various angles of emergence is given in Appendix B (IBM 360).

Detector and shot point arrays can be regarded as spatial filters, which differ essentially from electrical filters in that they discriminate between signal and noise on the basis of their apparent wave lengths. Both filters are generally applicable, since noise events may have substantial frequency content in the reflection frequency band. To obtain the instrument response in the most convenient form the effects of both types of filters were considered.

Smith (1956) presented a thorough discussion of noise analysis and multiple seismometer theory. He showed that the multiple seismometer power response as a function of wave number (the reciprocal of apparent wave length) may be given by:

$$\left| H_2^*(k) \right|^2 = \frac{1}{n^2} \frac{\sin^2 n \Delta x \pi k}{\sin^2 \Delta x \pi k} \quad (\text{Fig. 15}).$$

where: $n =$ the number of geophones/group

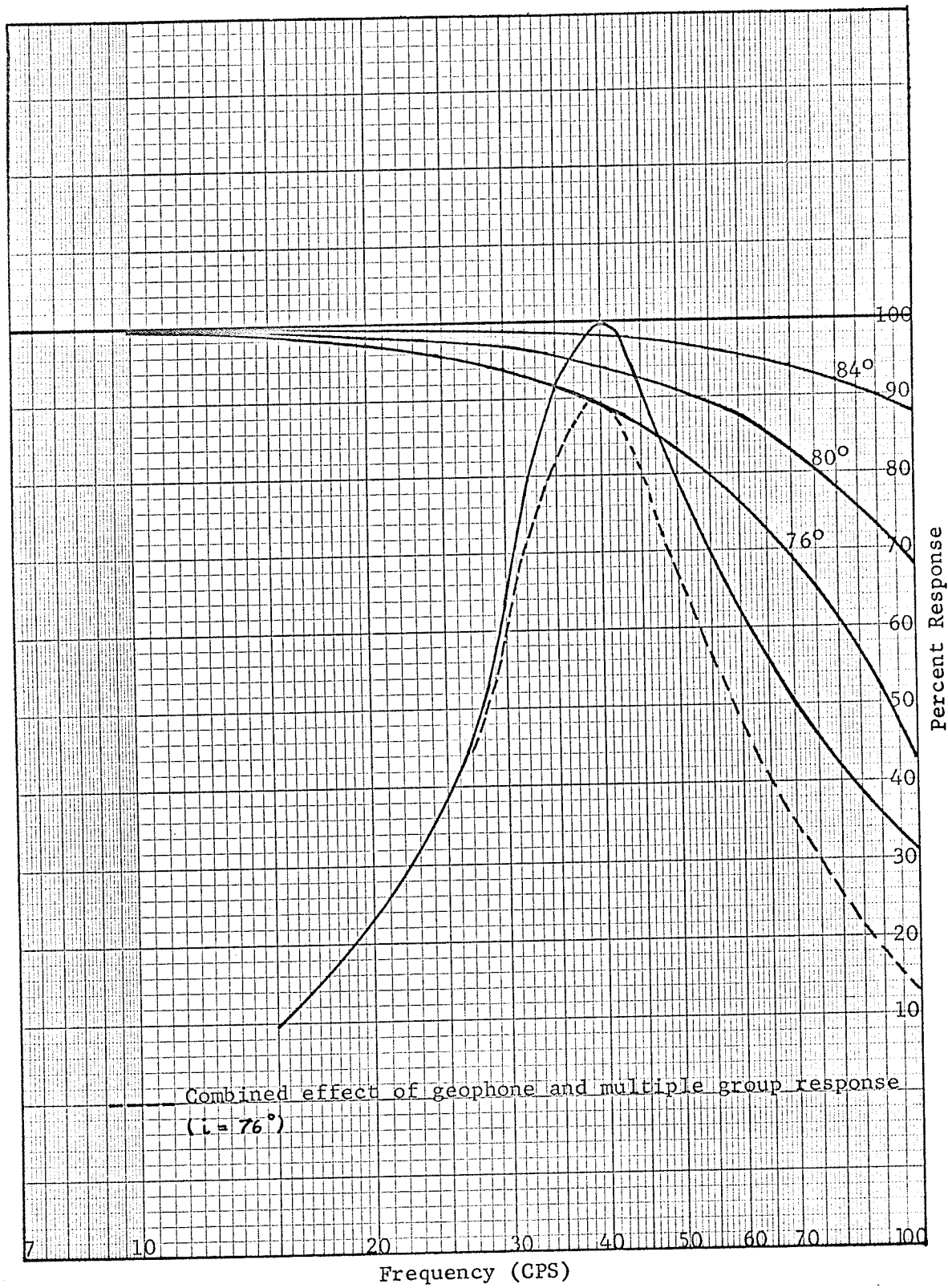


FIGURE 14. Modification of the instrument response as a function of frequency and the angle of emergence.

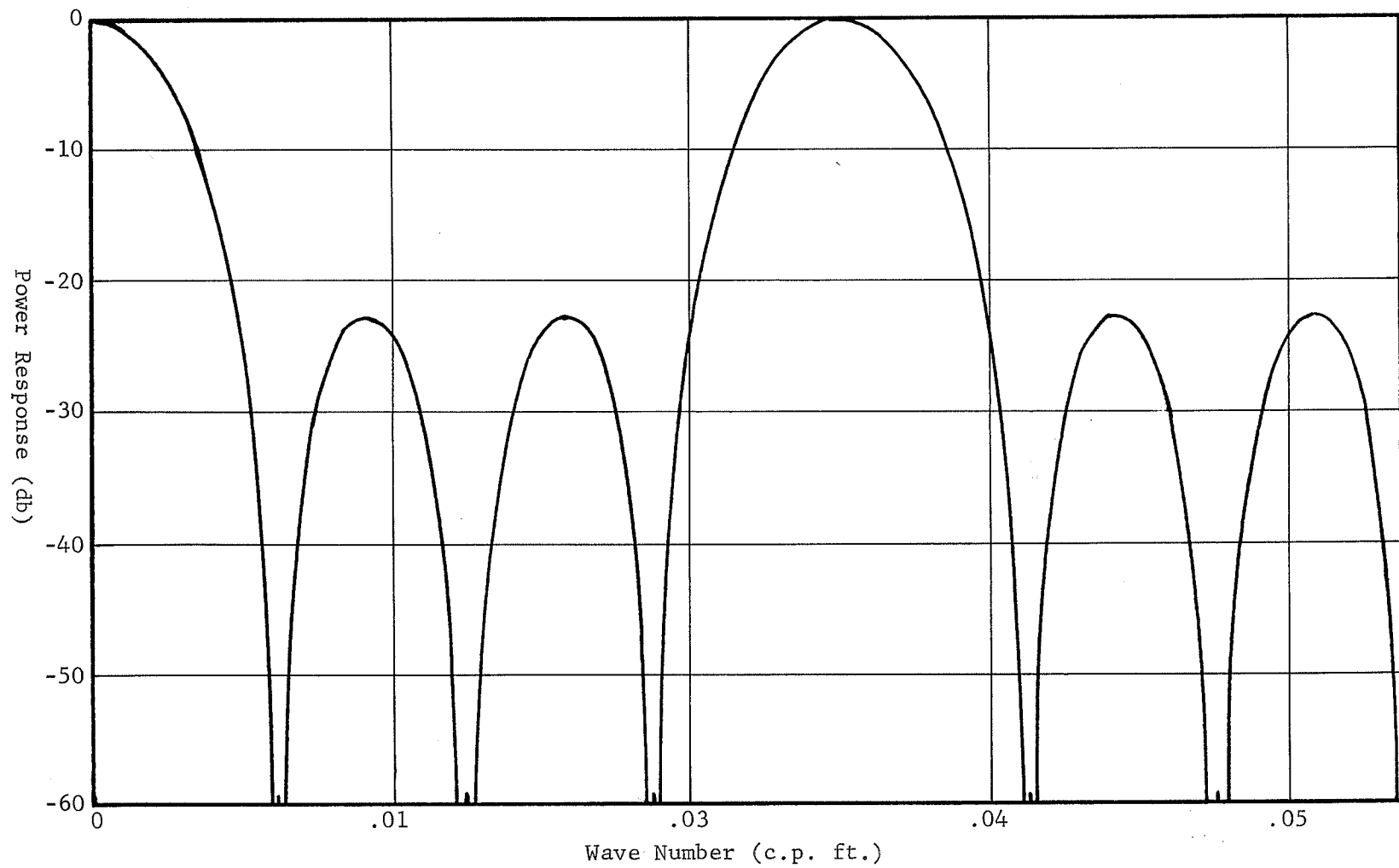


FIGURE 15. Multiple seismometer power response as a function of wave number.

Δx = the spacing between geophones

k = the wave number.

A computer program to calculate the system power response is given in Appendix B.

The response spectrum of a complete recording and playback system is the product of the response spectra of the shot point pattern, the detector pattern, the spaced pattern arrangement, and the playback mixing. The objective is to design the individual arrays in recording and playback in such a manner that their product yields a response spectrum having a reject band corresponding to the noise pattern, while reflection events are passed without appreciable suppression. Only the effects of the seismometer array and the effects of the electrical filters need be considered in this study. Figure 15 shows how the resultant power response of the amplifier and geophone response (as a function of frequency) may be combined with the power response of the multiple geophone array (as a function of wave number) to obtain the combined system power response contoured in db (Fig. 16). Thus for any particular value of k and f the system power response may be determined.

The noise and reflection events observed on the seismograph may be classified according to the magnitude of their moveout or the related parameter wave number (the reciprocal of apparent wave length). The apparent wave length is the wave length sensed by the detectors on the ground surface (Fig. 17) and is equal to the apparent phase velocity divided by the dominant frequency of the event. Apparent phase velocity may be defined as the distance per unit time of moveout on a record.

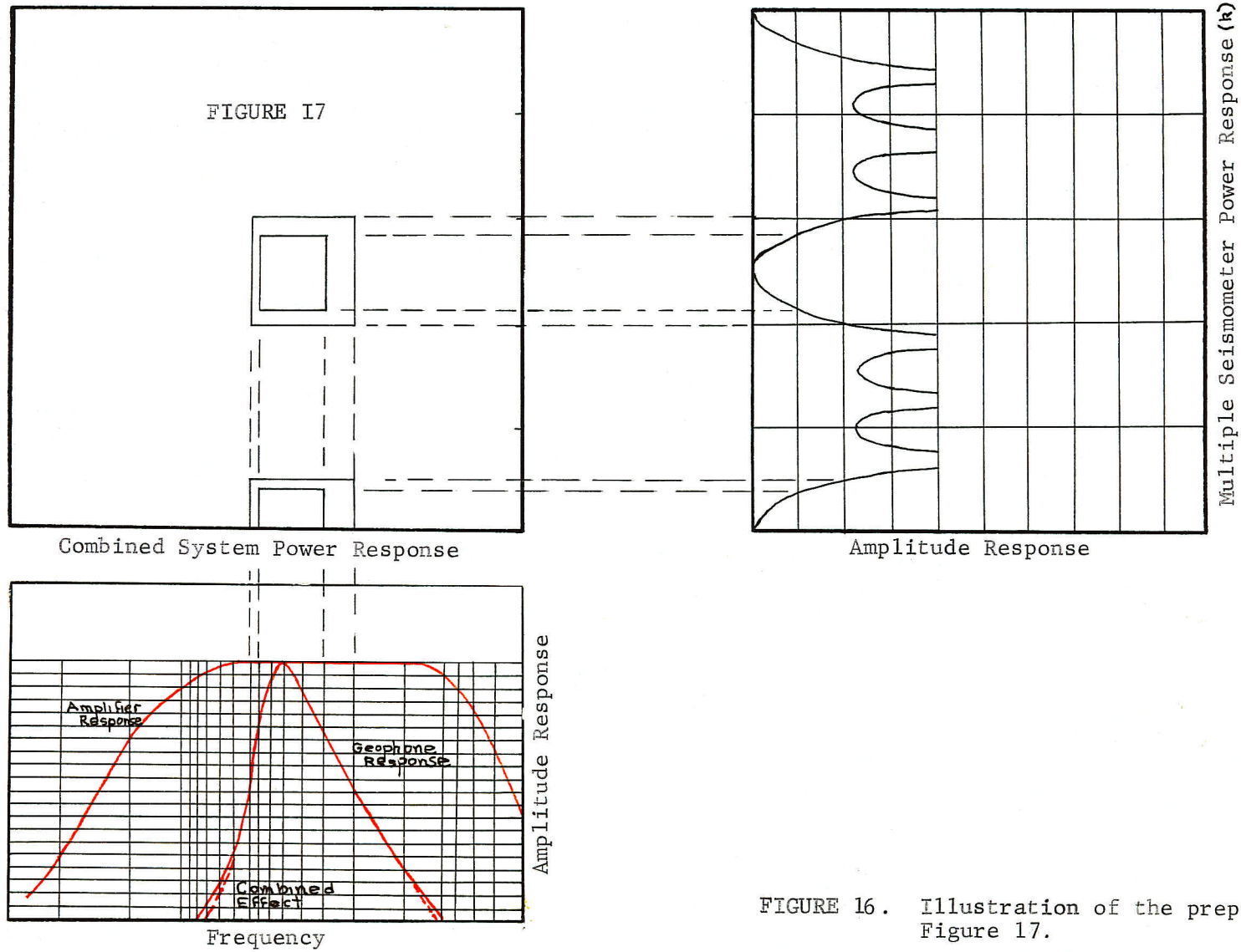


FIGURE 16. Illustration of the preparation of Figure 17.

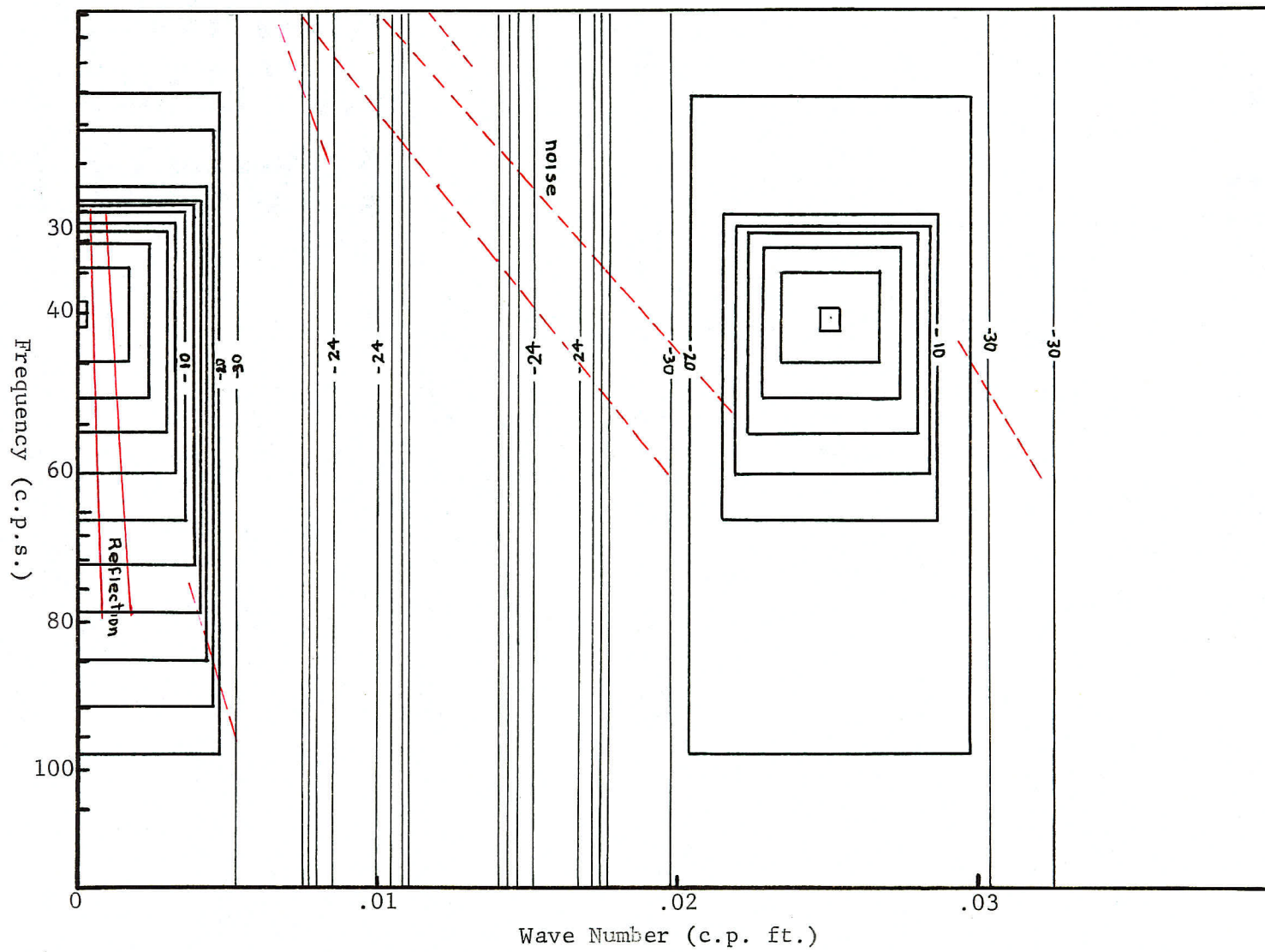


FIGURE 17. Combined system power response contoured in db.

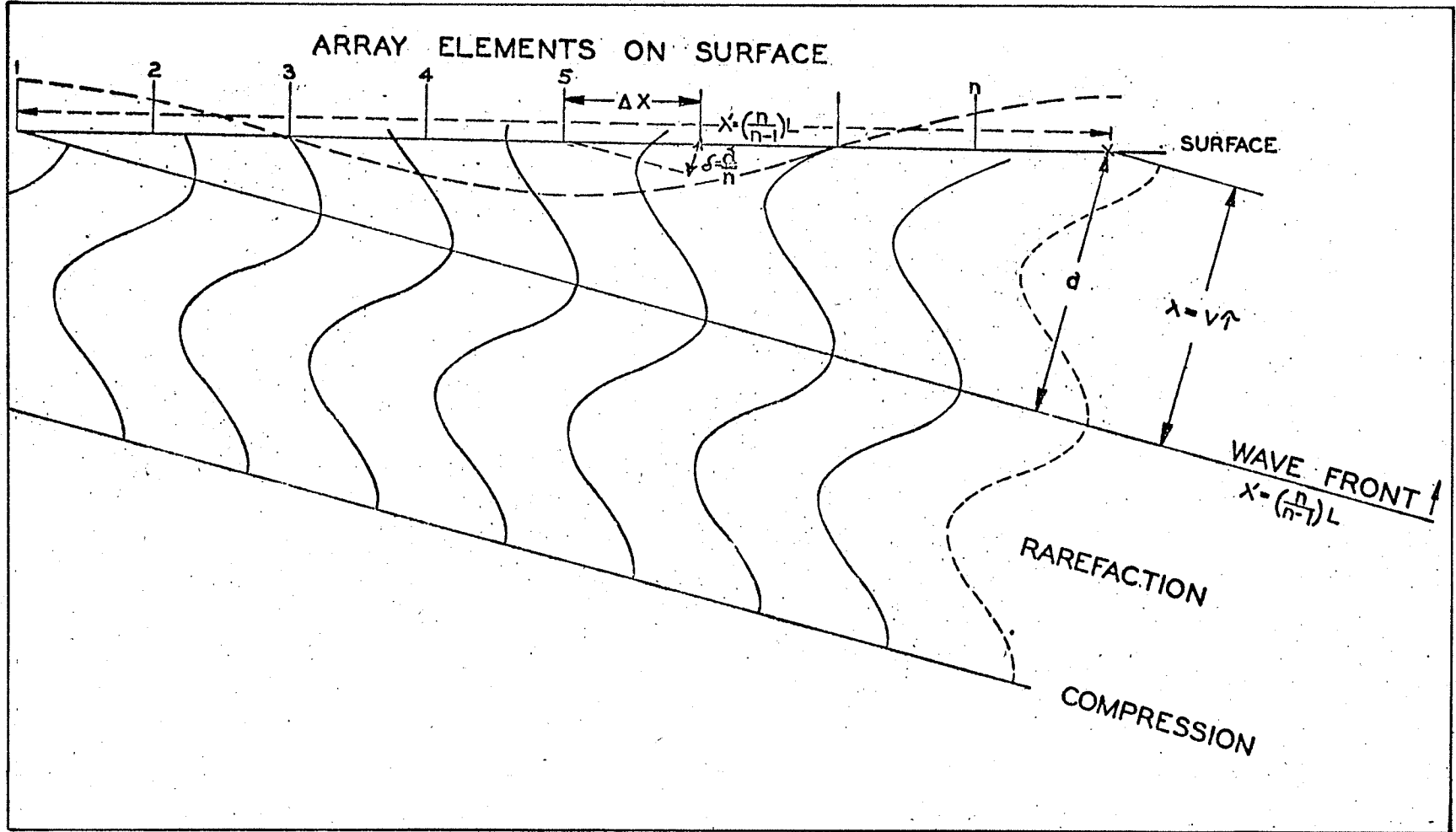


FIGURE 18. The response of a spatial array to an advancing wave front (for equal amplitude continuous waves).

Smith (1956) and noise studies performed by The British American Oil Company Limited indicated that most disturbing noise events range in apparent wave length from about 120 ft. ($k = .0083$) to 1600 ft. ($k = .0063$) and more. The spectra of some noise events are shown as dashed lines on Figure 17.

From the moveout of the Mississippian event k was calculated to range from .00055 to .00097 cyc./ft. from the nearest to the furthest geophone group on the spread. If the dominant frequency of the event were 50 cps (a good approximation from a power spectra analysis of the wavelet used to make the synthetic seismograms) the response of the system would be about 0.7 db (8.0%) lower at the end of the spread. This agrees fairly closely with the instrument sensitivity as represented by the polar diagram in Figure 13. The instrument sensitivity is given as a function of distance from the shot point in Figure 19C.

Data from Figures 13 to 19 can, of course, be used for a more thorough investigation of noise suppression and of the enhancement of the reflection event. However, this is beyond the scope of this study.

Only the effects of the automatic volume control (AVC) remain to be investigated before the over-all response of the recording system can be estimated. The master control elements of the recording system are matched to give the same reduction in gain for all amplifiers. This feature of the amplifiers makes it possible to recover the original relative amplitudes of the recorded signals thereby removing all effects of the AVC. The gain indicator trace

is recorded as a function of frequency on the seismograph (Fig. 6). A frequency of 30 cps. indicates full gain and a change of frequency of 1 cps. indicates a gain change of 1 db. Hence an indicated frequency of 40 cps. would show a gain reduction of 10 db. The following table gives an outline of the gain information obtained for the Mississippian reflection (M) along the survey line.

TABLE 2. Amplifier Gain Reduction for Reflection M.

Shotpoint	Frequency (cps.)	Gain Reduction (db)
444	30	0
448	30	0
452	32.5	2.5
456	32.5	2.5
460	32.5	2.5
464	32.5	2.5

Therefore, the gain values from records 452, 456, 460, and 464 are larger than those on records 444 and 448 by about 2.5 db or a ratio of approximately 1.33.

The total correction that must be applied to the amplitudes (neglecting the effect of amplifier gain) may be calculated from Figure 19d. The amplitude corrections for the amplifier gain may then be applied to the appropriate seismograph records as mentioned above.

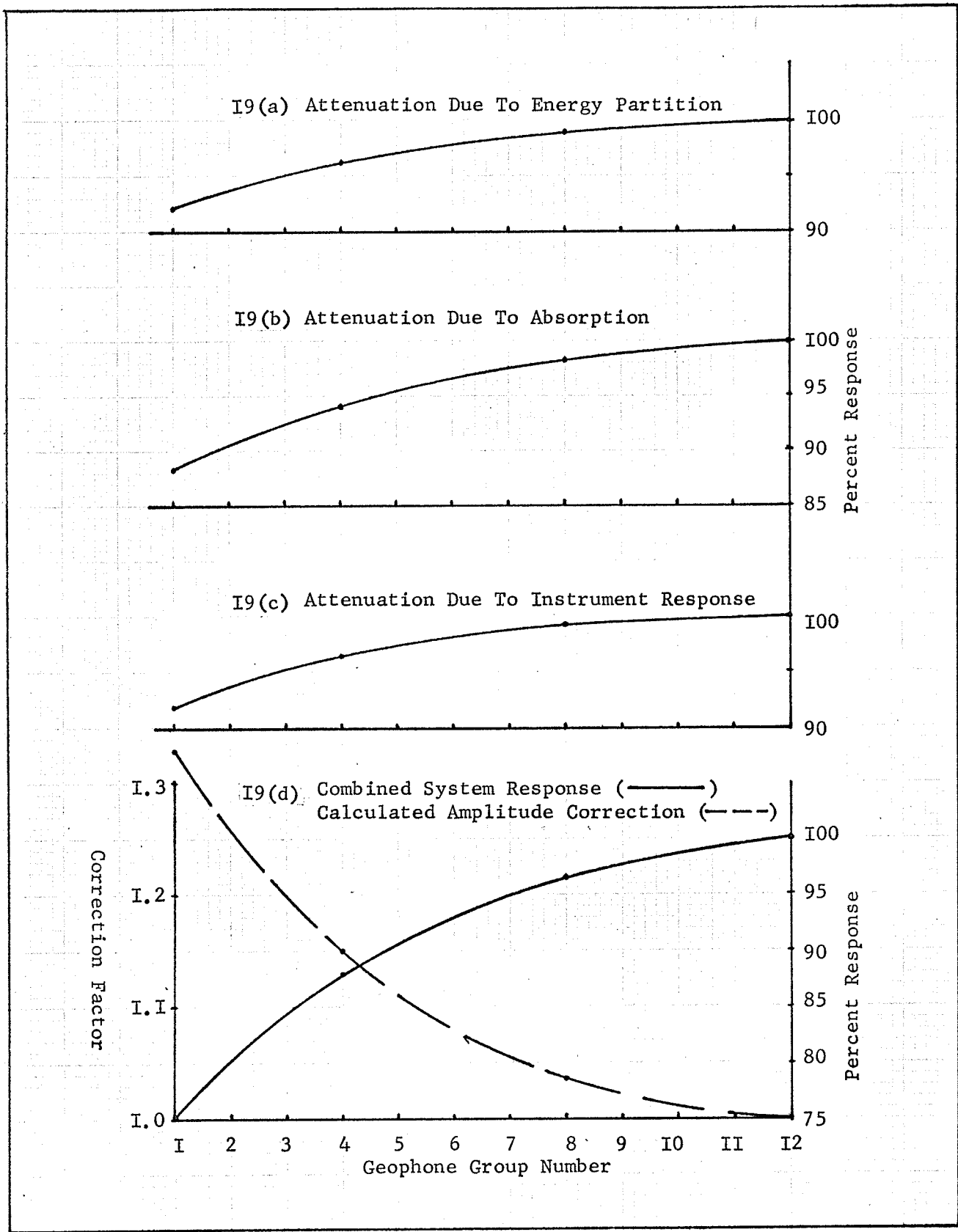


FIGURE I9. Calculation of the combined system amplitude attenuation and correction factor.

IV

INTERPRETATION OF THE AMPLITUDE DATA

Application of Corrections to the Amplitude Data

The corrections due to energy partition, absorption and instrument response (Fig. 19) were applied to the amplitudes recorded in Table 1. The correction for gain variations was then made for records 452 to 464. The resulting amplitude data were plotted as a function of the position of the reflection points (Fig. 20). The average of the plotted points was drawn so that rapid variations of amplitude values were smoothed.

If the detailed analysis of the factors influencing the amplitude data had been omitted, the correction factors applicable to the data could have been found intuitively from the estimated average curves in Figures 7 and 8. This comparison of correction factors is quite favorable since the average correction calculated from the estimated curves is very close to the calculated value (Fig. 19d). However, knowledge of the instrument response makes interpretation of the data easier and would help in areas where experimental conditions are not as uniform as in this study.

Conclusions Reached in the Study

As mentioned previously, amplitude measurements have been used in the interpretation of seismic data. They may provide the information necessary to establish the form of the layered earth model, detect pinchouts, and even indicate lateral lithologic variations. It is obvious

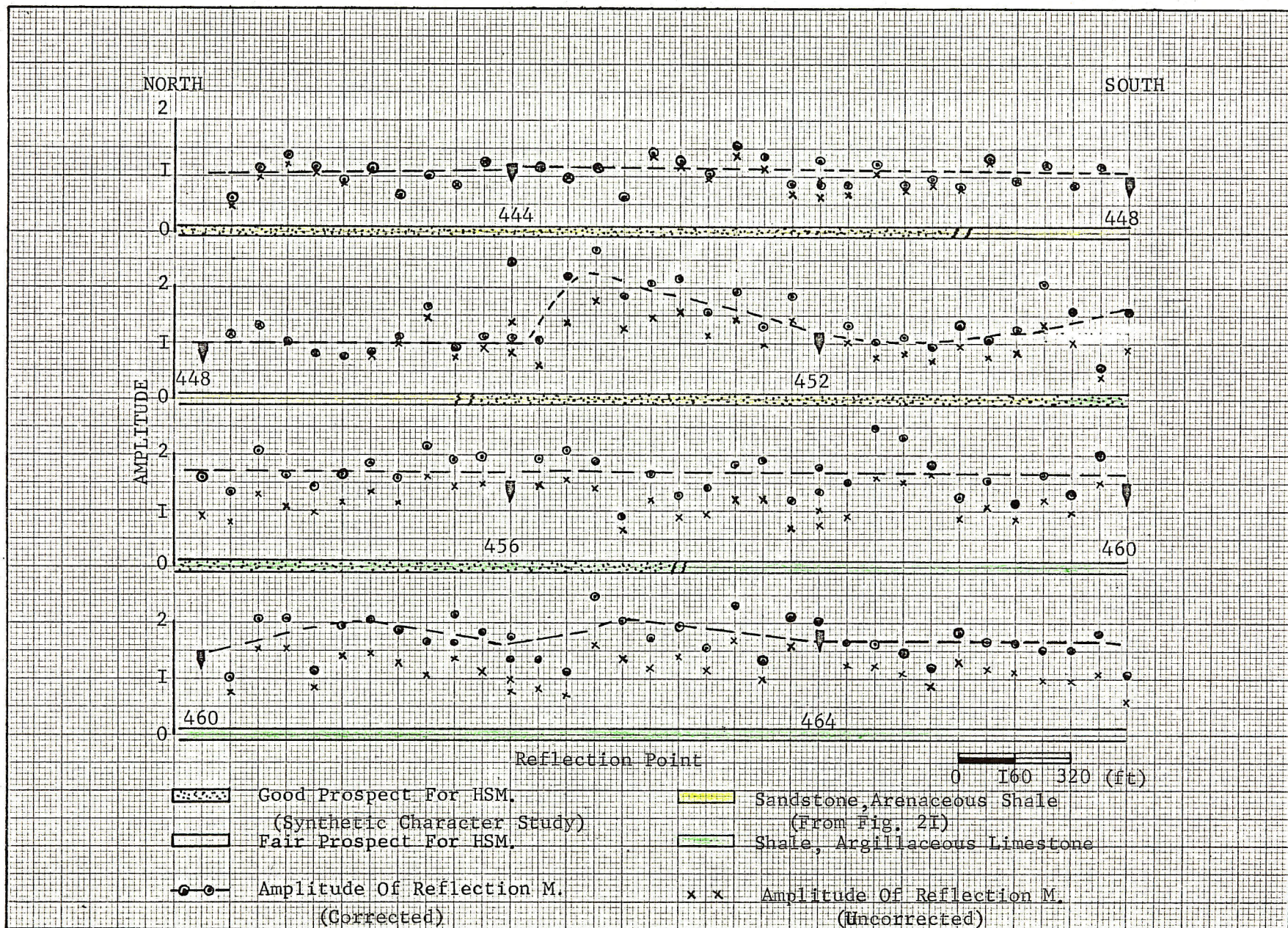


FIGURE 20. Relation of the corrected amplitudes and the position of the reflection point for the reflection M.

that many factors can influence an absolute amplitude study, but a thorough investigation of these factors can provide the geophysicist with another tool for the interpretation of seismic data. The usefulness of this study may come to light when the amplitude profile in Figure 20 is compared with the Upper Shaunavon Formation lithofacies map presented in Figure 21. Just south of shotpoint 452 the lithology of the Upper Shaunavon grades from a sandstone and arenaceous shale to a limy shale. It is proposed that the change in the value of the amplitudes from 1.00 (in sandstone) to about 1.70 (in shale) is an indication of this lithological variation. The sudden increase in amplitude just north of shotpoint 452 may be caused by a change of elevation of the Shaunavon and the Blairmore (Mississippian) formations as indicated by the reflection times. Koefoed (1960) suggested that a study of absolute amplitudes may indicate depressions of the reflecting boundary. The value of the amplitudes gradually decreases to 1.00 after the maximum at group 4 of shotpoint 452. This seems to indicate that the assumption concerning the influence of lithology on the amplitudes of the reflections is not altered by the change in elevation of the Mississippian surface beyond the region where the change occurred. It would be of great interest to continue the study of amplitude variations in the areas where limestone is indicated on the lithofacies map.

SUGGESTIONS FOR FUTURE WORK

Comparisons of the absolute intensities of waves and the microseism background make it possible to determine the effectiveness of the seismic explosion and to evaluate the recording conditions. The use in interpretation of not only the degree of wave attenuation with distance, but

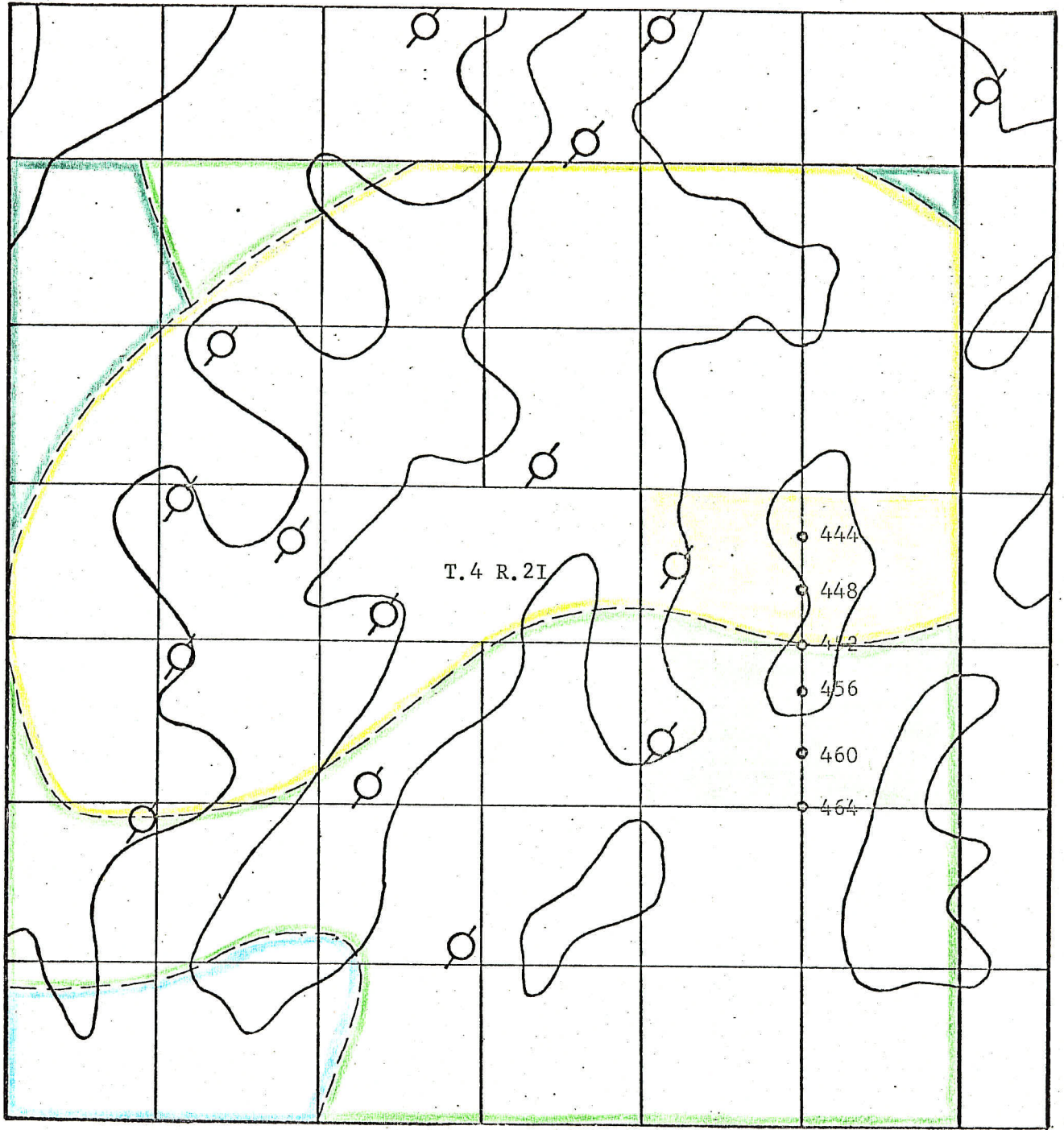
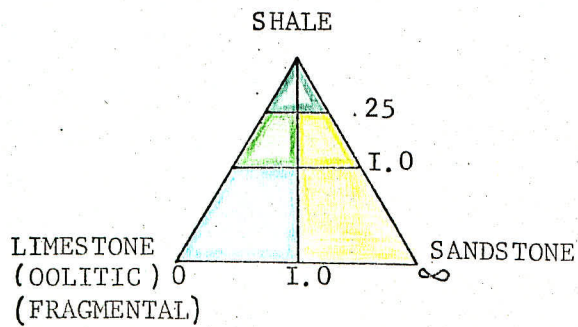






FIGURE 21. Upper Shaunavon Formation lithofacies map.



-  Well
-  Survey Line
-  Arenaceous Shale
Sandstone
-  Shale, Limestone
(Argillaceous)

also of the amplitude intensities of the waves, makes it possible to compare data from disconnected profiles. When the phase spectrum of the layered model is also considered, a unique determination of the type of model can be made. The range of thicknesses of the layers that can be dealt with and the accuracy of the results may both be increased by the simultaneous use of the amplitude and phase spectrum. In general, absolute amplitude measurements are of interest in seismology, the physics of explosions, microseismic zoning, and the design of apparatus for seismological prospecting.

As oil becomes increasingly difficult to find, exploration techniques, instrumentation and data processing must necessarily be refined. All the information desired is present in the complex seismic recording. The problem is the recognition of subtle response variations and the separation of the factors giving rise to these variations. It is obvious that more sensitive recording techniques (greater frequency band pass) would facilitate the solution of this problem.

The absolute amplitude study described here has many scientific applications; its use as a tool for a lithologic interpretation of seismic data needs to be tested further. However, the observed amplitude anomalies are present and as such warrant further investigation. A frequency analysis of the seismic traces, a cross-correlation from trace to trace, and additional information about the effective energy generated by an explosion would be immediate aids in making this study more meaningful.

It is suggested that a few simple experiments which could provide information about the factors found to influence the amplitudes of

reflected waves, be conducted whenever seismic exploration is begun in a new area. The results of these experiments would be immediately helpful in the interpretation of the data and would certainly facilitate the reappraisal of this data if any advancements on data analysis were achieved.

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APPENDIX A

IMPULSIONAL SYNTHETIC SEISMOGRAM WITHOUT
MULTIPLES WITH ATTENUATION

This program was designed to compute the reflection coefficient VK, according to the formula

$$VK = \frac{V_n - V_{n+1}}{V_n + V_{n+1}}$$

where VK = reflection coefficient related to the
interface between layers n and n+1

V_n = interval velocity in layer n

V_{n+1} = interval velocity in layer n+1

Part two of the program calculates the attenuation suffered by the direct reflection at each interface. No attempt was made to introduce the effects of multiples. The transmission coefficient, AK, may be represented by

$$AK = (1 - VK_1^2) (1 - VK_2^2) \dots (1 - VK_n^2)$$

where AK = Attenuation of the direct reflection at
interface n+1

The sequence of values $VK_1, VK_2 \dots VK_n$ represents the impulsional synthetic seismogram without multiples or attenuation. The computed sequence $VK_1, AK \cdot VK_2, \dots AK_{n-1} \cdot VK_n$ provides for attenuation and represents the true reflections with their true relative amplitudes. Approximations required to assure the validity of the seismogram mentioned above are:

- propagation by horizontal plane waves
- perfectly elastic medium composed of horizontal layers
- constant density
- negligible absorption.

The programs and Program three could have been combined, but the calculation of multiples, in the event of any further work in the area, would require the data in their present form.

SYNTHETIC SEISMOGRAM PLOT PROGRAM

This program was designed to produce a synthetic seismogram by convolving the impulse response of the recording equipment with the impulsional seismogram.

TABLE 3 SYNTHETIC SEISMOGRAM DATA

FORMATION NAME	INTERFACE NUMBER	V _n	V _{n+1}	ALPHA	
				HSM Model	No HSM Model
	1	5.80	6.31	.04211	.04211
	2	6.31	6.57	.02015	
	3	6.57	6.73	.01200	
	4	6.73	6.89	.01172	
	5	6.89	6.73	-.01171	
	6	6.73	7.33	.04256	
	7	7.33	6.96	-.02577	
Belly River	8	6.96	8.00	.06916	
	9	8.00	8.27	.01643	
	10	8.27	8.00	-.01642	
Lea Park	11	8.00	7.32	-.04392	
	12	7.32	7.48	.01067	
	13	7.48	7.32	-.01067	
Milk River	14	7.32	8.69	.08449	
	15	8.69	8.93	.01335	
	16	8.93	9.58	.03441	
Colorado	17	9.58	8.58	-.05389	
	18	8.58	8.33	-.01442	
	19	8.33	8.13	-.01185	
2nd White Specks	20	8.13	8.85	.04136	
	21	8.85	8.23	-.03534	
	22	8.23	8.58	.02024	
	23	8.58	8.23	-.02023	
	24	8.23	8.80	.03251	
Viking	25	8.80	8.13	-.03840	
Blairmore	26	8.13	9.70	.08531	
Cantuar Sand	27	9.70	9.00	-.03598	
Upper Vanguard	28	9.00	8.28	-.0400	
Middle Vanguard	29	8.28	8.98	.03886	
Lower Vanguard	30	8.98	8.80	-.00968	-.00968
Upper Shaunavon	31	8.80	10.60	.08877	
	32	10.60	13.30	.10715	.08427
	33	13.30	10.00	-.13262	
Lower Shaunavon	34	10.00	14.50	.16854	.15189
Gravelbourg	35	14.50	9.00	-.20751	-.21649
Watrous	36	9.00	12.40	.13315	.13891
Mississippian	37	12.40	20.50	.20133	.20983
	38	20.50			

C IMPULSIONAL SEISMOGRAM WITHOUT MULTIPLES BUT WITH ATTENUATION

1) DIMENSION V(50) , VK(50) , A(50) , AK(50)

READ 15, N

15 FORMAT (I2)

READ 10, (V(I) , I = 1,N)

10 FORMAT (8F10.2)

C REFLECTION COEFFICIENT CALCULATED NEXT

M = N - 1

3 DO 1 I = 1 , M

1 VK(I) = (V(I) - V(I + 1)) / (V(I) + V(I + 1))

2)C ALPHA ONE CALCULATED NEXT

A(1) = 1.- VK(1) * VK(1)

DO 2 I=2,M

C ALPHA OF THE FORM $\text{ALPH } 1 * (1 \text{ K} 2 \text{ SQUARED})$ CALCULATED NEXT

A(I) = A(I - 1) * (1.-VK(I)*VK(I))

AK(I)=A(I-1)*VK(I)

2 PRINT 20, I, AK(I)

20 FORMAT (3H A(,12,5H) = , F12.5)

CALL EXIT

END

```
DIMENSION X(1300), VALUE(100),Y(100)

77 CONTINUE

DO 1 I=1,1300

1 X(I)=0.

2 FORMAT(2F16.8)

READ 2, XMAX

CALL PLOT(1, -XMAX, XMAX, 8., XMAX, 0., 1250.,14.54 , 50.)

3 FORMAT(2I4)

READ3, NOPTS, NOFMAX

NO1=NOPTS-NOFMAX

C-----READING IN VALUES WAVELET

17 FORMAT(8F10.2)

READ 17, (VALUE(I),I=1,NOPTS )

READ 3, NOFSPK

DO 99 KLGZ=1,NOFSPK

READ2, SPIKE, NTIME

NOST=NTIME-NOFMAX

NOEND=NOST+NOPTS

I=0

NOSTX=NOST+100

NOEND=NOEND+100 -1

DO 33 L=NOSTX,NOEND

I=I+1

LL=L-100

IF(LL)33,33,44

44 Y(I )=VALUE(I)*SPIKE

XL=Y(I)

YY=LL

X(LL)=X(LL)+Y( I)
```

```
33 CONTINUE
99 CONTINUE
DO 55 I=1,1250
XI=I
XL=X(I)
55 CALL PLOT(90,XL,XI)
CALL PLOT (7)
GO TO 77
END
```

APPENDIX B

(1)

C RESPONSE OF A MULTIPLE SEISMOMETER ARRAY TO ENERGY WITH VARYING
ANGLES OF EMERGENCE

2 READ(1,1)C

DO 7 I=21,101,5

F=1

F=F-1.0

RESP = 0.25*(SIN(4.*C*3.1415926*F)/SIN(C*3.1415926*F))

7 WRITE(3,8) F,RESP,C

80FORMAT (18H AT THE FREQUENCY ,F8.2,17H THE RESPONSE IS ,F10.5,
129H OF UNIT RESPONSE FOR A C OF ,F10.5)

1 FORMAT(F16.8)

GO TO 2

999 CALL EXIT

END

.00167

.00143

.00120

.00096

.00072

.00048

(2)

```
C    POWER RESPONSE OF A MULTIPLE SETSMOMETER ARRAY
CALL PLOT(101,0.,.06,11.,.01,-100.,0.,8.0,10.0)
CALL SHIFT (0,1)
A = .0625
DO 7 1 = 11,601,3
C=1
C = (C-1.)*.0001
TOP = SIN(160.*3.1415926*C)**2
DENOM = SIN(40.*3.1415926*C)**2
POWER = A*TOP/DENOM
POWER = ALOG10(POWER)*20.0
7   CALL PLOT(90,C,POWER)
CALL EXIT
END
8   FORMAT (16H AT THE WAVE NO ,F6.3,29H WE HAVE A POWER
RESPONSE OF ,
1F10.5, 10H DECIBELS )
7   PUNCH 8,C,POWER
ENDX
```