A NEAR-VERTICAL-INCIDENCE REFLECTION SURVEY CONDUCTED OVER THE PRECAMBRIAN SHIELD OF SOUTHEASTERN MANITOBA

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ABSTRACT

A near-vertical-incidence reflection survey has been conducted in the Whiteshell area of southeastern Manitoba in an attempt to demonstrate the applicability of the method in investigating shallow crustal structure.

Arrays of seismometers have been used to attenuate shot-generated surface waves. The degradation of random noise has also been achieved and the signal-to-noise ratio correspondingly increased. The use of detector arrays is recommended for all future reflection work carried out in Precambrian Shield areas.

Boreholes have been drilled in granite gneiss and successfully used for the location of seismic sources. The ability to use predetermined shot points and thus attain a degree of freedom not otherwise possible, as when lakes, rivers, or abandoned mineshafts are used as source locations, has been demonstrated. The drilling of the boreholes is a time consuming and expensive process, although successful; it is recommended that patterns of surface charges be experimented with as a possible method of generating seismic energy.

A velocity filtering program has been designed and the method demonstrated as being a reliable and efficient processing technique, capable of improving the signal-to-noise ratio. Velocities have been determined for direct wave arrivals. However, no near-surface structural features were observed.

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CHAPTER 1

INTRODUCTION

1.1 The Project

The Geophysics Division of the Department of Earth Science at the University of Manitoba began using the seismic method to investigate the properties of the earth's crust in the early 1960's. The results have been published in several papers; Hall and Brisbin (1961), Hall (1964), Hall and Brisbin (1965), Hall (1969), Hajnal (1969 and 1970), Hall and Hajnal (1969), Gurbuz (1969), Hajnal (1971), Hall (1972a,b), Hall and Hajnal (1972).

Hajnal (1970) describes an experiment using near-vertical reflections to determine crustal structure in Southeastern Manitoba. He found that the near-vertical reflection profile disclosed near-surface geological features as well as possible arrivals interpreted as possibly coming from the Intermediate (Conrad) Discontinuity. These results indicated that some modification of the technique and that further experimentation were necessary, if near-vertical reflection surveys were to be used with success to determine crustal structure in Precambrian Shield areas.

Clowes (1969) has demonstrated that reflection surveys, carried out over a few small areas, may be used in combination with large scale gravity, magnetic and refraction surveys to provide a somewhat detailed interpretation of crustal structure over a widespread area. The promising results of the near-vertical reflection survey, described by Clowes, was attributed to the acquisition of data using predesigned arrays of detectors and multiple shot holes, to eliminate shot-generated long period surface waves. However, Clowes' survey was carried out in southern Alberta, where some 1.5 km of sediments overlie the basement rocks. The use of the near-vertical reflection method in the Precambrian environment poses a different set of problems.

Hall and Hajnal (1969) and Wilson (1971) indicate the need for the development of a successful reflection method for investigating shallow crustal structure. This thesis reports on part of the experimentation connected with the devising of such a method.

The project encompasses development in the following areas

1) The development of suitable seismometer arrays, to be used on Shield areas to eliminate shot-generated surface waves.
2) The development of a technique permitting the economical use of diamond drill holes, at predeter-

mined locations, as source sites.

3) The development af a suitable processing technique based on the stacking of seismic data, obtained with a multichannel system.

1.2 Instrumentation

1.2.1 Recording Equipment

The seismic recording equipment used throughout the survey consisted of a Texas Instruments Incorporated VLF-2 refraction system, an Ampex Model CP-100 analog magnetic tape recorder, a Southwestern Industrial Electronics Model MU-21 modulator-demodulator unit and a WWVT receiver for timing purposes. A complete description of the seismic instrumentation available at the University of Manitoba is given by Hajnal (1970).

1.2.2 Seismometers

The only divergence from the University's standard refraction equipment was the substitution of 10 Hz detectors for the 1 Hz geophones at some recording sites. This substitution was made necessary because of frequency considerations.

The HS-10-1 type seismometers supplied by Geo-Space Ltd. were employed at recording site-shot-point locations 3 and 4 (see Table 2.1). They have high output velocity sensitivity with a natural frequency of 1 Hz and were connected singly, one to a trace.

The seismometer arrays used in the survey consisted of L-10A Digital Grade Subminature geophones supplied by Mark Products, 12 to a stringer. They have a natural resonant frequency of 10 Hz.

Figures 1.1a and 1.1b show the principal characteristics of these seismometers.

1.2.3 Analog to Digital Conversion

All data acquired throughout the survey was recorded on analog FM magnetic tape and later converted into IBM compatible 7 track magnetic tape. The conversion process was carried out by means of a Radiation Incorporated A/D converter. The digitizing interval was 2.448 milliseconds resulting in an aliasing frequency of about 200 Hz.

A complete description of the A/D converter as well as the digitizing process is given by Hajnal (1970).

1.3 Location

The near-vertical incidence reflection survey, under consideration, was conducted over a 6.5 km (4 mile) portion of the West Fireguard Road. The road runs north from Manitoba Provincial Highway 44 to intersect Provincial Road 307, 100 meters west of the Whiteshell Park Gate. The actual location of the survey area is shown in Figure 1.2. The precise location of the array and shot hole systems, as determined by chain and transit is indicated in Figure 1.3.

The survey was conducted along side the West Fireguard Road for the following reasons.

1) The road was used infrequently and hence control of traffic was accomplished with a minimum of inconvenience to the motorist and members of the seismic crew.

2) The location of the recording site was sufficiently removed from the major arteries such that the contribution of extraneous signals from passing automobiles, trains and construction activities was insignificant.

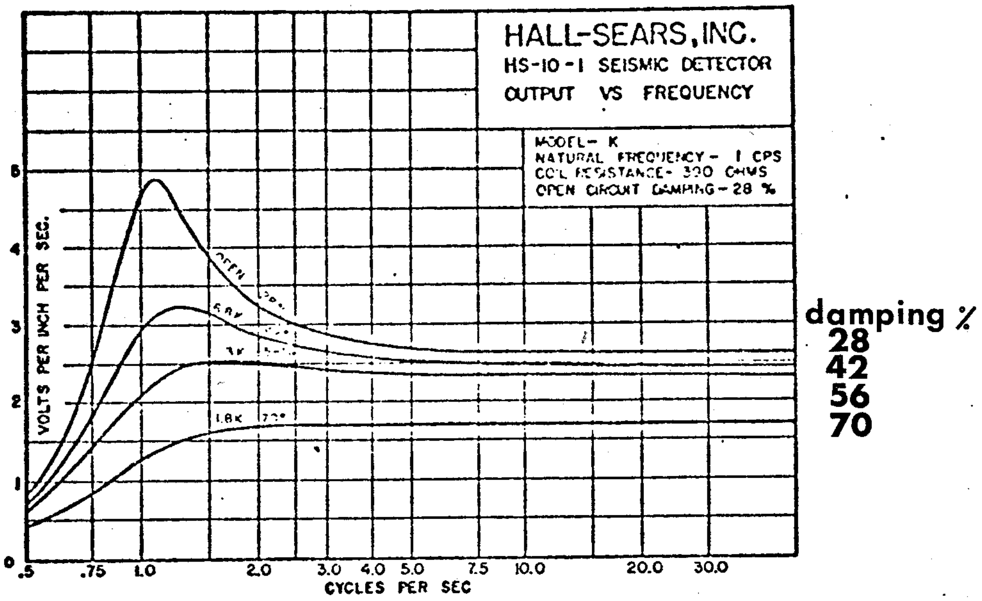
3) The nature of the Precambrian outcrop was such that the apparent absence of major fractures, limited weathering layer and exfoliation would not impede the drilling of shot holes and would allow the repeated use of the shot holes as source locations.

4) The rocks at the shot holes appeared to be relatively homogeneous, therefore good coupling would be achieved and elastic theory applicable.

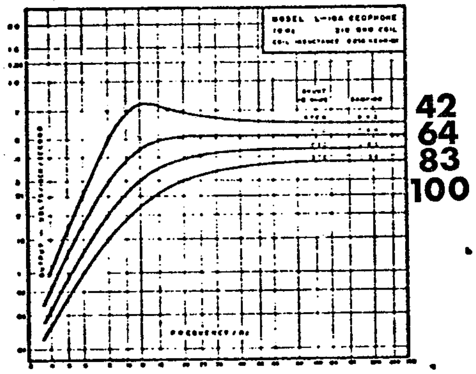
5) The equipment necessary for the drilling of the shot holes could be easily transported to the chosen sites. Water, necessary for diamond drilling and tamping the holes, was within pumping distance.

6) Coles (1970) has measured Curie Temperatures of the surface rocks in an attempt at relating

crustal structure to regional magnetic anomalies in the area. A more extensive analysis of the magnetic properties of the surface rocks is currently being undertaken and the additional contribution of seismic information would therefore be pertinent.

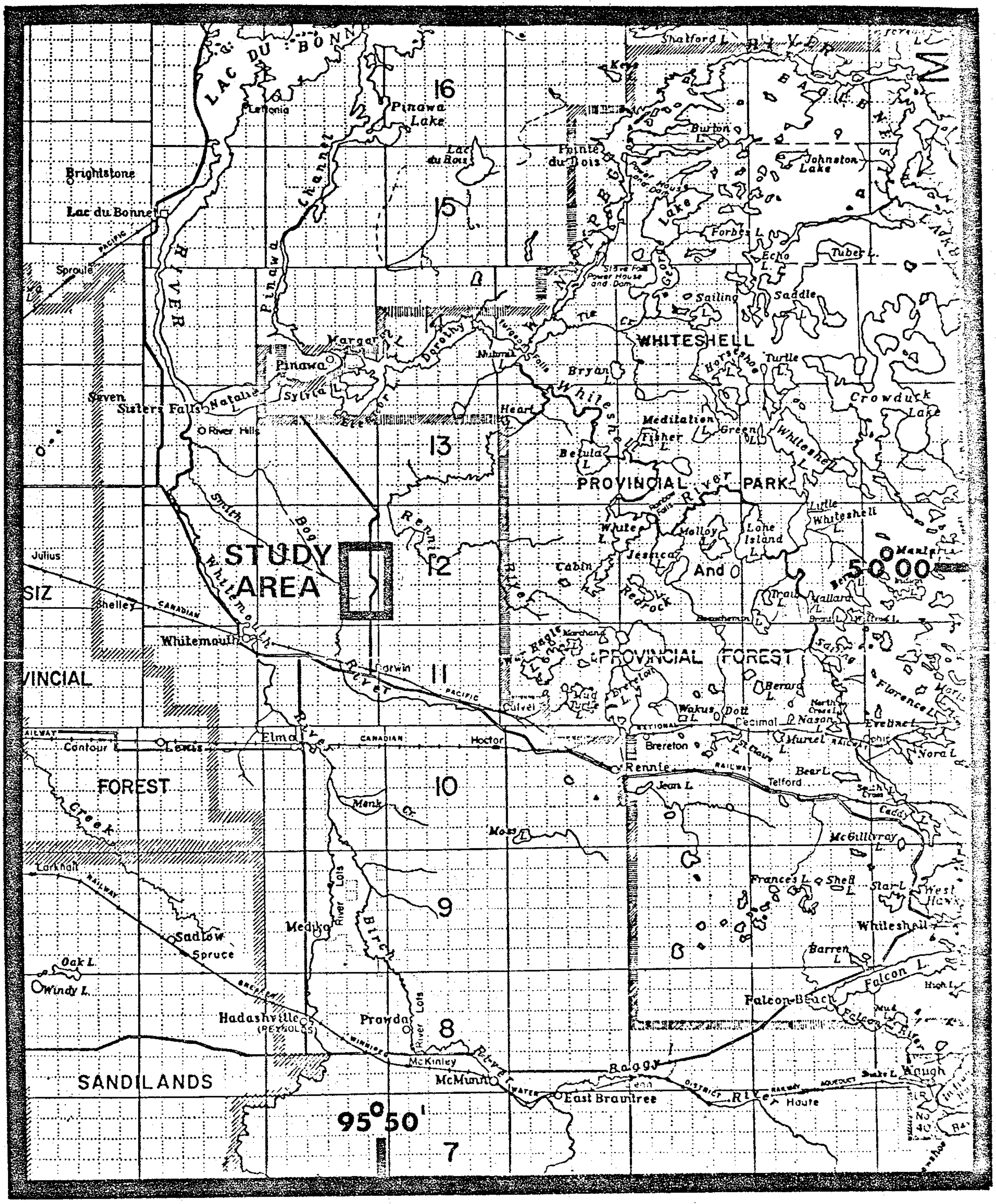


a) HS-10-1 Geophones



b) L-10A Geophones

FIG. 1.1 Seismometer characteristics



1 inch:13 kilometers (approx.)

Fig.1.2 LOCATION MAP

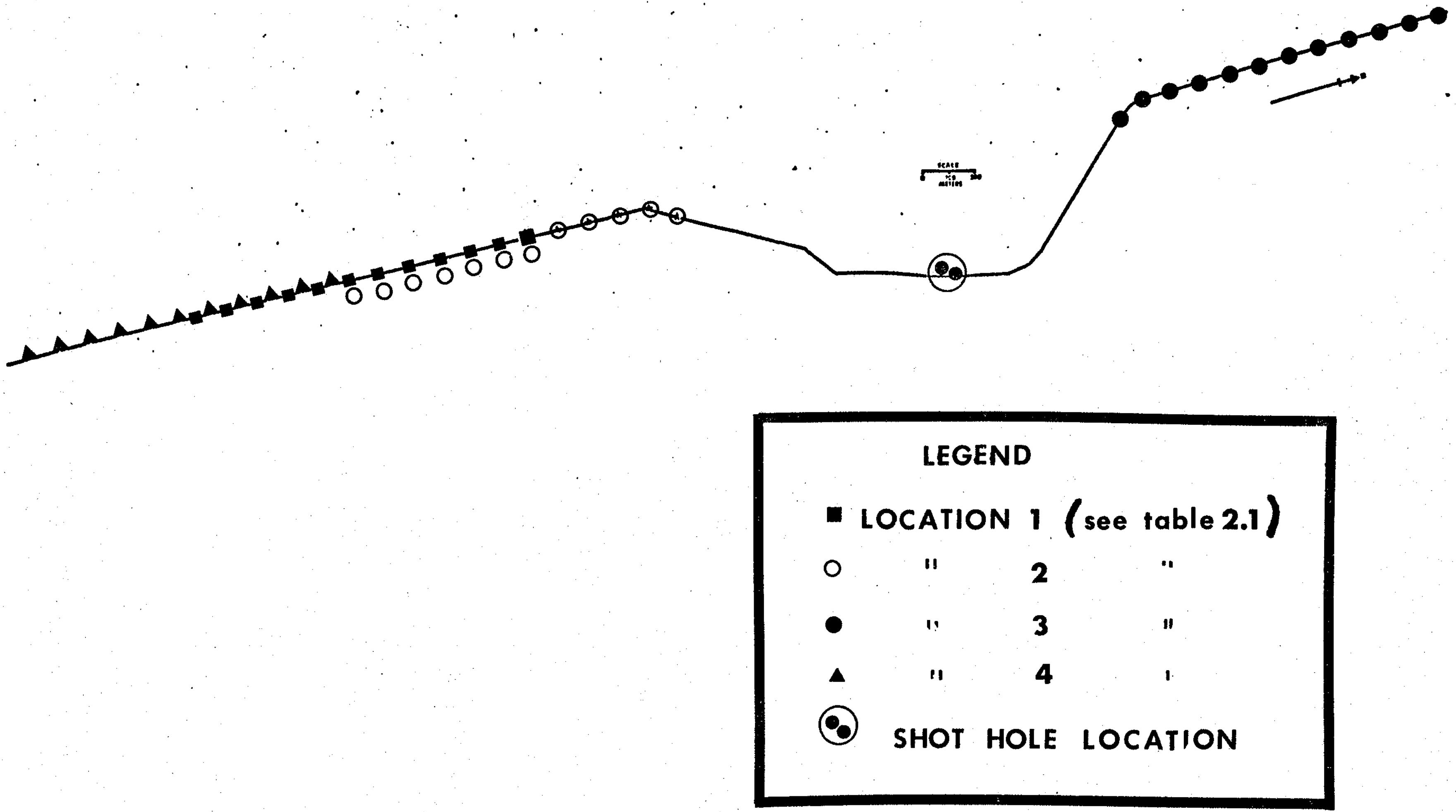


FIG. 1.3 Fireguard Road Recording Site – Shotpoint Location Map

CHAPTER 2

MULTIPLE SEISMOMETER THEORY AND ARRAY DESIGN

2.1 General Considerations

High-amplitude ground roll (surface waves), extraneous body waves, wind noise, ground unrest, high frequency chatter due to near-surface high-velocity layers, hole blow, wind noise, high line interference, ghost reflections and refraction interference are undesirable forms of energy that are typical to reflection surveying. Some of these forms of seismic noise can be completely removed or greatly attenuated, by conventional frequency filtering, so that they are no longer a hinderance to the interpreter. The removal or attenuation of seismic noise corresponds to an increase in the signal-to-noise ratio. An increase in the signal-to-noise ratio can be achieved by conventional filtering methods only when the reflected energy can be distinguished from the noise, on the basis of frequency. If the seismic noise, have frequency spectra which are similar to, or which include those of the reflected signal, improvements in the signal-to-noise ratio must be achieved by other means. A filtering device, the response characteristics of which are a function of apparent horizontal wavelengths, rather than frequencies, is necessary; seismometer arrays are such a device.

Geophysicists in the petroleum industry have employed seismometer arrays, to suppress seismic noise and hence increase the signal-to-noise ratio, for a great many years. Weatherby (1940) mentions that by 1938 multiple seismometer arrays were in general use in reflection surveys involved in the search for petroleum. However, the use of predesigned arrays of seismometers to improve the signal-to-noise ratio in crustal reflection surveys, conducted in North America, did not become accepted practice until the mid-1960's (Hall and Brisbin (1961) employed in-line arrays in a refraction survey). One of the first successful reflection surveys, to employ seismometer array theory, to map the upper crust in central Alberta was done in 1964 and is reported on by Kanasewich and Cumming (1965).

The most prominent form of undesired energy expected in near-vertical-incidence reflection surveys conducted over Precambrian Shield areas are high-amplitude surface waves (ground roll). Hammond and Hawkins (1958) consider continuous profiling to be a practical method, only when predesigned arrays are employed to eliminate surface waves. Hajnal (1970) used a single seismometer every 134 meters (440 feet), in an experiment with the near-vertical-incidence reflection continuous profiling method. He concluded that high-amplitude surface waves (Rayleigh type) were of so prominent a form that they were the dominant form of energy for several seconds on the seismogram and would obscure any reflection events from within the shallow crust.

The use of predesigned multiple seismometer arrays in crustal surveys can effectively transform surface waves into low-amplitude, short-duration events and hence into less troublesome phenomena than Hajnal had experienced. In addition to the filtering function that arrays perform on surface waves, multiple geophone arrays also cancel random energy and improve the average coupling between geophone and ground.

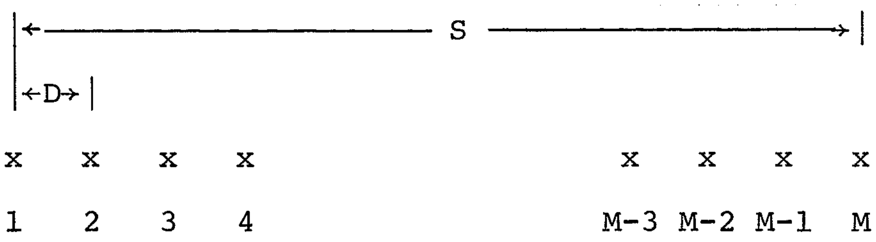
Random energy denotes that energy which occurs at such times on a record that the response of a given trace in the energy band cannot be predicted by the study of other traces. Random disturbances actually consist of a number of high-frequency transients, which have low apparent horizontal velocities. Jenkins and White (1957), p. 218-219, in a generalized theory of wave combination have concluded that the effectiveness of an array of geophones in cancelling random energy varies with the square root of the number of geophones used.

2.2 Multiple Seismometer Theory

Empirically it has been noted that the use of multiple seismometers and multiple shot holes were responsible for significant improvements in the signal-to-noise ratio in difficult reflection areas (Savit *et al*, 1958).

Swartz and Sokoloff (1954), Lombardi (1955), Muir and Hales (1955), Hammond and Hawkins (1958) and Graebner (1960), provide a rather qualitative treatment of the use of multiple seismometers and multiple shot hole patterns. A somewhat more rigorous discussion of the subject is presented by Hales and Edwards (1955), Parr and Mayne (1955), Smith (1956) and Savit *et al* (1958). A graphical method for computing the response of an array system, which can easily be performed in the field, is presented by Verma and Roy (1970). The mathematical summary of multiple seismometer theory presented here is similar to that presented by Savit *et al* (1958).

The normalized response of an array of seismometers can be computed using antenna theory. Consider an array of M elements, each element separated by a distance D from its neighbour and spread over a distance S, where $S = (M - 1)D$.



The input to the seismometer array can be expressed by the following double Fourier series, since the form of any wave arriving at a finite point will be a function of both time and frequency.

$$U_{input} = \sum_{n=1}^{\infty} \sum_{p=1}^{\infty} R_{p,n} \sin(2\pi\omega_p t + 2\pi\alpha_n x + \beta_{p,n}) \qquad (2.2.1)$$

where:

ω_p = angular frequency

α_n = spatial frequency

$\lambda_n = 1/\alpha_n$ = wavelength of any Fourier component

$l_p = 1/\omega_p$ = period of any Fourier component

$v_{p,n} = \omega_p \lambda_n$ = the phase velocity of a single Fourier component along the array and varies with the nature and direction of the incident angle.

Now consider an input to the seismometer of a single frequency (ω) and a single wavelength (α)

$$U_{input} = R \sin(\omega t + 2\pi\alpha + \beta) \qquad (2.2.2)$$

The signal output for a uniformly distributed array of M elements over an interval of length S will have the form:

$$U_{output} = \frac{1}{M} \sum_{k=0}^{M-1} \sin(2\pi\omega t + \beta + 2\pi\frac{k}{M-1}\alpha S) \qquad (2.2.3)$$

Using Lagrange's trigonometrical identity equation 2.2.3 becomes:

$$U_{\text{output}} = \sin \frac{(2\pi\omega t + \beta + \pi\alpha s)}{(M \sin(\frac{\pi\alpha s}{M-1}))} \cdot \sin \frac{M}{M-1} \pi\alpha s \qquad (2.2.4)$$

which indicates that the output is a sinusoid signal of frequency ω and whose amplitude is given by:

$$R_m = \left| \frac{\sin(\frac{M}{M-1} \pi\alpha s)}{M \sin(\frac{\pi\alpha s}{M-1})} \right| \qquad (2.2.5)$$

Substituting $\lambda_n = 1/\alpha_n$ into equation 2.2.5 gives

$$R_m = \left| \frac{\sin(\frac{M}{M-1} \frac{\pi s}{\lambda_n})}{M \sin(\frac{1}{M-1} \frac{\pi s}{\lambda_n})} \right| \qquad (2.2.6)$$

Equation 2.2.6 is the basis for a computer program which was written to compute the normalized response for any seismometer array consisting of m elements spread over any distance s. Figures 2.1, 2.2 and 2.3 are examples of the expected amplitude response of three different arrays of the same length s. Using these figures, a comparison of the amplitude as a function of the dimensionless spatial frequency, s/λ, for arrays of the same total length but differing in the number of identical geophones, can be made. The amplitude is an even periodic function of s/λ for groups with a finite number of seismometers. The periods for the 3, 6 and 12 seismometer arrays are 2, 5 and 11, respectively.

It can be seen, from an examination of the response curves, that there is an optimum number of elements; about 6 in these examples. If more geophones of equal output were added and the array length fixed at a constant value, no appreciable improvement in moveout (phase velocity) discrimination can be achieved when long wavelengths are considered. A comparison of Figures 2.2 and 2.3 illustrates this point further in that the response curves are not greatly different for the critical wavelengths (s/λ less than about 3.0).

Improvements in the filtering effect of seismometer arrays can be achieved if tapered arrays are used. However, the use of tapered arrays involves the addition of a significant number of seismometers. For instance, the response of the tapered array (123321), where the numbers give the relative sensitivity of the array elements, is equal to the sum of the responses of the arrays (111111), (1111), and (11).

Since one of the objectives of this experiment is to develop an expedient field procedure, which would enable multiple seismometer arrays to be used in near-vertical reflection crustal surveys, the use of tapered arrays was not seriously considered as it would involve the handling of a great many geophones as well as necessitate the use of a more complicated cable arrangement.

The theory involving the use of multiple shot-hole patterns to effectively filter out certain wavelengths is identical to multiple seismometer theory. A combination of multiple shot holes and an array of seismometers can be synthesized into an effective means of eliminating long-period surface waves. Kanasewich and Cumming (1965) and Clowes (1969) successfully employed geophone array and shot hole combinations on crustal surveying.

Unfortunately, in some parts of the Precambrian Shield, outcrop suitable for locating a prospective shot-hole array is scarce and it is difficult to find such locations. Lack of suitable shot hole locations along the Fireguard Road prevented the use of predesigned multiple shot holes and the shot point sites were chosen without considering multiple shot hole theory.

2.3 Array Systems

Graebner (1960) mentions that some of the methods or tools which the geophysicist may control to achieve an improvement in the signal-to-noise ratio are the type of seismometer, method of planting, the number of seismometers in a group, the number of simultaneous shots, configuration of shot and seismometer arrays, shot point offset, charge size, shape of charge, charge depth and filter-pass bands. However, the control of some of the aforementioned parameters, although possible, is not practical in some situations.

The major criterion, which must be considered with the implementation of methods of control, is cost. For instance, there is an optimum number of seismometers which can be manipulated effectively by a small seismic crew. Also there are limited configurations of seismometer arrays of given natural resonant frequencies, which are available through industrial supply companies. The use of arrays other than those available through commercial suppliers would mean that the arrays would have to be made-to-specification and purchased by the user at great cost and certainly would eliminate the flexibility of rental arrangements.

An examination of Hajnal's near-vertical reflection results revealed that surface waves were present in the frequency range 12 - 18 Hz, indicating that the seismometer array should be designed to effectively eliminate wave lengths of 165 to 250 meters.

The site of both Hajnal's near-vertical reflection survey and the survey considered here are within the Superior geological province of the Precambrian Shield. Although detailed studies of the surface geology of both areas are not available it appears that the general geology of the two areas are similar in some respects. In both areas, granite gneisses make up a significant portion of the rock type (Davies, 1951; Wright, 1938). Also the topography of both areas are similar. Considering the similarities in rock type and topography, the assumption that the surface wave phenomena observed at both sites would be similar, was made.

An event consisting of horizontally travelling energy is considered to be eliminated by an array of detectors, if its response is down 50 per cent relative to the response of a single detector (Graebner, 1960, p. 293). The 50 per cent amplitude response of a 6 seismometer array corresponds to an s/λ of 0.7, as is evident from an examination of Figure 2.2. If the array is to be an effective filter and discriminate against surface waves with an apparent horizontal wavelength of 250 meters or less, the spread length (s) must be:

$$s = 0.7\lambda = 0.7(250) = 175 \text{ meters}$$

Arrays with the required spread length could not be obtained from industrial suppliers. However, arrays with spread lengths of 91.5 meters (300 feet) and a natural resonant frequency of 10 Hz, which are commonly used in the petroleum industry, were obtained. Two of these arrays could be connected in parallel to give a spread length of 183 meters (600 feet) which was suitable.

Unfortunately the detector spacing was 7.7 meters (25 feet), which meant that each 183 meter array consisted of 24 seismometers and that it was necessary to handle 288 seismometers at every recording site.

Three different array systems were employed during the course of the survey to test the efficiency of the seismometer arrays and to determine if the use of arrays of detectors was justifiable in terms of expenditure and the quality of data.

2.3.1 The Cable Arrangement

The two cables used throughout the near-vertical reflection survey were originally designed for the purpose of obtaining information by the refraction seismic method. Each cable is 737 meters (2440 feet) long, capable of handling 6 channels of seismic information, with a takeout located every 134 meters (440 feet) along the cable. Both cables were used at each of the recording sites occupied. The instrument truck was located at the center of the cable network. The first trace on the seismograms was always that channel of seismic information delivered from the takeout closest to the shot point. Figure 2.4b illustrates the cable geometry.

2.3.2 The 183 Meter Arrays

The expected wavelength of the surface waves (165 - 250 meters) can be effectively attenuated by using an array with a spread length of 183 meters. Figure 2.5 is the response curve for the 24 seismometer, 183 meter array. Note that the array is actually an effective filter for apparent horizontal wavelengths of up to about 300 meters. One array of this type was connected to each takeout to form the array system used to record shots 1 - 14 (see Table 2.1). Figure 2.4a illustrates the configuration of the arrays at the first 3 takeout locations. It can be seen that each array overlapped the adjacent array by 48 meters (157 feet). Figure 2.7a is a digitized Calcomp plot of the seismic record corresponding to shot 11.

2.3.3 The HS-10-1 Geophones

Signals from shots 15 - 25 were recorded utilizing twelve Geo-Space HS-10-1 type geophones (see section 1.2.2 for the geophone characteristics) normally used by the Geophysics Division for refraction experiments. The natural resonant frequency of the geophones is 1 Hz.

Eight of the geophones were of the vertical component type and the remaining four recorded the horizontal component. Each of the seismometers occupied a single takeout and the geometry of the recording sites 15 - 25 is illustrated in Figure 2.4b.

The single seismometers were employed so that a comparison could be made with the arrays and that the advantages and/or disadvantages of the use of arrays instead of single detectors could be determined. The use of both horizontal and vertical component detectors serves

Table 2.1 Recording parameters

Shot Number	Array System	Location	Shot Weight (lbs)	Shot hole(s)	Attenuation		Frequency	
					Channel	Setting (dB)	Channel	Setting (Hz)
1	A*	1**	4.05	N***	1-6,8	30	all	24
					7,9-11	36		
					12	42		
2	A	1	4.05	N	same as 1	-	same as 1	-
3	A	1	2.70	N	1-6,8	36	all	32
					7,11	42		
					9,10	48		
					12	54		
4	A	1	4.05	N	1-4,7,11	30	all	32
					5,6,8	36		
					9,10	42		
					12	54		
5	A	2	4.05	N	all	36	all	32
6	A	2	4.05	N	all	36	all	32
7	A	2	4.05	N	all	36	all	32
8	A	2	4.05	N	all	36	all	32
9	A	2	4.05	N	all	36	all	32
10	A	2	4.05	N	all	36	all	32
11	A	2	4.05	N	all	36	all	32
12	A	2	5.40	N	all	42	all	32
13	A	2	5.40	N	all	42	all	32
14	A	2	5.40	N	all	36	all	32

Table 2.1 (cont.)

Shot Number	Array System	Location	Shot Weight (lbs)	Shot hole(s)	Attenuation Channel	Attenuation Setting (dB)	Frequency Channel	Frequency Setting (Hz)
15	B	3	2.70	N	all	36	all	32
16	B	3	4.05	N	all	42	all	32
17	B	3	6.75	N and S	all	42	all	32
18	B	3	8.10	N and S	all	42	all	32
19	B	3	5.40	N and S	all	42	all	32
20	B	3	8.10	N and S	all	42	all	32
21	B	3	5.40	N and S	all	42	all	32
22	B	3	6.75	N and S	all	42	all	32
23	B	3	9.50	N and S	all	42	all	32
24	B	3	9.50	N and S	1-4	60	all	32
					5-8	54		
					9,10	48		
					11,12	42		
25	B	3	9.50	N and S	same as 24	-	all	32
26	C	4	6.75	N and S	all	36	all	32
27	C'	4	5.40	S	all	36	all	32
28	C	4	5.40	S	all	36	all	32
29	C	4	5.40	S	all	36	all	32
30	C	4	1.35	S	all	36	all	32
31	C	4	2.70	S	all	24	all	32
32	C	4	5.40	S	all	36	all	32
33	C	4	4.05	S	all	30	all	32
34	C	4	2.70	S	all	36	all	32

Table 2.1 (cont.)

*Array system used:
A - 183 meter, 24 geophone arrays (see section 2.3.2)
B - HS-10-1 geophones (see section 2.3.3)
Channels 5-8 are horizontal type geophones
C - 274 meter, 36 geophone arrays and HS-10-1 geophones (see section 2.3.4)
C'- 183 meter, 24 geophone arrays and HS-10-1 geophones (see section 2.3.4)

**Location:
(see Figure 1)
1 - First takeout is 1840 meters south of shot point.
2 - First takeout is 1985 meters south of shot point.
3 - First takeout is 1009 meters north of shot point.
4 - First takeout is 2520 meters south of shot point.

***Shot holes:
N - northerly most shot hole
S - southerly most shot hole

to establish the incident character of the recorded signal. The seismogram shown in Figure 2.7b corresponds to the seismic information gathered from shot 15 and illustrates the character of the signals received from the single detector system used.

2.3.4 Array and Single Seismometer Combinations

Seismometer arrays in combination with single seismometers were used to record shots 26 - 34. Channels 1 - 6 recorded seismic information collected using arrays; HS-10-1 geophones were used for channels 7 - 12. The seismometer arrays used for shot 27 are identical with those described in section 2.3.2. Arrays which consisted of 36 detectors were used to record shots 26 and 28 - 34. The arrays were 274 meters (900 feet) in length. The detector spacing and type of geophone were identical to those described earlier.

The amplitude response for the 36-seismometer, 274 meter array is given in Figure 2.6. The array is an effective filter for surface waves of apparent wavelengths of 450 meters and less. Figure 2.4c illustrates the array geometry; each array overlapped its nearest neighbouring array by 148 meters and its second nearest neighbour by 15 meters.

The use of both the 183 meter and the 274 meter arrays in combination with single detectors facilitate direct comparison of the array systems with single geophones, enabling the effectiveness of the array network to be determined. Figures 2.7c and 2.7d are digitized Calcomp playbacks of the seismograms obtained from shot 29 (274 meter arrays and single geophone) and shot 27 (183 meter arrays and single geophone) respectively.

2.4 Evaluation and Discussion of Array Systems

It is evident from the earlier discussion that multiple seismometer arrays can be used to theoretically eliminate horizontally travelling surface waves. It is also well known that, in theory, one can place two detectors a half-wave apart and effectively cancel horizontally travelling energy. In practice, because of varying frequency spectrum, velocity and angle of incidence, the complete cancellation of horizontally travelling disturbances by employing theoretically designed arrays is seldom achieved. The best result that can usually be obtained is a partial cancellation which varies with the apparent velocity of the disturbance.

Multiple seismometer theory assumes that the arrays and shot holes form a linear system. However, because of the curvature of the Fireguard Road, it was necessary to locate the shot holes off of the line through the axis (line of traverse) of the array systems. Figure 2.8 diagrammatically illustrates the shot hole array geometry for the array corresponding to the first channel of shots 26 - 34.

It can be seen on Figure 2.8 that each seismometer of the array samples the wavefront of a different ray paths rather than sampling the wavefronts travelling along the ray path corresponding to the axis of the array.

The array serves as an effective filter for horizontal travelling surface waves with a wavelength 5 per cent shorter than if the shot hole and array were a linear system. The reduction in the dimension of the wavelength which can be effectively discriminated against is not considered critical in this instance. However, if the angle α (see Figure 2.8) is increased and/or the distance of separation between the recording site and the shot point are increased significantly, the effectiveness of the array will be greatly reduced. With a broadside shot, that is with $\alpha = 90°$, the filtering effect of the seismometer array will be lost and the array will act as a single geophone (provided that the dimensions of the system are such that the wavefronts can be considered planar) when coherent noise is considered.

A regular increase of the period of the Rayleigh wave train with increasing shot point-detector distance can be attributed to dispersion. A detailed experiment investigating the dispersion effects of Rayleigh waves is described by Dobrin *et al.* (1951). The dispersion of Rayleigh waves is governed by the layering in the near-surface materials, specifically by the thickness of the layers and the contrast in the densities and elastic constants between the layer or layers and the material below. An examination of the surface conditions of the survey area did not reveal that any obvious layering was present; therefore, the effect of dispersion was not considered in the design of the arrays. No readily discernable dispersion phenomena on the seismograms presented in Figures 2.7a, b, c, and d exist. However, if an increase in the dimensions of the Rayleigh waves were expected, it would be necessary to consider dispersion effects when designing seismometer arrays.

The effectiveness of the array systems can be qualitatively determined from examining Figures 2.7a and 2.7b. The latter is a seismogram of shot 15, recorded with single seismometers; the former is a seismogram for shot 11, recorded with the arrays described in section 2.3.2. The recording site and shot point parameters for each shot are given in Table 2.1.

The high-amplitude more or less sinusoidal waves observed near the first breaks of each record, with the onset designated by R, are identified as Rayleigh waves. Immediately apparent is the "clipped" nature (where excursions beyond a certain amplitude are cut off, thus destroying their character completely) of the Rayleigh waves on record 11, despite the fact that the attenuation and the highcut frequency settings are the same and that a smaller charge of explosives was used in recording shot 15, indicating that the amplitudes of the Rayleigh events are attenuated by the seismometer arrays. The clipping of the surface waves in Figure 2.7b does not facilitate a quantitative analysis of the filtering done by the arrays. However, it appears that the amplitude response is at least 25 - 50 per cent lower for the array system compared with the single detector, thereby proving the effectiveness of arrays. The amplitude reponse of the seismometer array for surface waves with wavelengths of 250 meters (the wavelength as determined from an examination of record 11) is theoretically 60 per cent lower than the amplitude response that would be expected from a single seismometer, as is evident from Figure 2.5.

O'Brien (1967, p. 158) states that for small charges of explosives the amplitude of an event is proportional to the charge weight. The charge weight used to generate the energy recorded on records 11 and 15 were 4.05 lbs and 2.70 lbs, respectively. Considering O'Brien's theory it is evident that the amplitude of the events on record 15 should be 67 per cent of the amplitudes observed on record 11. The amplitudes of record 15 are, in fact, greater, further demonstrating the effectiveness of the arrays.

A reduction in the length of the Rayleigh wave train for the seismometer array system as compared with the single seismometer is also evident from the examination of Figures 2.7a and 2.7b.

The foregoing discussion assumes that the surface conditions and geology for the two recording sites is not significantly different. An examination of the area did not reveal any conditions that would contradict this assumption. Further, Coles (personal communication) has obtained and examined drill core specimens from outcrops at half-mile intervals along the Fireguard Road, throughout the survey area and has not noted any major changes in rock type, at the surface.

The arrival between 3 and 4 seconds, the onset of which is designated by A in Figure 2.7b, is a direct air wave. It can easily be identified by its low-apparent velocity (0.33/km/sec). The air wave results from compression due to the expanding gases which accompany the detonation of an explosive charge. It can be particularly troublesome in near-vertical-incidence crustal reflection surveys, in that it has not dissipated and its amplitude is still of a magnitude sufficient to mask possible reflected events. The air waves visible on record 15 are still very evident even though the HS-10-1 geophones were placed approximately two feet below ground surface. An examination of Figure 2.7a will reveal that the air waves are effectively removed by the filtering action of the seismometer arrays.

The recording site geometry for the seismograms reproduced in Figures 2.7c and 2.7d has been discussed in some detail (section 2.3.4). The first 6 channels are reproductions of the particle motion as recorded by the 274 meter and 183 meter arrays (Figures 2.7c and 2.7d, respectively). Channels 7 - 12 report the particle motion as observed by single HS-10-1 vertical component geophones.

The effectiveness of the attenuation characteristics of the arrays is illustrated by a comparison of traces 1 - 6 with traces 7 - 12 on each record. The effectiveness of the arrays in cancelling random noise is also apparent.

Both of the seismograms were obtained with identical charge weights, attenuation and frequency settings. Divergence existed in the length of the arrays used, however. A comparison of the first 6 traces of each record reveals that they are very much alike considering the different array lengths. The addition of 12 seismometers to extend the array length to 274 meters did not significantly alter the amplitude characteristics of the observed surface waves. Indicating that the optimum number of seismometers is 24 or less and that an array length of greater than 183 meters offers no particular advantage.

On both record 27 and record 29, the amplitudes of the first arrivals (direct compressional wave), the onset of which is designated as P and the second arrivals (direct shear wave), the onset of which is designated as S, have been attenuated as a result of experiencing the filtering effect of seismometer arrays. The amplitudes of these two arrivals are significantly greater on the traces corresponding to the channels 7 - 12 in which ground motion was recorded on HS-10-1 geophones. The lower noise level on traces 1 - 6 is also apparent. The character of each trace corresponding to an array is uniform in comparison to the variability displayed by traces 7 - 12. The uniformity is a direct result of the better "average plant" attained by the utilization of arrays of geophones.

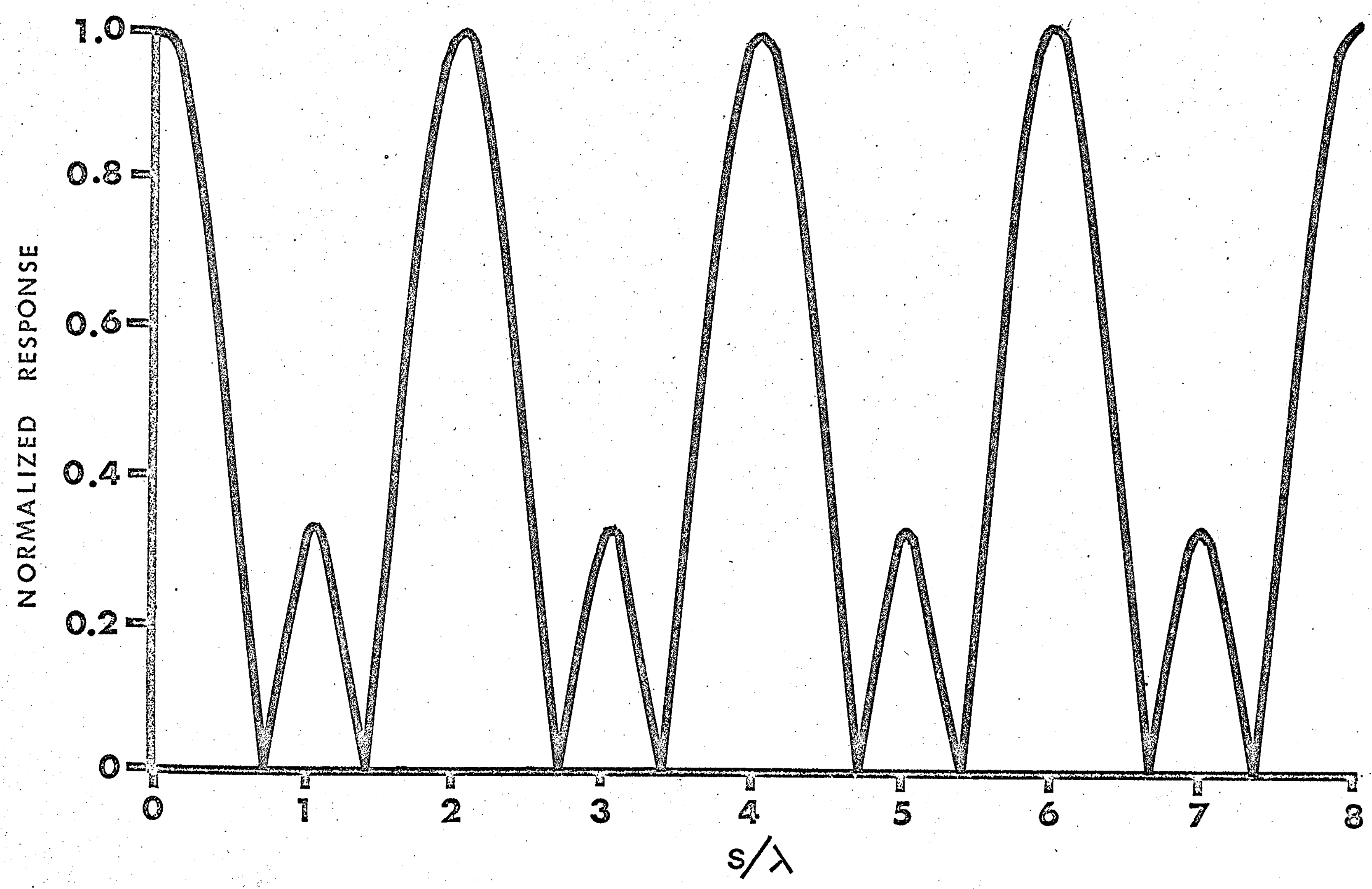


FIG. 2.1 AMPLITUDE RESPONSE FOR A 3 SEISMOMETER ARRAY

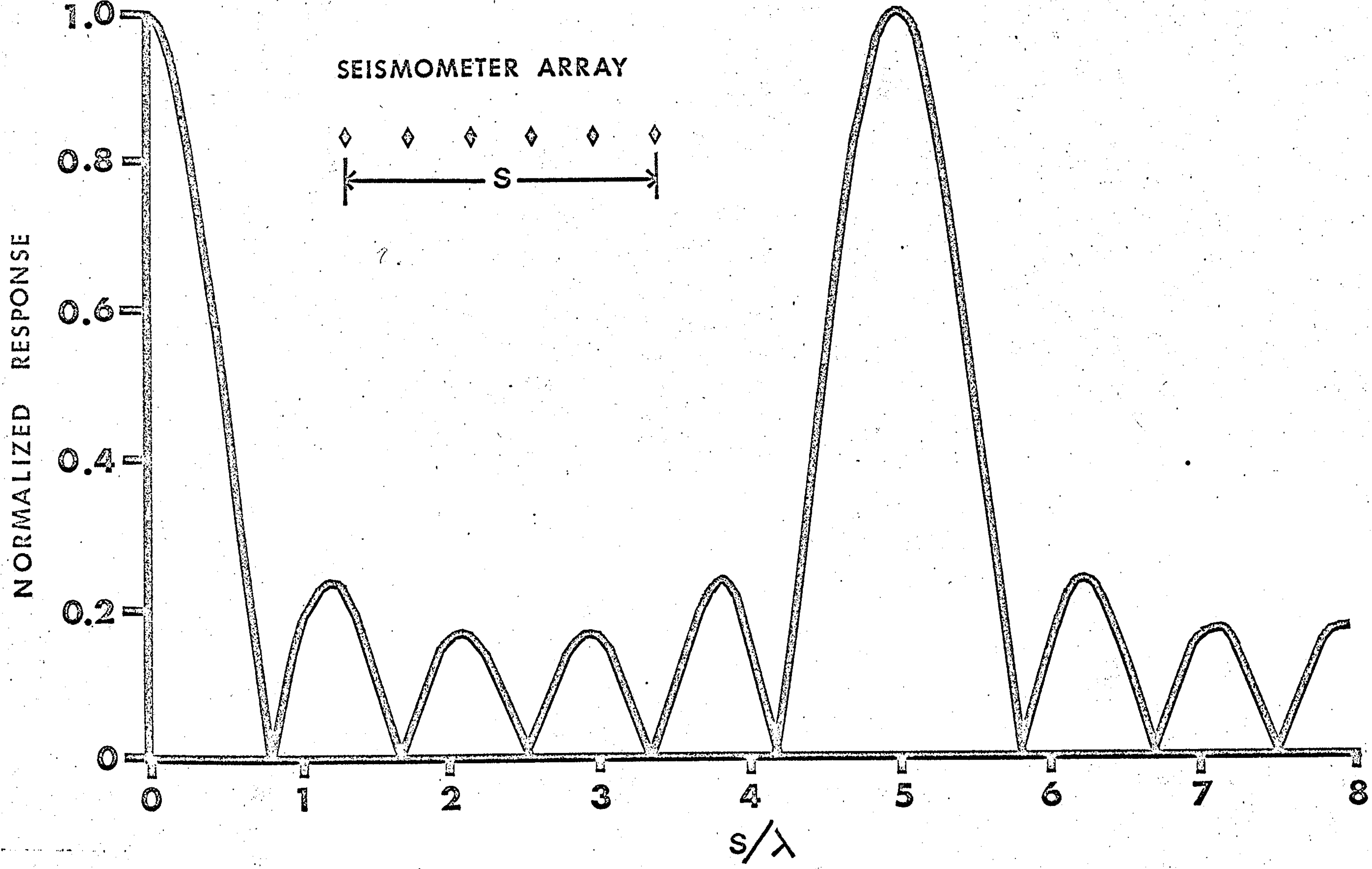


FIG. 2.2 AMPLITUDE RESPONSE FOR A 6 SEISMOMETER ARRAY

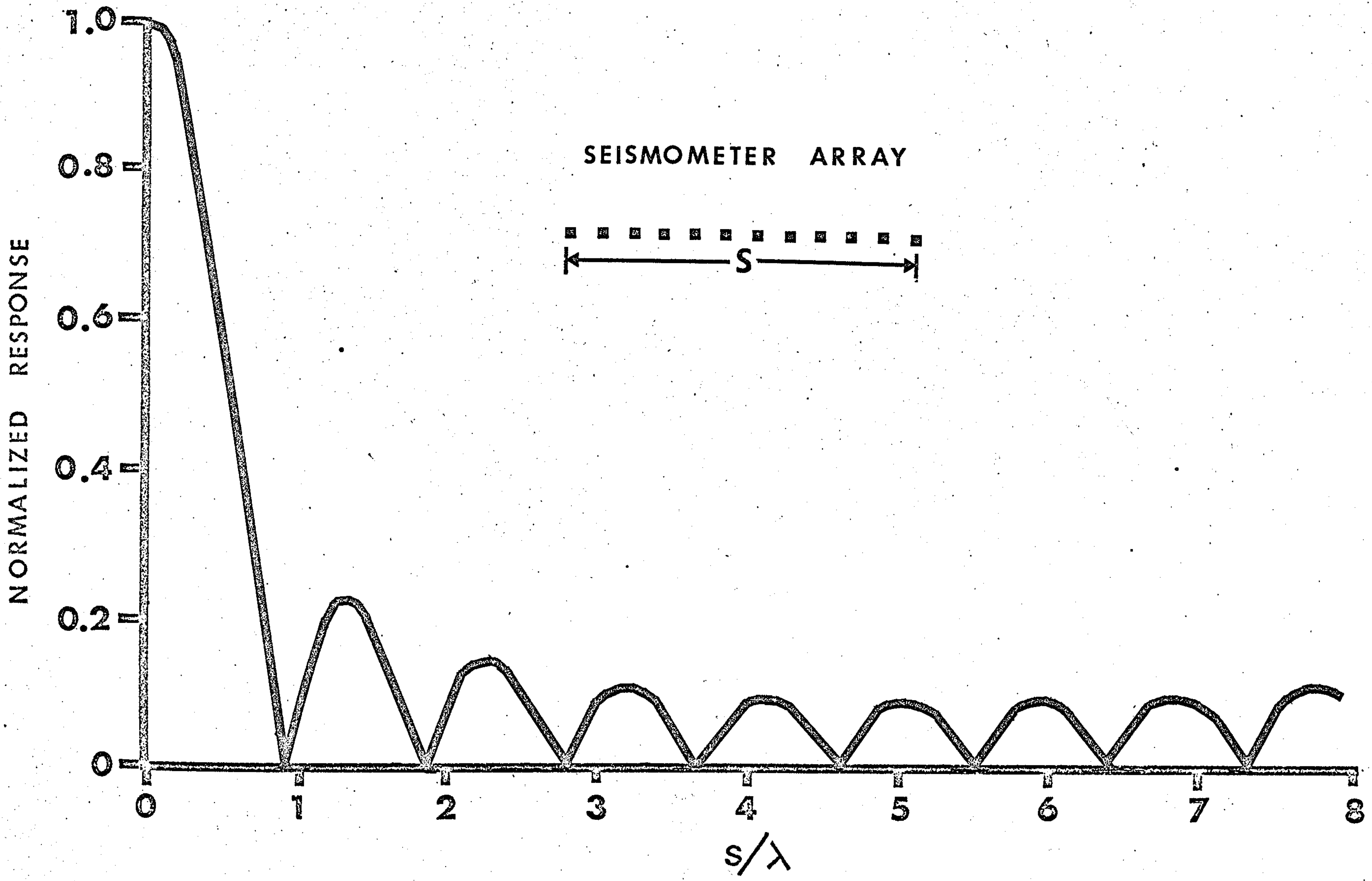


FIG. 2.3 AMPLITUDE RESPONSE FOR A 12 SEISMOMETER ARRAY

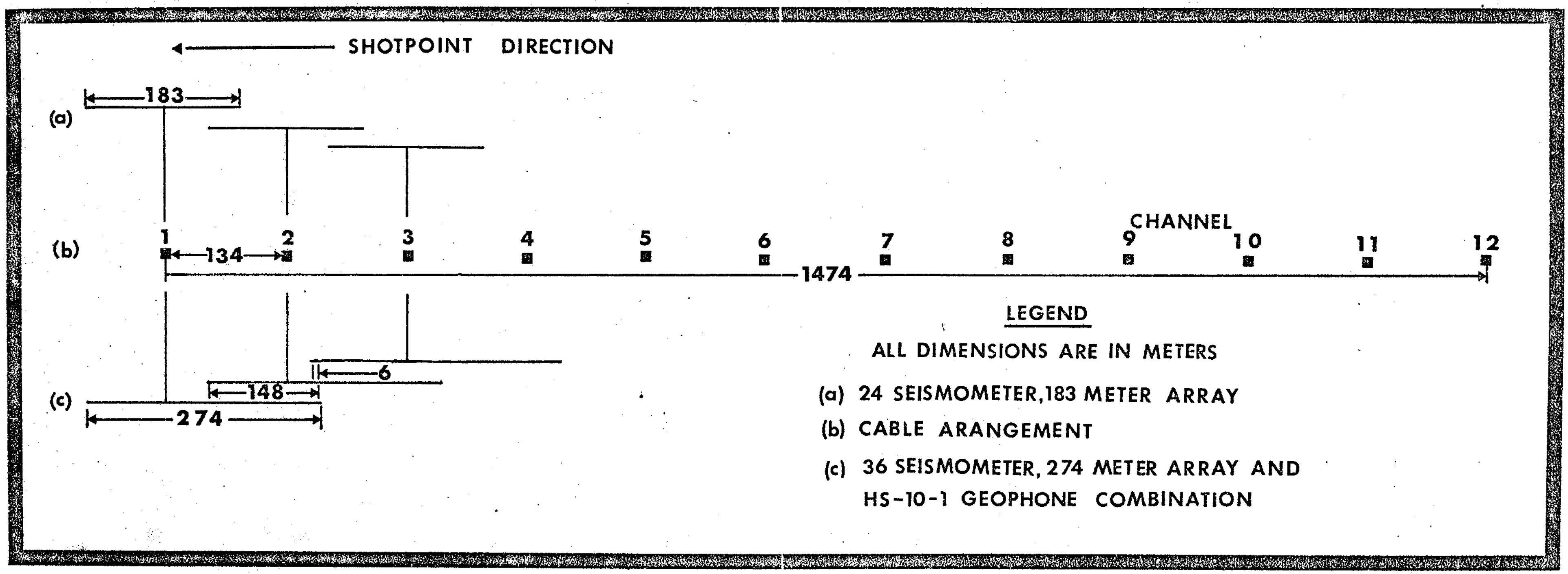


FIG. 2.4 RECORDING SITE GEOMETRY

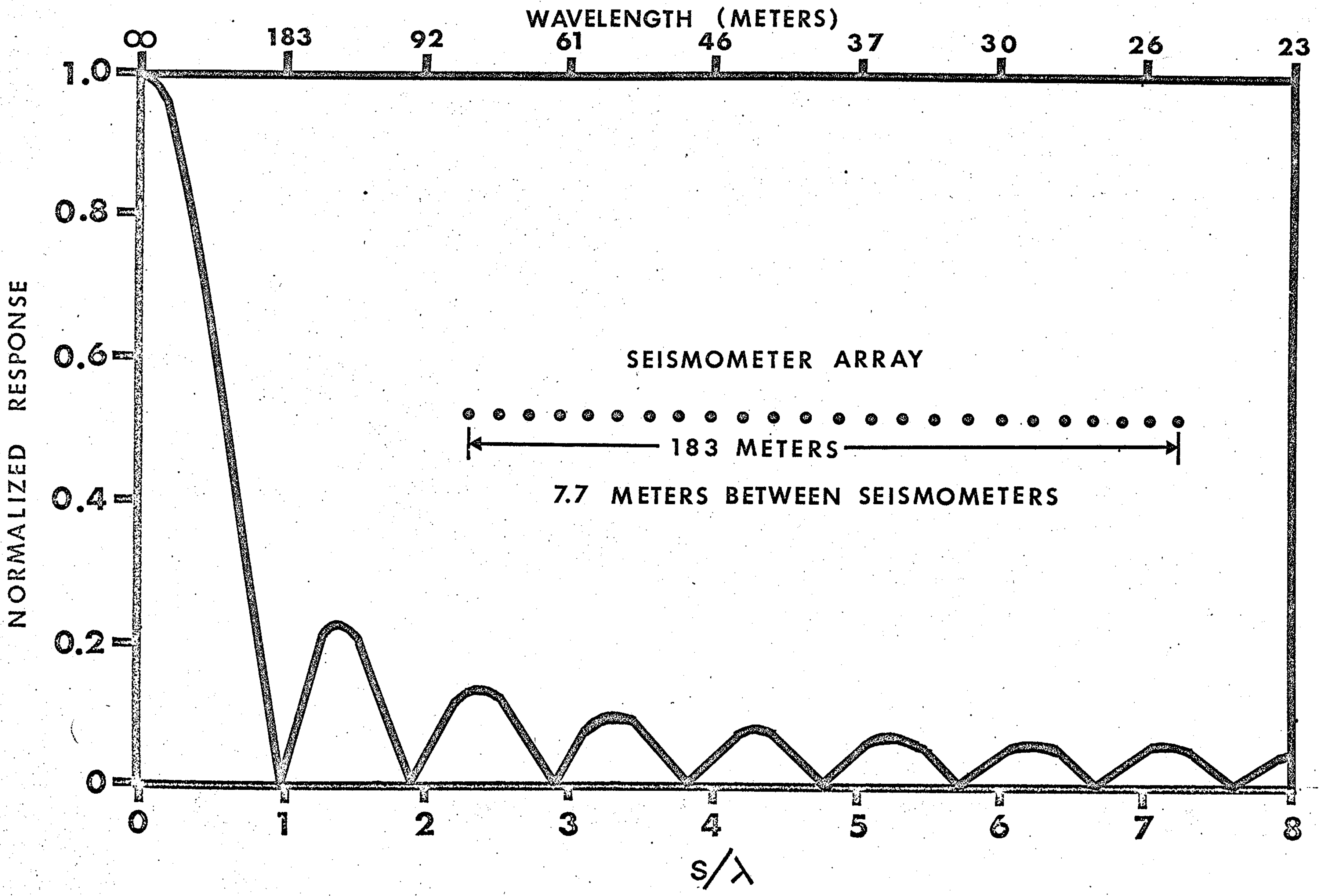


FIG. 2.5 AMPLITUDE RESPONSE FOR A 24 SEISMOMETER ARRAY

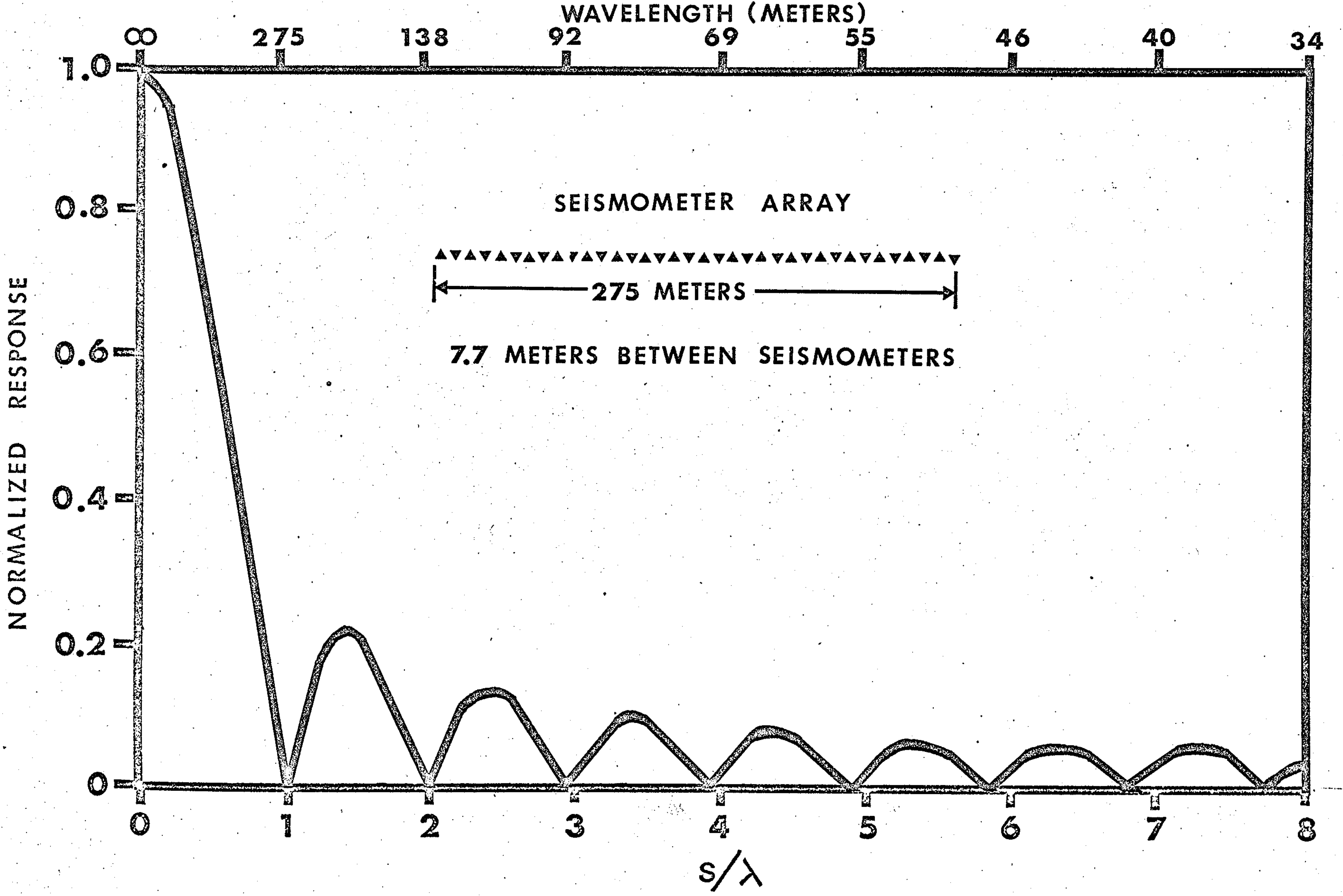


FIG. 2.6 AMPLITUDE RESPONSE FOR A 36 SEISMOMETER ARRAY

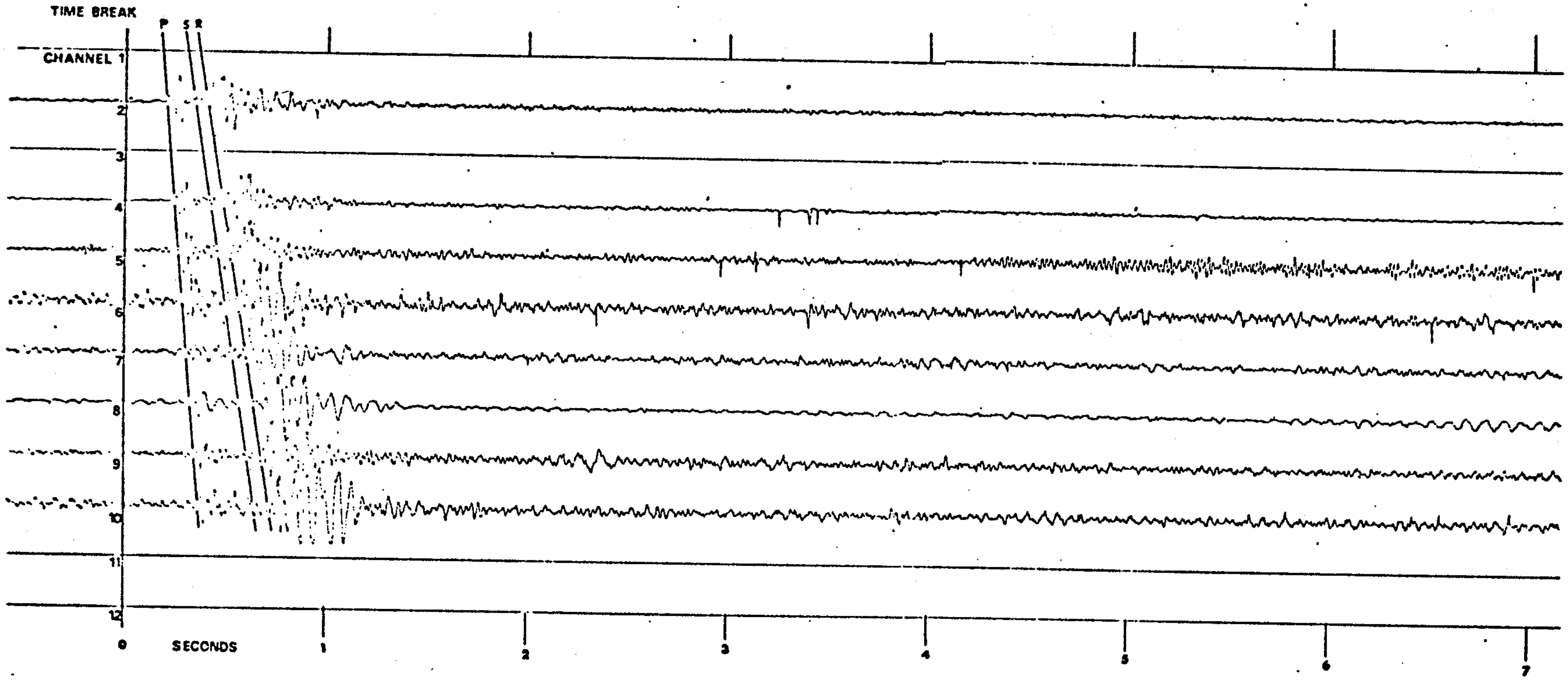


FIG. 2.7a RECORD 11 (SEE TABLE 2.1 FOR DETAILS)

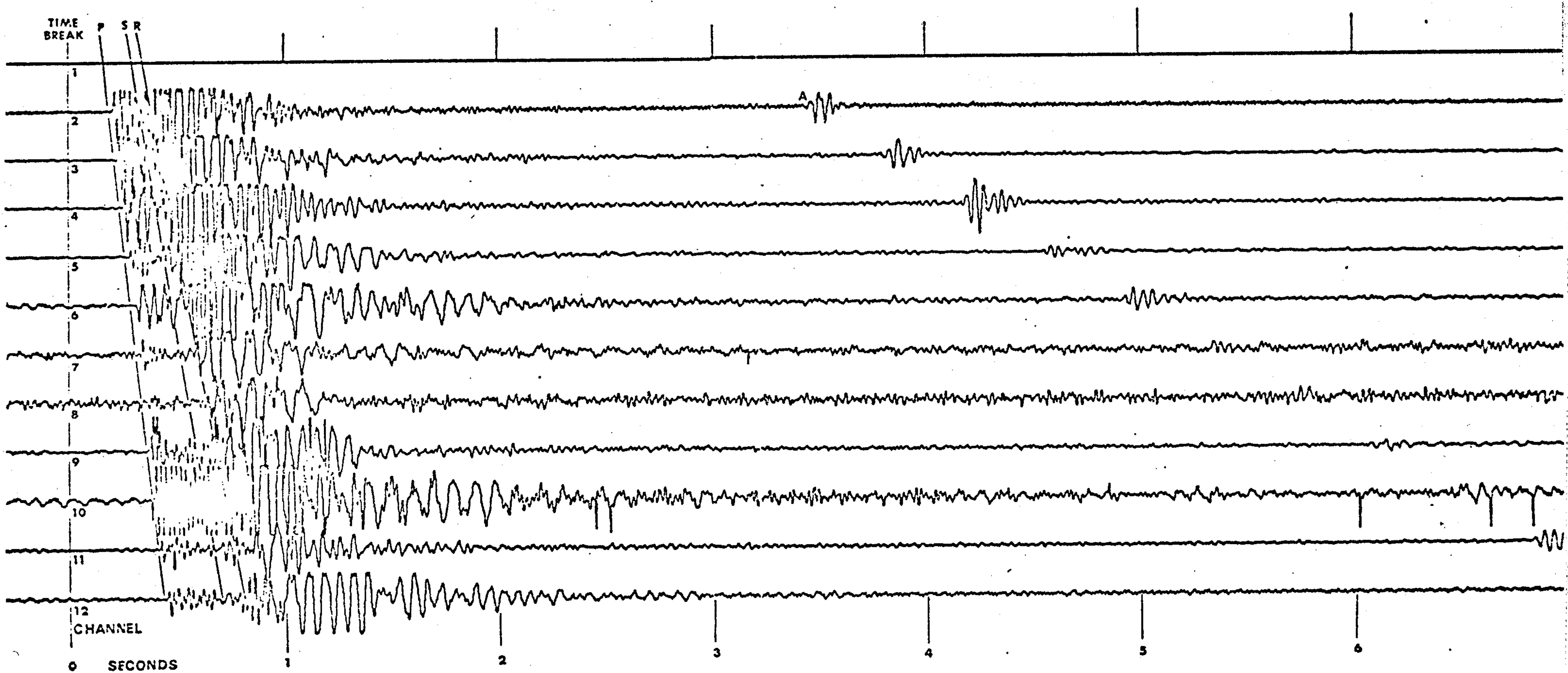


FIG. 2.7 b. RECORD 15 (SEE TABLE 2.1 FOR DETAILS)

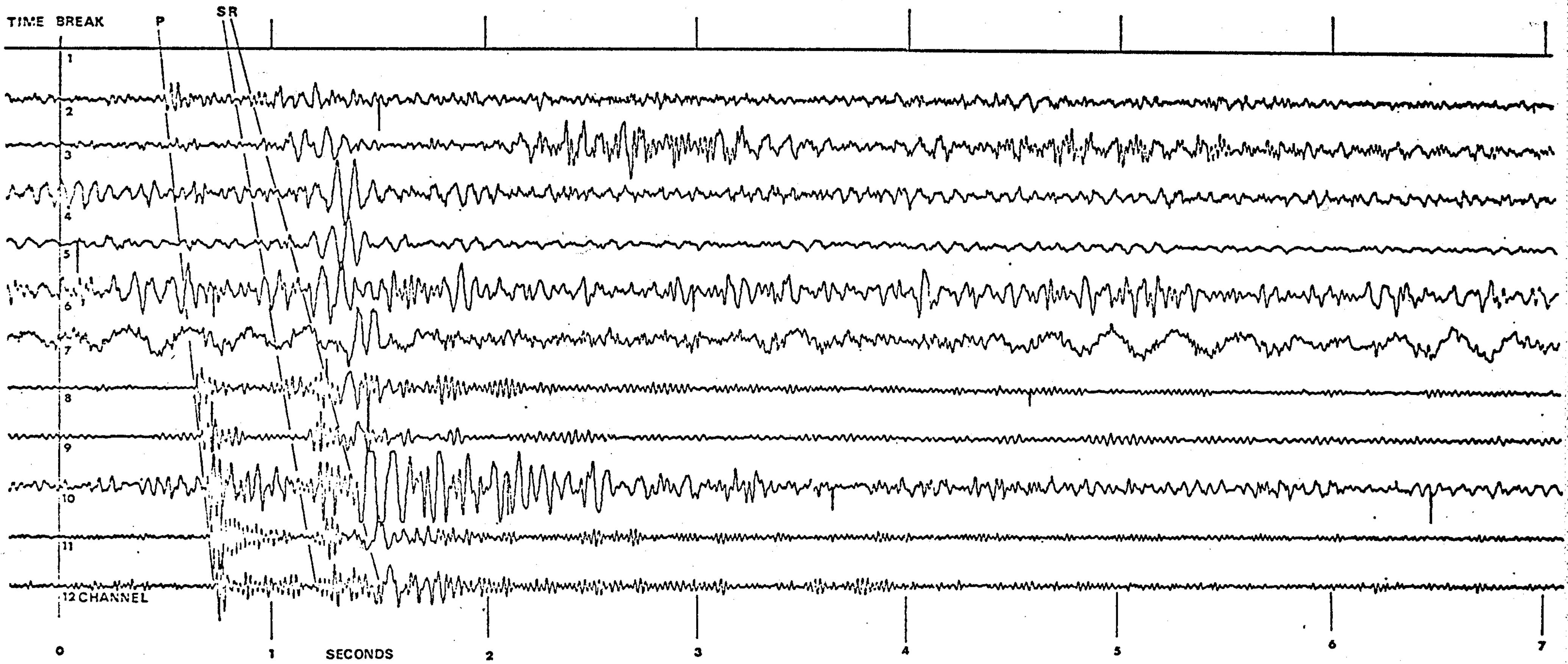


FIG. 2.7c. RECORD 29 (SEE TABLE 2.1 FOR DETAILS)

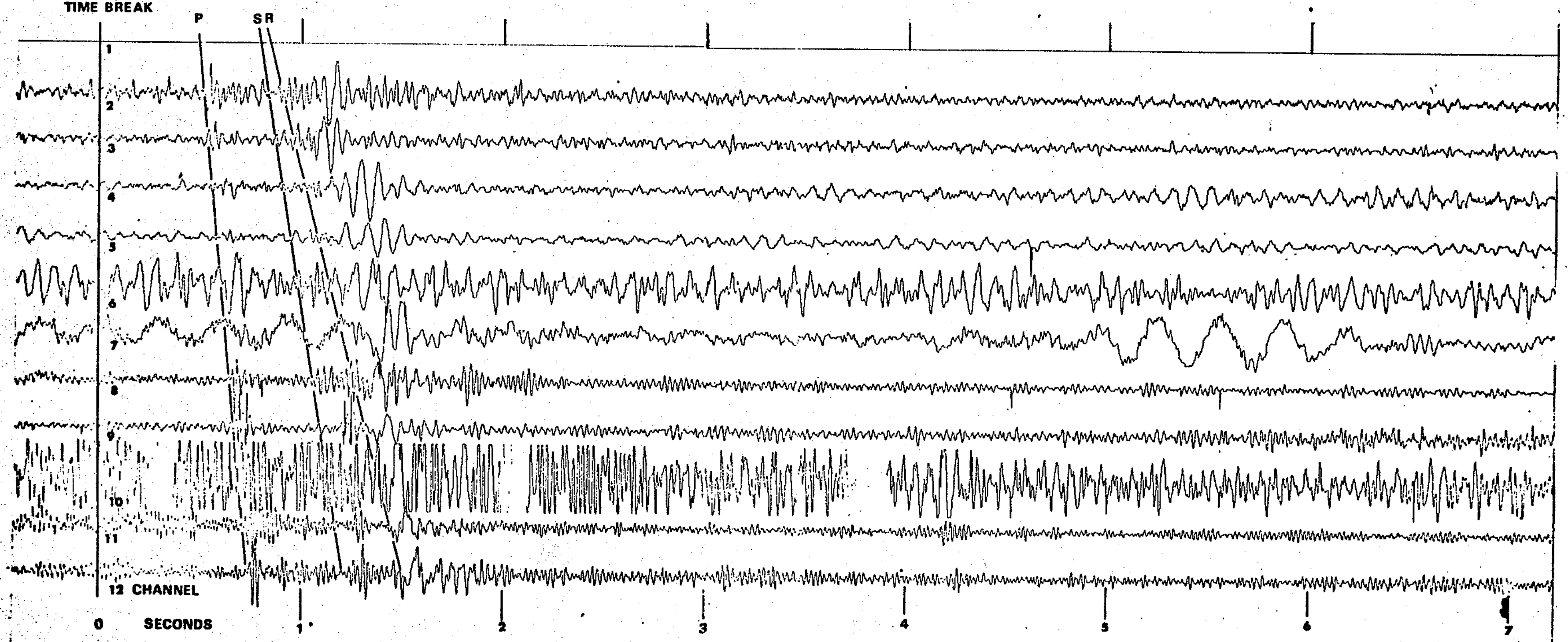


FIG. 2.7d. RECORD 27 (SEE TABLE 2.1 FOR DETAILS)

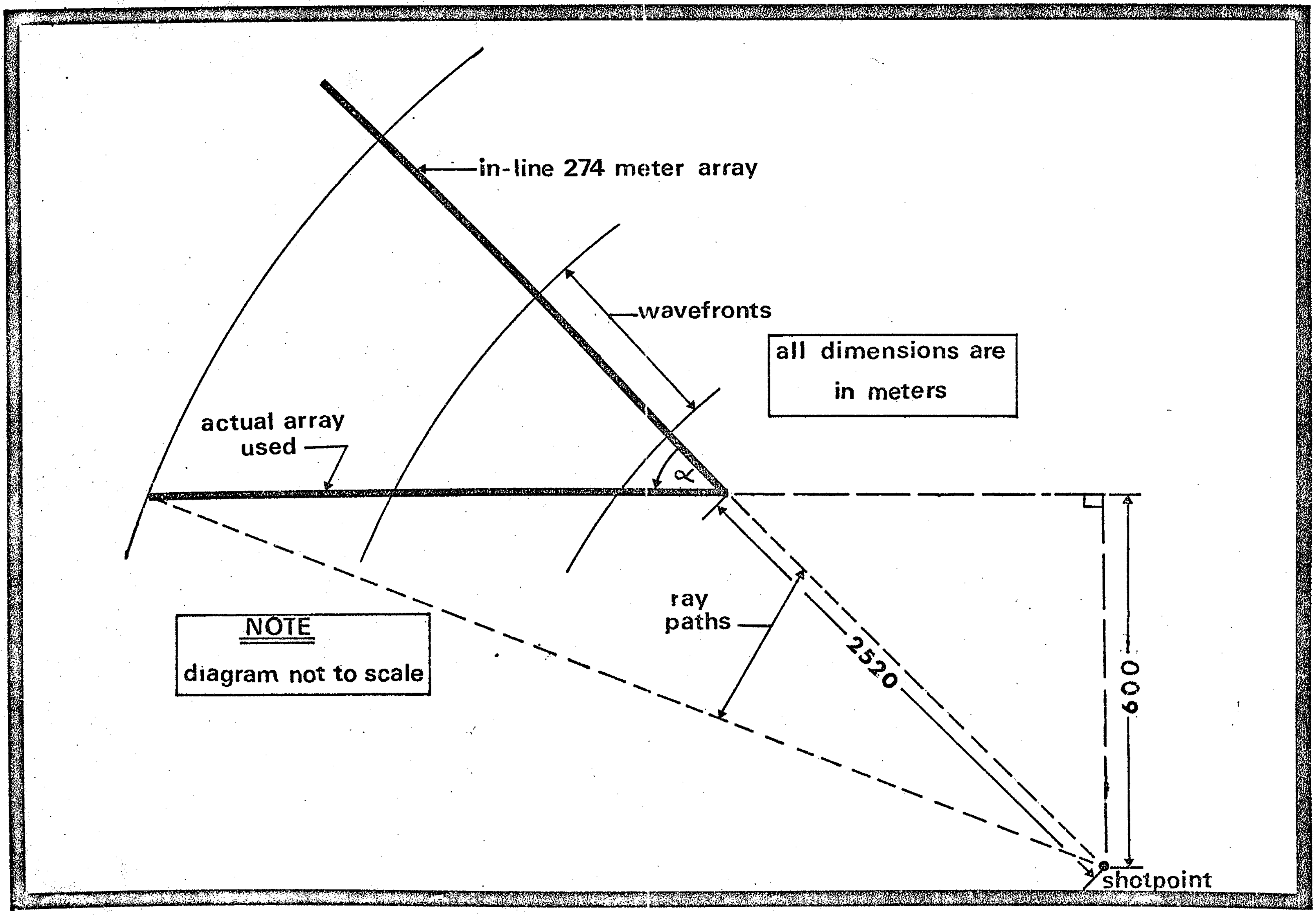


FIG. 2.8. Diagramatic sketch of array location for shots 26–34

CHAPTER 3

ANALYSIS OF SHOT POINT PROCEDURE AND CHARACTERISTICS

3.1 Introduction

The seismic method has been considered by Sharpe (1942) to consist of three distinct processes, namely; the initiation of the seismic impulse, the transmission of the seismic energy through the medium and the arrival and recording of the seismic energy at the recording site with the appropriate instruments.

Improvements in the seismic method have been obtained by the refinement of equipment and recording procedures necessary for the acquisition of seismic data. Anstey (1957) and O'Doherty and Anstey (1971) as well as others discuss such advancements. Heiland (1968), Pearson (1966) and White (1965) provide a classical treatment of the propagation of elastic waves. The last two processes mentioned in the first paragraph are therefore adequately represented in the literature and are fairly well understood. The generation of the seismic impulse, although recognized as a most important phenomenon by geophysicists and studied in considerable detail, is still far from being completely understood.

A complete knowledge of the explosive parameters as well as the physical and mechanical properties of the shot hole medium are necessary for an analysis of the initiation of the seismic impulse. The seismic experiment, reported in this thesis, was not specifically designed to investigate shot hole conditions. Although adequate quantitative information is absent, a qualitative analysis of shot point conditions can be made and improvements in the shot point procedure can be recommended. These recommendations may aid in making the seismic reflection method in the Precambrian Shield areas more viable.

3.2 Shot Hole Location

In earlier regional refraction crustal studies conducted by the Geophysics Division, underwater explosions as the energy source were used exclusively. The shot point locations were either abandoned water-filled mine shafts or ventilation raises (Hall and Brisbin, 1965), or deep lakes (Hall and Hajnal, 1969), or rivers (Hajnal, 1970). The use of these locations for shot points was necessitated by the requirement that large charges of explosives (up to one thousand pounds) be used and by the fact that the remote locations of suitable shot points did not facilitate the transportation of heavy drilling equipment. The additional economic burden inherent in the drilling of a number of shot holes could not be justified. Hajnal (1971) reports that the use of such locations for shot points resulted in the development of techniques which make lakes and mine shafts in the Shield area very successful shot locations.

Since the abovementioned surveys were of the reconnaissance type the exact location of the source site was not critical and the fixed location of the shot point inherent in using lakes or mine shafts was accepted as part of the technique.

The success of the refraction seismic method in delineating the gross features of important structures in the Precambrian crust, and the preliminary results obtained by the higher resolution reflection method in determining shallower structures as part of Project Pioneer, suggests the need for the further development of a near-vertical reflection method (Hall and Hajnal, 1969; Wilson, 1971). The use of the reflection method to investigate specific structures necessitates that freedom in the choice of the location of the shot point be incorporated in the technique. Baer (1972) in an effort to further develop the crustal near-vertical reflection method used an abandoned mine shaft as the location of the seismic source. The survey was designed to aid in the advancement of processing techniques rather than to demonstrate the flexibility of the method, however.

In order to demonstrate the flexibility of the near-vertical reflection method, boreholes were drilled and used as source locations as part of this project. The actual location of the shot holes is given on Figure 1.3. The dependence of the shot hole location on the physical properties of the medium (to be discussed later) and the availability of water for drill lubrication eliminate the freedom of choice in the exact location of the shot holes. However, their location could be determined with considerable license as compared with the more restrictive location imposed on the survey when either lakes or mine shafts were used.

3.3 Drilling Equipment and Procedure

The actual drilling of the borehole in which the explosive charges were detonated was accomplished with a Packsack Diamond Core Drill, Model 4-M. The drill is lightweight and can be operated efficiently by two men. The Packsack Drill, its apparatus and operation is described by Cumming (1956).

The drill bit is diamond studded and a cored interval of the rock through which it passes is recovered. The core size is AX, the diameter of which is 1 9/32 inches. The use of diamonds as the abrasive requires that the penetrating bit be lubricated and the rock particles removed with a constant supply of water. A small gasoline driven centrifugal pump was used for this purpose and the necessary water was obtained from a road cut near the drill site.

After some expertise in drilling was developed a two man crew could drill about 3 feet per hour. The slow rate penetration was due to the hardness characteristics of the shot point rocks. The durable nature of the rock was also made evident by the rate of consumption of the diamond set bits. It was found that about 6 feet of core could be recovered before the abrasive action of the diamonds was lost and the drilling rate noticeably decreased.

The depth to the bottom of the borehole was limited to about 20 feet; as beyond this depth the weight of the core barrel and drill rods was formidable and more equipment would be needed to raise the drill stem. The maximum depth which can be attained before undue strain is placed on the drill itself is considerably greater than this (about 180 feet), but a mechanical winch and drill platform is necessary to aid in the extraction of the core barrel and drill stem.

Percussion type drilling equipment was also considered. However, small portable percussion drills, the type used by prospectors for trenching mineral showings, are not suitable for drilling shot holes because of their limited depth of penetration (about 8 feet). Larger percussion drills, the type used in the construction and mining industries, are capable of penetrating hard rocks to considerable depths more economically than any other drilling method, but the accompanying air compressor necessary to power the drill would limit the shot-point site to regions which are accessible by road. Thereby the areas in which the near-vertical reflection method can be applied are restricted.

3.4 Properties of the Shot-Point Medium and Explosives

It is generally recognized that equipment suitable for the accurate study of the processes involved in the initiation of a seismic impulse are not yet available (Saluja, 1968) and that at best only a semi-quantitative analysis of the phenomena can be made (Kutter and Fairhurst, 1968). It is important that the properties of the shot-point medium be known if the existing theory is to be extended to the seismic reflection method used in the Precambrian.

3.4.1 Petrography of the Shot-Point Medium

An analysis was made of a thin section prepared from a core specimen recovered from drilling. The specimen can be considered as representative of the outcrop in which the shot holes were placed. The composition is given in Table 3.1, and indicates that the rock is granitic.

The texture is weakly gneissoid and characterized

Table 3.1. Composition of a representative sample.

Mineral	Amount (%)
K-feldspar	35 - 40
Quartz	25
Plagioclase	15 - 20
Microcline	10
Biotite	7
Magnetite	3
Chlorite	1
Saussurite	1
Apatite	Trace
Sericite	Trace

by a weak alignment of the biotite minerals. The rock is medium-grained, with the potassium feldspar minerals forming the largest crystals, typically 4 mm in diameter. Quartz crystals are generally 2 mm in diameter. The plagioclase grains are typically smaller.

The biotite flakes are about 1 mm in length and are present interstitially between the quartz and feldspar grains and display a sub-parallel alignment.

The chlorite, where present, is intimately associated with the biotite flakes and appears mostly at the edges. Magnetite grains are also intimately associated with the biotite.

3.4.2 Physical and Mechanical Properties of the Shot-Point Medium

Gnirk and Pfleider (1968) attempt to investigate the correlation between explosive crater formation and rock properties. The mechanical and physical properties that they consider necessary for such an analysis are: tensile strength, compressive strength, Young's modulus of Elasticity, Poisson's ratio, longitudinal velocity, and density - all of which can be determined by conventional laboratory techniques or derived from theory.

If the medium is considered to be elastically isotropic (an ideal Hookean elastic substance), all of its elastic parameters can be determined in terms of two fundamental constants (Johnson, 1970). These are Young's modulus and Poisson's ratio. If an elastic rock is definitely anisotropic (possesses a low symmetry of internal structure), 21 different elastic moduli are required to describe its elastic properties completely. An authoritative discussion on the elasticity of an anisotropic material is given by Polakowski and Ripling (1966). The only truly isotropic earth materials would be non-crystalline rocks such as glass. However, Johnson (1970), p. 203, states that polycrystalline rocks can be treated as isotropic materials if their minerals are randomly oriented. This type of assumption is necessary if elastic theory is to be used in a discussion of the phenomena accompanying the detonation of explosives in boreholes. The thin section analysis presented in section 3.4.1 indicates that the homogeneity of the shot-point rock is sufficient to warrant the calculation of elastic parameters from Young's modulus and Poisson's ratio. These quantities were determined from uniaxial compression tests conducted on typical core specimens retrieved from the shot-hole site.

The compression tests were made in the Department of Civil Engineering Testing Laboratory at the University of Manitoba. The tests were performed in accordance with the procedure and specifications established in the A.S.T.M.'s standard method of test for static Young's modulus of elasticity and Poisson's ratio in compression of cylindrical specimens (A.S.T.M., 1965). The testing apparatus consisted of a Baldwin National Testing Machine (capacity 30,000 pounds), wire resistance strain gauges and a wheatstone bridge. A description of similar apparatus and the procedure followed in its use can be found in any text on engineering materials (e.g., Polakowski and Ripling, 1966).

The compressive test was performed on three rock samples which were considered to be representative of the cored interval recovered during drilling. The data obtained from one of the cores tested were not accepted because correct alignment between the lapped ends of the specimen and loading platens was not achieved. The "end effects" problem is common to the testing of materials and is discussed in Stagg and Zienkiewicz (1968).

The test data are presented graphically in Figure 3.1, a and b. The average value of Poisson's ratio is 0.31 and the average Young's modulus of elasticity is 11.8×10^6 pounds per square inch (psi). The average ultimate compressive strength is 15,600 psi. The stress-strain curves resemble those presented by Hendron (1968), p. 24, and are considered to be typical for granite gneiss. The average density of the tested rocks was 2.77 gm/cm^3 (172.93 pounds per cubic foot).

Table 3.2 summarizes the properties discussed above and includes additional moduli calculated according to the

Table 3.2. Properties of the shot-point rocks.

Property	Value British Units	 Metric Units
Density (ρ)	172.9 lbs/cu ft	2.77 gm/cc
Ultimate compressive strength (σ_c)	15,600 psi	1050 kg/sq cm
Ultimate tensile strength (σ_t)	550 psi	386 kg/sq cm
Young's modulus of elasticity	11.8×10^6 psi	8.4×10^5 kg/sq cm
Average Poisson's ratio	0.31	0.31
Range of Poisson's ratio	0.26 - 0.36	0.26 - 0.36
Bulk modulus (K)	10.4×10^6 psi	7.3×10^5 kg/sq cm
Lame's constant (λ)	7.4×10^6 psi	5.2×10^5 kg/sq cm
Rigidity modulus (G)	4.5×10^6 psi	3.2×10^5 kg/sq cm
Average longitudinal wave velocity (V_p)	21,400 ft/sec	6.5 km/sec
Range of longitudinal wave velocity	20,500 - 23,400	6.1 - 7.1 km/sec
Average shear wave velocity (V_s)	11,200 ft/sec	3.4 km/sec
Range of shear wave velocity	10,900 - 11,500 ft/sec	3.3 - 3.5

formulae presented by Birch (1966), p. 100, and by Hendron (1968), p. 23.

3.4.3 Explosive Properties

The explosive used during the entire near-vertical reflection survey was Forcite 60 per cent. The explosive, its properties, and accepted handling procedure is described in the Blaster's Handbook (C.I.L., 1964).

The explosive is water resistant and is referred to as an ammonia gelatin. It is a detonating explosive and is initiated by shock from a detonating agent such as an electric blasting cap. It was chosen because of its convenient size and more particularly for its high detonation velocity (15,400 feet per second) and water resistance.

3.5 Analysis of Shot Hole Phenomena

The stacking method of improving the signal-to-noise ratio on seismograms is discussed in Chapter 4. Briefly, the procedure encompasses the collection of a number of seismograms on magnetic tape with the location parameters of the recording site and shot point held constant. The resultant seismograms were then added together, with the aid of a digital computer, to form one final output trace. This procedure was followed for the four individual recording-shot point systems occupied during the experiment (Table 2.1). The use of the same shot hole or the use of a number of shot holes in close proximity, such that the geometrical similarity required for the application of the stacking process will not be violated, for each of the recording shot point system occupied is fundamental to the process.

The drilling and repeated use of the same shot hole is much more economical and efficient than the drilling and use of a number of closely spaced shot holes. It is necessary to have some knowledge of the mechanism of (igneous) rock failure resulting from the detonation of explosive charges in boreholes if the same site is to be occupied repetitively.

The following discussion is taken from the theory presented by many authors and the observations made at the site of the shot holes used in this experiment. It is presented in the hope that a basic understanding of the shot hole process and the accompanying phenomena will aid in the selection of future sites for the purpose of drilling shot holes to be used as locations for the seismic energy source.

3.5.1 Mechanism of the Generation of Seismic Waves by Explosions

The classical theory of the detonation of explosive products is presented by Morris and Thomas (1947) and Paterson (1947) and wave propagation in solid media is discussed by Blake (1952), Sharpe (1942) and Heiland (1968). Cole (1948) presents an authoritative account of underwater explosions.

A general description of the explosive process starts with the detonation of the priming cap which instigates the ignition of the high explosive used as the seismic source. The detonation wave is the fastest disturbance which can pass at a stable velocity through the explosive (Morris, 1950). This velocity is a function of both the chemical properties and the degree of confinement of the explosive and is known as the detonation velocity. The detonation process continues until all of the chemical energy of the explosive has been converted to heat, gas and an impulse pressure. The pulse spreads out spherically from the center of the charge, which can be assumed as being spherical if its length is 30 to 40 feet or less (O'Brien, 1967, p. 164). The stress induced on the borehole wall can be calculated from the approximate formula given by Brown (Bahjat and Kisslinger, 1970, p. 224).

$$P_D = D^2 \rho \frac{0.45}{1 + 0.8\rho}$$

where: P_D = detonation pressure

D = detonation velocity

ρ = loading density

Forcite 60 per cent has $D = 4.7$ km/sec and $\rho = 0.35$

gm/cc. The calculated value of the detonation pressure is 2.72 kbars (394,000 psi), well above the compressive strength of the shot hole medium (Table 3.2). As a result of the high pressure the rock will fail in compression and crushing will occur until the compressive strain pulse decays in amplitude as it moves outward to a value equal to the compressive strength of the rock.

The size of the cavity produced by the crushing action of the explosive can be determined from the formula presented by O'Brien (1967), p. 156.

$$R = BW^{(\frac{1}{3})}$$

where:
R = radius of the cavity in feet
B = 0.46 for granitic rocks
W = weight of charge in pounds

Approximately 6 pounds was the largest charge used at the shot point (Table 2.1); the resulting cavity is about 0.9 feet in radius. The formation of the cavity by crushing can be regarded as the first stage of the mechanism responsible for the generation of seismic waves.

In stage two the shot-hole medium fails in tension. Tensile forces at the cavity-medium boundary are still much larger than the tensile strength of the rock and a network of cracks results. As the pulse spreads outwards it decreases in amplitude due to the expenditure of energy in forming the new surfaces of the crack system. The cracks form a fine network near the cavity wall and becomes coarser outward until the point is reached where the tensile forces due to the pulse equals the tensile strength of the rock medium. At this point (the elastic limit), the fracture system terminates and stage three begins.

The imaginary surface around the volume of rock which has failed in tension and compression is the "equivalent radiator" described by Sharpe (1942) and Gaskell (1956). O'Brien (1967), p. 156, states that the radius of the equivalent radiator can be assumed to be two or three times as large as the cavity radius (R) and is directly proportional to it. In the case of the granite medium considered here, the radius of the equivalent radiator will be 1.8 to 2.7 feet. Figure 3.2 illustrates the sequence of events resulting from the detonation of a fully-contained explosive charge.

At the surface defined by the equivalent radiator the stresses degenerate into an elastic pulse which displaces the medium according to the formula of Blake (1952), p. 212.

$$A = \left(\frac{P_\omega \kappa}{\rho V^2}\right) \cdot \omega \cdot \left(\frac{a^3}{r}\right) \left\{ \left(\frac{\omega}{V}\right)^2 + \left(\frac{1}{r}\right)^2 \right\}^{\frac{1}{2}}$$

$$x \left\{ 1 + (1 - 2\kappa) \left(\frac{\omega a}{c}\right)^2 + \kappa^2 \left(\frac{\omega a}{c}\right)^4 \right\}^{-\frac{1}{2}}$$

where: P_ω = amplitude of radial stress at ω radians/sec

$\kappa = (1 - \sigma)/2(1 - 2\sigma)$

σ = Poisson's ratio

ρ = density

a = radius of equivalent radiator

r = distance from center of radiator

A knowledge of the form of the stress pulse at the surface of the equivalent radiator is necessary to solve for the amplitude in the above equation. Measurements of this type require the design and employment of specialized instruments, as described by Duvall (1953) and Fogelson *et al.*, (1959) at the shot hole. No attempt was made at obtaining such measurements in the near-vertical reflection survey described here.

The repeated use of a shot hole results in additional crushing and fracturing as a result of a more complex distribution of forces. The theory of dealing with the extension of fracturing and crushing is generally unknown and difficult to determine. It is known, however, that the fractures are extended with each subsequent shot, probably according to the Griffin criterion of fracture until they reach the surface (Johnson, 1970). The extension of the fracture system and the influence of the free surface will be discussed in the next subsection.

To prevent failure from the immediate effect of crushing and fracturing which accompanies the detonation of the explosive, it is only necessary to bury the charge deeper than the radius of the calculated equivalent radiator. However, failure will eventually take place as a result of the forces acting at the tips of the fractures and resulting in their subsequent propagation to the surface. The number of times an individual shot hole can be used before failure results cannot be determined from the existing theory. The number of shots that can be repeated from the same site, will increase with depth to the center of the charge, however. The increase in depth of burial will prolong the fracture system from reaching the free surface.

3.5.2 Mechanism of Rock Failure at the Surface

A knowledge of the process whereby rocks are broken as a result of the detonation of a chemical explosive is fundamental to such industries as mining and quarrying. Experiments involving rock breakage by investigators in this field are well documented (Stagg and Zienkiewicz, 1968; Grosvenor and Paulding, 1968; for example). An adequate theory to predict the volume of rock broken and the size of the inherent crater is lacking, however.

If the shot holes occupied in seismic surveying are to be used repetitively it is necessary that the existing empirical laws regarding rock breakage be examined with the view that the volume of broken rock per unit weight of explosive is to be minimized; rather than be at a maximum, which is frequently the desire of those experimenting in the field of rock mechanics.

The shock wave theory of rock blasting is based on the stress wave generated on the detonation of an explosive charge. According to this theory a compressive wave travels spherically outward from the center of the charge of explosive, as described in section 3.5.1. The compressional wave travels through the rock media and undergoes some modification when energy is expended as the wave front performs the crushing and fracturing function. At the free surface the compressional wave is reflected as a tension wave. If the difference between the reflected wave and the incoming compressive wave is greater than the dynamic tensile strength of the rock, the rock fails in tension at that point. This phenomenon is called scabbing and it repeats itself from the new free surface if the remaining part of the incoming compression wave is still of high intensity.

The velocity of the compressional wave may be equal to the longitudinal wave velocity of the medium when it arrives at the free surface. In this case the transient wave is an elastic wave rather than a true shock wave.

The scabbing process has been described in detail by Saluja (1968). He found that scabbing begins almost exactly opposite the explosive charge (on a perpendicular line from the charge to the surface) and that the first scab formed is thickest. The thickness of the scabs formed depends upon the tensile strength of the rock and the shape of the pulse.

Fogelson *et al.* (1959) have examined the shape of the pulse in specially designed experiments. They found that the degree and amount of fragmentation resulting from a given blast depends on the amplitude and shape of the strain pulse reflected from the free rock surface. For breakage to occur, enough energy must be transmitted from the shot point to the free surface to account for the energy contained in the broken rock in the form of kinetic energy of motion of the rock fragments and potential energy of the new surface produced by the breakage.

It is necessary then, to put the charge of explosives at a sufficient depth to insure that the tensile strength of the rock at the free surface will be greater than the tensile forces resulting from the reflection of the compressive wave. Gnirk and Pfleider (1968) have attempted to determine the possible mathematical relationship between charge depth and maximum volume of broken rock. Although they observed that the volume of broken rock decreases with increasing charge depth, a simple linear or exponential correlation between the rock properties and outer dimensions could not be made. Figure 3.2 is a diagrammatic sketch of rock failure as a result of the scabbing process.

Failure as a result of the scabbing process is greatly influenced by the planar features of the rock medium. Johnson (1970), p. 357, points out that sheet structures are common features of many bodies of granitic rocks. These sheet fractures are usually flat or broadly curved and tend to be parallel to the overlying ground surface. They are difficult, if not impossible, to observe from a surfacial examination of the outcrop. The sheet fractures are effective free surfaces and form the reflecting surface necessary to initiate the scabbing process.

Other features common to bodies of igneous rocks, such as joints, faults and shear zones also influence the volume of broken rock resulting from the detonation of an explosive. They all have the effect of increasing the volume and fragmentation of the rock as a result of the blast.

These features, especially sheet fractures and joints, often cannot be recognized from examination of the outcrop and are visible only after failure has occurred. Since the features are characteristic of the rocks found in the Precambrian Shield, their detection difficult, and their influence indeterminate, any theory on rock breakage would be rendered useless and the evaluation of the applicability of such locations for suitable shot point sites would have to necessarily be cut-and-try.

The shot hole sites used in this experiment eventually failed as a result of scabbing and partial movement along fracture surfaces, neither of which could be expected from an examination of the outcrop previous to drilling. Usually the rock fragments could be cleared away, the lower free surface located and the borehole used again. One of the shot holes was used as the source site for 26 successive recordings; the charge weight never exceeding 6 pounds for a single shot.

Considering the above discussion, shot hole sites with visible planar features at the surface should not be considered. Depth to the center of the charge should probably be 6 or 7 times the radius of the equivalent radiator if failure as a result of scabbing is to be postponed until the shot hole has been used as many times as required. This figure is based on observations made in the field during the course of this experiment and from the theory, presented previously, on the equivalent radiator. The number of repetitions of detonation of the explosive charge cannot be predicted.

The location of a successful shot-point site will depend on a cut-and-try procedure in the Precambrian Shield, although some areas which are not suitable can be rejected if a careful examination of the prospective drilling site is made.

3.5.3 Dynamics of the Shot-Point Mechanism

It was recognized by Sharpe (1942) from empirical observations that if a shot hole is sprung by an initial large charge, in order to form a sizeable cavity, later smaller charges would result in a larger amplitude of reflected motion than would be produced in the absence of springing, since the displacement of the medium is directly proportional to the radius of the cavity. He also observed that the frequency spectrum of reflected motion is a function of charge size, a larger charge having a tendency to increase the proportion of low frequencies in the reflected motion.

Sharpe (1942) states that the dominant frequency component generated from explosives detonated in boreholes is given by

$$f = \frac{\omega}{2\pi} = \frac{\sqrt{2}}{3\pi} \frac{V}{R}$$

where:

ω = angular frequency

V = velocity of the medium

R = radius of the cavity

In the medium considered here, V = 6.07 km/sec (see Chapter 4) and R = 0.9 feet; indicating that the dominant frequency component is about 3,000 Hz. To generate lower frequencies would require a medium with unusually low velocities or a very large cavity radius.

If a frequency component of 5 Hz were to be generated from the shot holes considered in this survey a cavity radius of about 180 meters would be required.

O'Brien (1967) concludes that the amplitude from underground explosives increases in direct proportion to the weight of the charge fired, up to a certain limiting weight. For shots with charges above this weight the amplitude becomes closely proportional to the cube root of the charge weight. The limiting weight depends upon the elastic properties of the rocks at the shot point and empirical results indicate that it is of the order of a couple of hundred pounds. For shots which would require more explosive than the limiting value, it would be more efficient to divide the charge into smaller portions which are below this limit. The variation in charge weight used in this survey (2 to 10 pounds) was insufficient to test O'Brien's relationship. Further the fracturing and crushing of the brittle granitic rock probably influenced the observed amplitude of the first arrivals from record to record, more than did the variation of charge weight.

Bahjat and Kisslinger (1970), using three-dimensional model experiments, observed that tightly-coupled charges produced smaller amplitudes than charges detonated in a cavity. The maximum amplitude was generated when the cavity radius was 2 or 3 times the charge radius. The amplitude of P waves was observed to decrease for larger radii but never fell below that for a well tamped tightly coupled charge.

They interpret their results as follows: For cavity radii up to that used to obtain the maximum amplitude the peak stress in the medium exceeded its compressive strength. The largest radius for which the peak stress exceeded the compressive strength corresponds to the maximum amplitude. For larger radii the peak stress is below the compressive strength of the medium, but sufficiently high to cause failure in tension. For larger cavities, increases in the size of the equivalent radiator are much smaller and the maximum amplitude approaches a limiting value.

Considering the above results it would seem that there would be some merit in springing the shot holes to 2 or 3 times the charge radius, in order to maximize the observed amplitude. The first shot should, therefore, be larger than the subsequent shots. Although this procedure could be followed and used effectively for the first few shots made in the granite gneiss, the principle could not be exploited any further in light of the discussion of borehole failure presented earlier. However, it is recommended that the springing of the borehole should be incorporated into the procedure involving the detonating of explosives in boreholes drilled in igneous rocks for the purpose of obtaining reflections from the shallow crust; as the lifespan of the borehole will be prolonged substantially in contrast to the situation when the borehole is fully loaded.

3.6 Surface Shots as Seismic Sources

An authoritative account of phenomena accompanying underwater explosions is presented by Cole (1948). A description of the explosive process used to generate seismic energy from charges detonated underground in boreholes has been presented here. The use of surface charges to provide seismic energy has been presented by Poulter (1950). A brief description of the use of air shooting as an energy source (sometimes called the Poulter Seismic Method) will be presented and its possible use as a source in reflection surveying in the Precambrian Shield will be discussed.

The air shooting technique has been used in areas where shot hole driving is difficult. Problems in drilling result when the medium is either very soft or very hard. Buffet and Layat (1960), Hermot (1948), Pieuchot and Richard (1958) as well as Poulter (1950) describe experiments using the air shooting technique in areas where soft rocks, unconsolidated weathered material and absence of sufficient water supply make drilling difficult; the Sahara Desert is such an area. The method still appears to be untried on hard rock (Precambrian) areas.

The surface shooting technique is generally recognized as the least efficient method of generating seismic energy (O'Brien, 1967). The high acoustical contrast between air and rock results in a major portion of the chemical energy, available through explosive detonation being reflected, at the ground surface, into the atmosphere. Although figures representing the amount of energy available as seismic energy cannot be determined accurately, O'Brien (1960) states that 3 per cent of the available chemical energy is used to generate seismic waves when the shot is detonated underwater. Weston (1960) states that about 1 per cent of the chemical energy is available for seismic purposes when the shot is detonated underground. Fogelson *et al.* (1959) place this figure slightly higher for charges detonated in granite. Hermot (1948) states that air shots are 15 to 20 times less efficient than underground shots. Poulter (1950) states that if proper attention is paid to spacing, a pattern of air shots will require at most twice as much explosive as would be required for a single underground shot. Buffet and Layat (1960) found that a 3:2 ratio existed for experiments conducted in the Sahara.

Considering Hajnal's (1970) results, certainly not less than 100 pounds of explosive, placed underwater, would be required to obtain a reflection from the Intermediate (Conrad) Discontinuity. Based on the previously mentioned efficiencies, 300 pounds detonated underground would be the required amount of explosive to produce equivalent reflections. If a single air shot were used, approximately 6000 pounds of explosive would be necessary; if a pattern of air shots were used, 600 pounds of explosive would be the required amount. As will be demonstrated in Chapter 4, about four 20 pound charges of explosives, placed underground, detonated individually and the resultant records correctly processed, will probably be suitable for investigating the shallow crust if arrays of detectros are used. The equivalent air pattern shot would require about 160 pounds of explosive per shot.

Using the criterion established by Poulter, a possible pattern of surface charges suitable for use on the Precambrian Shield would consist of 7 separate explosive charges arranged in a hexagonal pattern. Each shot would consist of about 25 pounds of explosive and would be mounted on the top of a wooden stake approximately 8 feet off of the ground surface. A spacing of about 35-40 feet between adjacent charges is recommended as a starting point. The most efficient spacing will have to be determined in the field by a cut-and-try procedure; however, once determined it can be universally applied to Shield areas.

Other patterns are also possible. It appears that 7 individual charges arranged in a hexagonal pattern will be easier to manipulate than patterns which require a larger number of charges. Smaller patterns would require each individual charge to greatly exceed Poulter's recommended optimum of about 15 to 25 pounds. Figure 3.3 illustrates the recommended pattern of surface charges.

Any divergence from the pattern suggested here will be easily facilitated in the field,as the only additional equipment required would be some extra wooden mounting stakes.

Considering the time involved in drilling shot holes in rocks such as granite, the limited use of each shot hole as a source site, the difficulties involved in transporting even lightweight drilling equipment, and the relatively small increase in explosive requirements, it is recommended that an attempt be made to determine the feasibility of the use of surface charges as the energy source for reflection surveying in the Shield. Further, it must also be recognized that although a larger amount of explosive is required for surface shooting the total cost may be less, as water resistance will no longer be a necessary property and the explosive may be purchased in bulk form. The abandoning of the drilling equipment and procedure will result in a considerable reduction in the time involved in the survey and therefore result in lower operating costs and justify the use of larger quantities of explosive.

It should also be recognized that the amount of explosive to be used for an air shot, specified earlier, should not by any means be considered as exact, and the danger of generalizations pertaining to energy considerations, also made clear. The only way to determine the necessary amount of explosive and a suitable pattern is by conducting a properly designed experiment. However, once the required amount of explosive has been determined, the possibility exists that further experimentation at the individual sites for future reflection surveys will not be necessary, as the criterion which determines the amount of explosives required will be fairly constant throughout the Precambrian Shield. Such a generalization cannot be made for shot holes because of the influence of the structural characteristics of the medium.

3.7 Summary

A thin section analysis of a representative specimen indicates that the composition of the shot point rocks is granitic and that the texture is weakly gneissoid.

The physical properties of the rocks have been determined and are presented in Table 3.2. The values obtained are typical of granites.

The radius of the equivalent radiator was determined to be between 1.8 and 2.7 feet for this experiment.

It was suggested that the scabbing process could be eliminated if the charges were placed at depths of 6 or 7 times the radius of the calculated equivalent radiator.

An experiment employing the surface shooting technique is recommended. About 160 pounds of explosive would be required to obtain reflections from the Intermediate Discontinuity. An equivalent underground shot would consist of about 80 pounds of explosive. Figure 3.3 illustrates the hexagonal explosive pattern recommended for the surface shot.

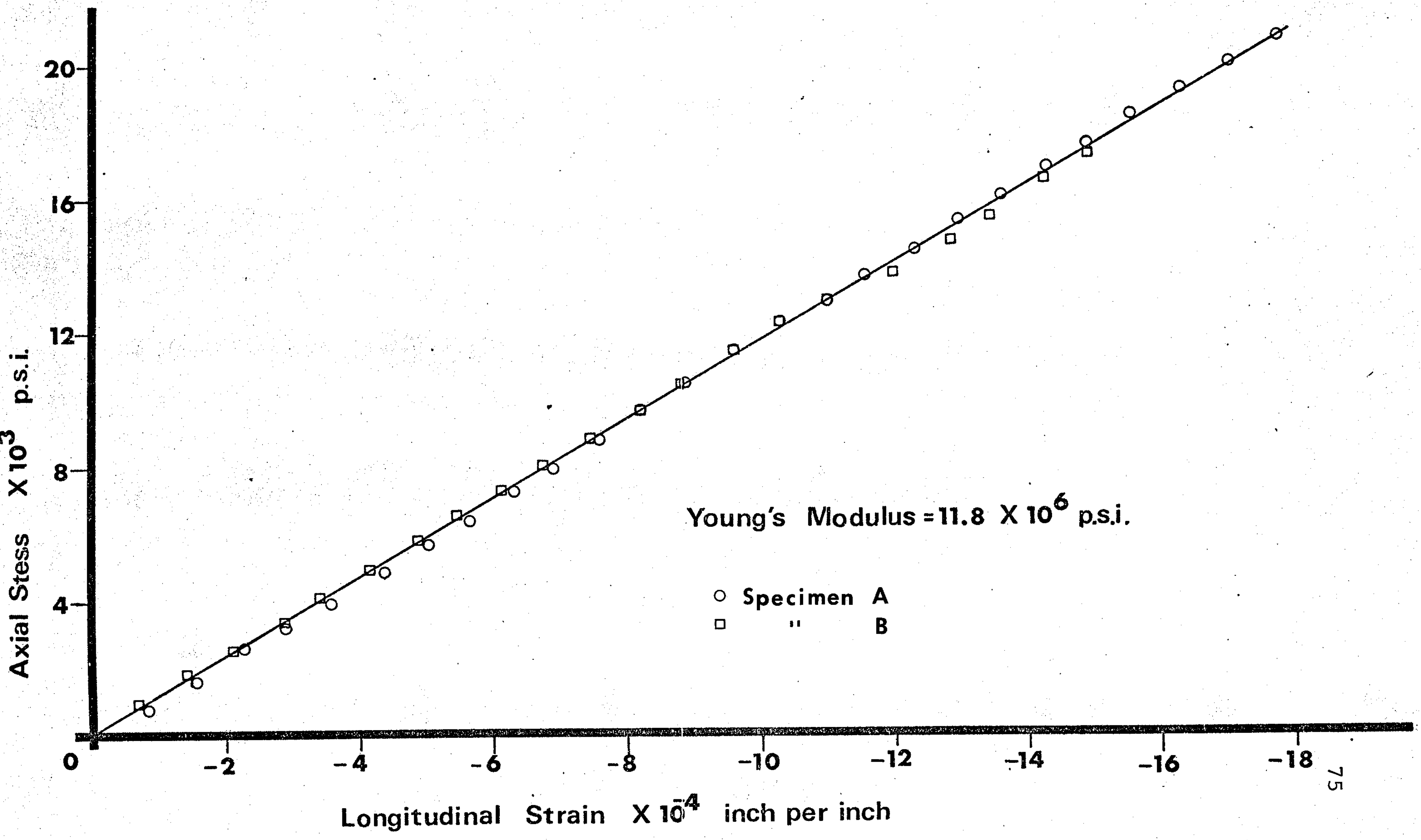


Fig. 3.1 a Stress-strain curve for cored specimens from shot holes

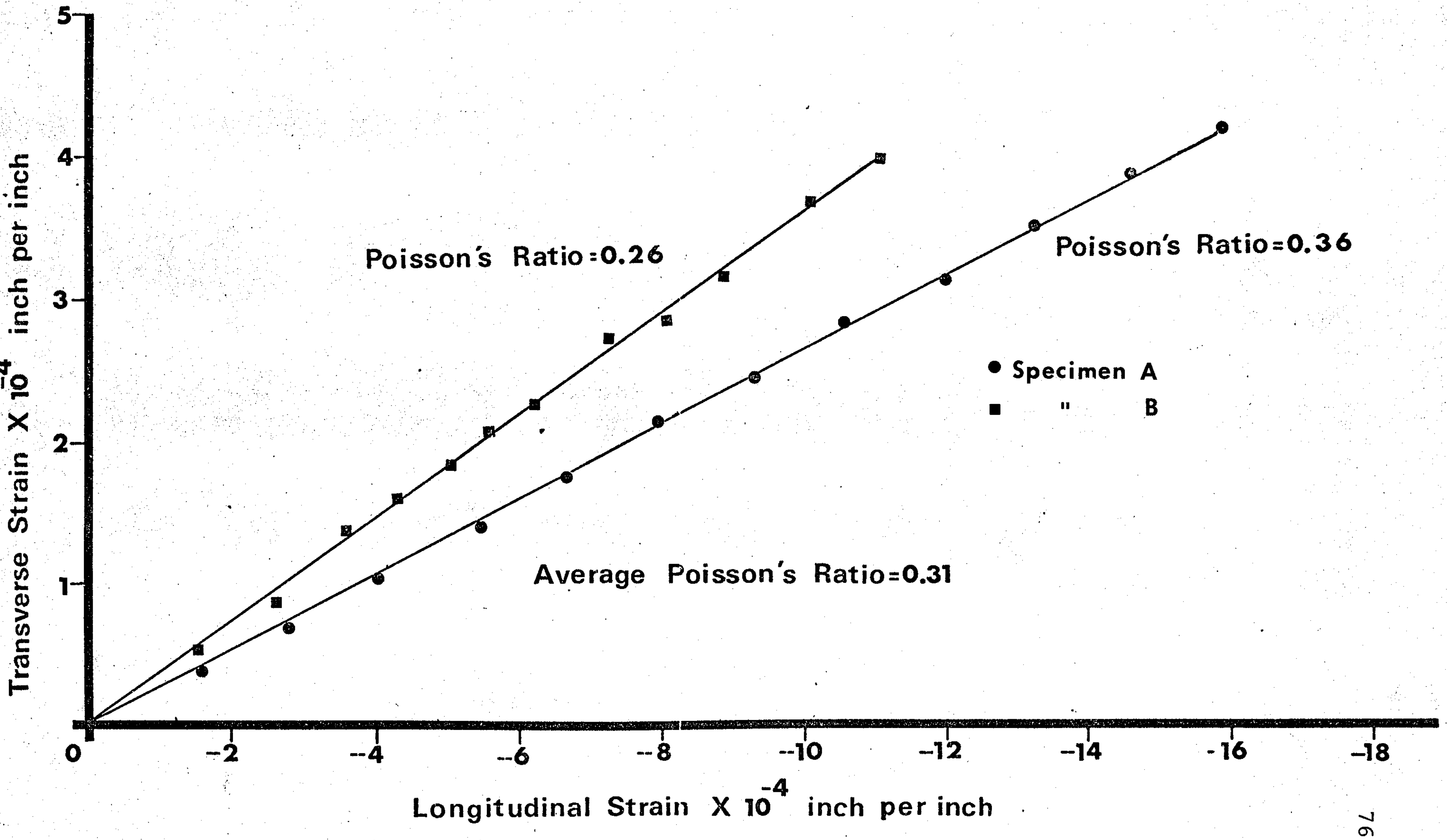
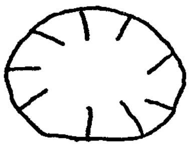
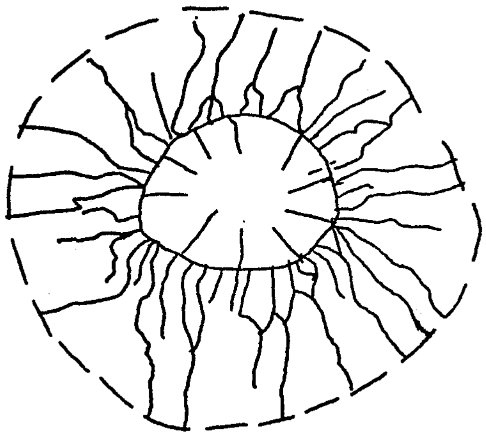


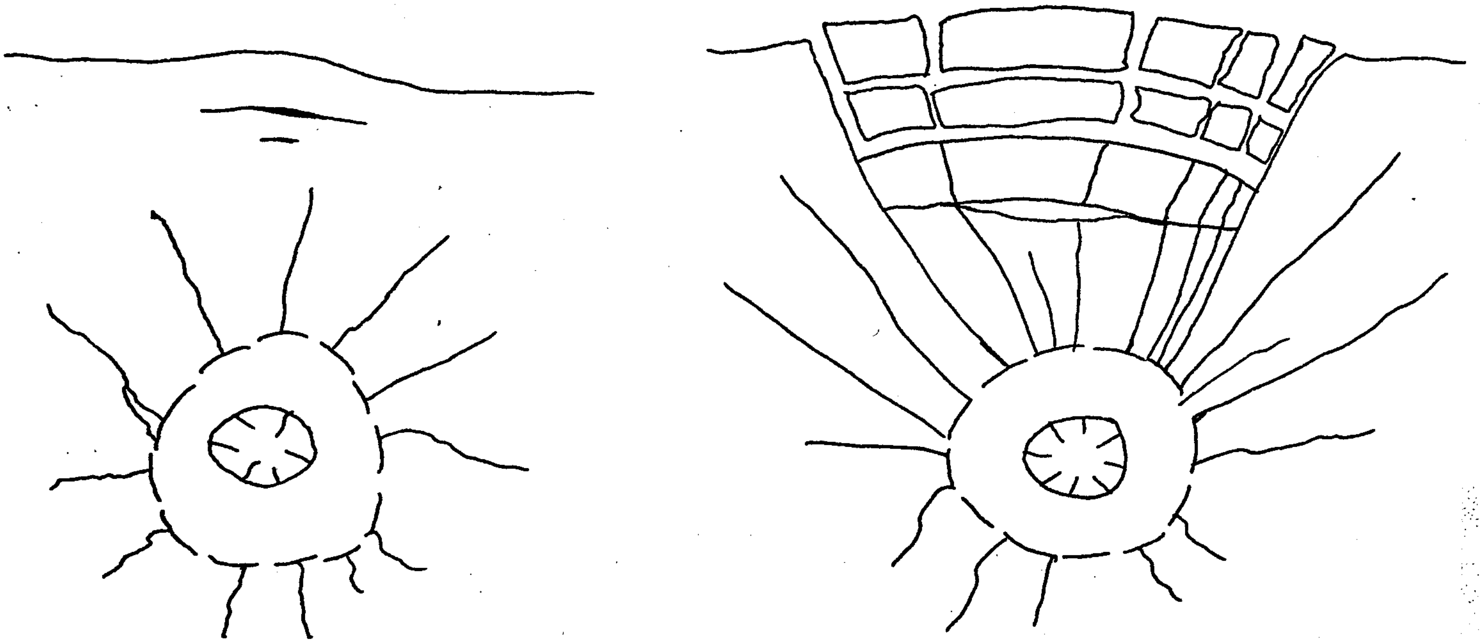
Fig. 3.1 b Average Poisson's Ratio for core specimens from shot holes



a) formation of cavity by crushing, after initiation of the explosive.



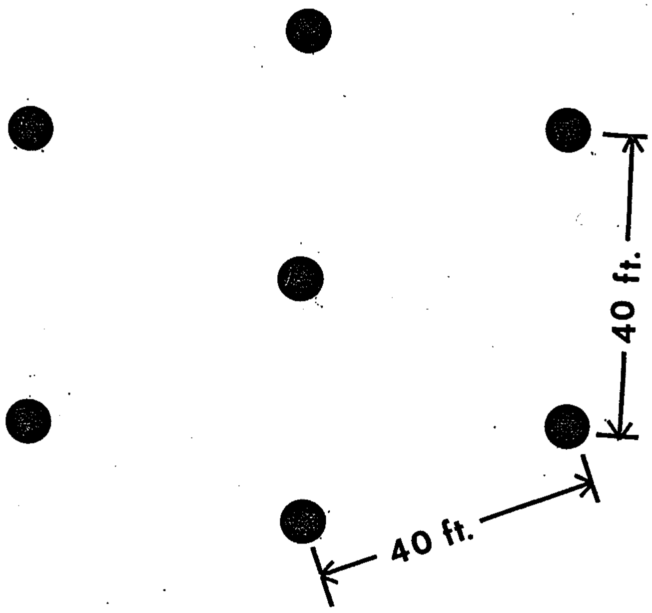
b) development of fracture system, the sphere defined by the termination of the cracks is the equivalent radiator.



c) initiation of scabbing at the free surface and the extension of the fracture system.

d) complete failure of shot-point rock as a result of scabbing and the extension of the fracture system to the free surface.

Fig. 3.2 Sequence of events resulting from the detonation of an explosive charge.



7 - SHOT HEXAGONAL PATTERN

FIG. 3.3 Recommended pattern of 7 surface charges. Adjacent charges are separated by 40 feet. Each charge consists of 25 lbs. of explosives mounted on the top of an 8 foot wooden stake. Priming cap should be placed in the middle of the charge.

CHAPTER 4

DATA PROCESSING AND INTERPRETATION

Hajnal (1970) describes the seismic program package written for the Department of Earth Sciences, University of Manitoba. Bates (1971) presents a discussion of the analog playback mechanism, incorporated in the VLF-2 system and indicates the relative merit of both the analog and digital filtering of seismic data.

Clowes (1969) and Hajnal (1970) report improvements in the signal-to-noise ratio when a stacking procedure was used as part of the processing package.

Their initial favourable indications in the application of the stacking method indicated that it could be used, with some modification, in near-vertical reflection work, to a greater extent. One of the objectives of this survey was to evaluate and demonstrate the applicability of the stacking (velocity filtering) method to near-vertical reflection data collected on the shield.

4.1 Data Processing

4.1.1 List of Programs

The following list of computer programs forms the basic seismic processing package available at the University of Manitoba. A brief description is given.

BINBIN: converts a 12 bit signal binary number on 7 track tape to a 16 bit signal binary number on 9 track tape.

PLOTMOD: prepares the digitized seismic data for plotting.

BLOCK 50: prints out numeric values of digitized seismic data.

BANDPASS: computes weighting co-efficients of a bandpass filter and determines the frequency response of the computed filter.

CONVOLVE: filters the seismic data with a set of weighting co-efficients calculated by "bandpass".

A complete description of these programs and their operation is given by Hajnal (1970).

4.1.2 Velocity Filtering

The common-depth-point (CDP) method of reflection surveying is well known and frequently used by petroleum seismologists. Mayne (1962), Schneider *et al.* (1964), Meyerhoff (1966) and Galbraith and Wiggins (1968) provide documentation of the theory involved and present results illustrating the successful application of the method.

The CDP method can be applied only when multiple coverage of the subsurface has been achieved. All channels which have common reflection points are then combined, or stacked after appropriate correction for angularity and travel time to datum have been applied. Linear multichannel filtering may also be applied to discriminate against noise.

The method of data collection used in this near-vertical reflection survey can be considered as a variation of the CDP method. The difference results as a consequence of the location of recording site-shot point remaining constant and hence the reflecting point and the ray parts of the propagating energy are the same for each shot detonated. The resulting seismic traces are then summed to provide one trace for each record and one trace for all the records with the same recording site-shot-point location. The procedure could easily be modified to become a CDP survey.

The increase in the signal-to-noise ratio that can be accomplished by this method is reported by Mayne (1962, p. 927) to be proportional to the square root of the number of signals (traces). The enhancement of the signal over the noise is analogous to the pattern performance of seismometer arrays as described in Chapter 2.

As previously indicated the array systems are eventually confronted with an inherent limitation. As the spread length and the number of detectors used for each array becomes larger and larger, the subsurface area which is averaged increases correspondingly. The detail being sought is thus obscured. The stacking method provides a practical means of increasing the signal-to-noise ratio and avoiding the limitation imposed by employing arrays, because it is necessary to repeat the shot several times so that the use of shallow boreholes may be successfully employed (see Chapter 3).

The velocity filtering program used to process the data collected in this survey was originally written by Z. Hajnal and has undergone subsequent modification by A. Bates and this writer. The modified version of the Fortan program and its description is presented in the Appendix.

The successful application of velocity filtering requires a multichannel system and the assumption that the coherent signals can be correlated from trace to trace. The best correlation results when each trace is shifted by the amount of time corresponding to its normal moveout. Perturbations which have moveouts other than that postulated for a particular ray path will be degraded relative to the desired signal, when the individual traces are summed together.

Figure 4.1 illustrates the application of the velocity filtering program to 9 of the records obtained at location 3 (see Table 2.1). The velocity filter used corresponds to the moveout of the first arrivals (6.07 km/sec) and their corresponding enhancement over the other perturbations is evident. Each trace in the figure is the result of adding 11 traces of each record together; providing a theoretical improvement in the signal-to-noise ratio of $\sqrt{11}$ (i.e. of 3.3).

The last trace at the bottom of the figure represents the addition of all the above stacked records into one resultant trace. This corresponds to an increase in the signal-to-noise ratio of $\sqrt{11 \times 9}$ (about 10).

Each of the resultant traces can be compared to record 15 (Figure 2.7b), which is representative of the recording site - shot-point setup. The improvement is evident and a quantitative analysis of the amplitudes of the first arrivals of each record relative to the rest of the trace corresponds to an increase in the signal-to-noise ratio of about 3. It is difficult to evaluate the increase in the total summation as correct alignment of the beginning of each record used in the summation process is needed and is difficult to achieve; however, the improvement is very evident when the total trace is compared to the traces above it in Figure 4.1.

The application of the velocity filtering method to near-vertical reflection surveying would involve the stacking with velocity filters based on the moveouts of expected events. That is, the stacking process would begin with a time shift corresponding to the moveout of the first arrival and the time shift continually decreased on each subsequent application of the routine. The process would terminate when an infinite apparent velocity is reached (zero moveout) which would correspond to a perfectly vertical reflection path and would be approached if a very deep reflection surface were present. Baer (1972) illustrates such an application of the program to his data. The degree of attenuation of the perturbations, which do not correspond to the input moveout, is apparent.

Figure 4.2 is a stack with an apparent velocity of 0.0 km/sec. The reduction in the signal-to-noise ratio is evident. The greater attenuation of the first arrival as compared with those of Figure 4.1 illustrates the effect of using different velocity filters.

The reduction of the later arriving air-wave is also apparent on the total trace. This reduction, of the amplitude of air waves by stacking,is important if surface shots and a single detector system were employed to collect reflection data, as the inherent high amplitude air-wave may mask possible events.

4.2 Interpretation and Discussion

Hajnal (1970) reports on a preliminary trial of the near-vertical reflection method as applied to the Shield. His results indicate the need for the further development of the method. The objectives of this experiment were to apply array theory, develop a technique employing the use of boreholes drilled in extremely hard media and to develop a processing technique based on the velocity filtering of the data

It was hoped at the onset of the experiment that a reflection from the Intermediate (Conrad) Discontinuity would be observed. However, the size of the charges used as sources for seismic energy were probably below the minimum energy requirement to permit a reflection from the Intermediate to be observed after the stacking procedure was applied.

The inability in the determination of the "depth of investigation" achieved, precludes the statement that reflectors shallower than the Intermediate are absent. The processing of the data with the velocity filtering technique did not reveal any shallow discontinuities although the applicability of the processing technique was demonstrated.

The necessity of having prior knowledge of the amount of explosive necessary to obtain a recognizable crustal reflection led to the development of a method for calculating the equivalent charge weight. It is briefly presented here and is discussed in detail by Baer (1972).

$$W = \sqrt{t/r} \sum_{i=1}^{r} w_i$$

where: r = the number of records (shots) to be included in the stacking process.

t = the number of traces to be included in the stacking process.

W = the weight of explosive necessary to obtain a reflection from any interface with a single shot.

w = the weight of explosive necessary for each of 12 shots to obtain an equivalent reflection from a single charge W, provided w is above the minimum energy requirement to observe a reflection.

The development of the formula was subject to many assumptions and should only be considered as approximate.

When applied to Hajnal's results, where a minimum charge of 100 pounds was used to obtain a possible reflection from the Intermediate. It was found that for recording site - shot-point system 3 (Table 2.1) where r = 11 and t = 9, the equivalent charge weight was about 80 pounds. The value is below the minimum charge weight calculated on the basis of Hajnal's experience. This indicates that the velocity filtering of the records will probably not result in obtaining a recognizable signal from the Intermediate.

Based on the above-mentioned calculation it is recommended that 4 individual shots consisting of 20 pounds of explosive each will yield the amount of energy necessary for the successful application of the velocity filtering method to obtain a reflected signal from the Intermediate Discontinuity. The same result can be achieved if 4 simultaneous shots of 20 pounds of explosive in each shot hole are made and the resulting 12 traces velocity filtered.

Other combinations are possible if the charge weight and the number of holes are varied. The correct combination will depend on the economic considerations involved.

The previous calculations are exclusive of the additional improvement in the signal-to-noise ratio obtained when seismometer arrays are employed.

The velocities of direct-travelling P-waves, S-waves and Rayleigh waves have been determined and are indicated on Figure 4.3, a time-distance plot. The difficulty arising in picking the onset of S- and Rayleigh waves is made evident by viewing Figures 2.7a, b, c, and d. An air-wave has also been identified in the records obtained with HS-10-1 geophones.

The application of frequency filtering techniques (using the CONVOLV program) to the acquired data did not result in any significant improvement over the velocity filtering technique.

4.3 Summary

It has been proven that specific seismic events can be significantly enhanced relative to other perturbations when the seismic record is processed using a method of velocity filtering (stacking). The increase in the amplitude of the first arrivals that can be obtained by the velocity filtering method is illustrated in Figure 4.1. The increase in the signal-to-noise ratio is about 3.

A stack with an apparent velocity of 0.0 km/sec. is presented in Figure 4.2 and the corresponding attenuation of the first arrivals is readily apparent when compared to Figure 4.1.

It was determined that 4 individual shots, each consisting of 20 pounds of explosive will yield sufficient energy to obtain a reflected signal from the Intermediate Discontinuity if the velocity filtering method is incorporated into the technique.

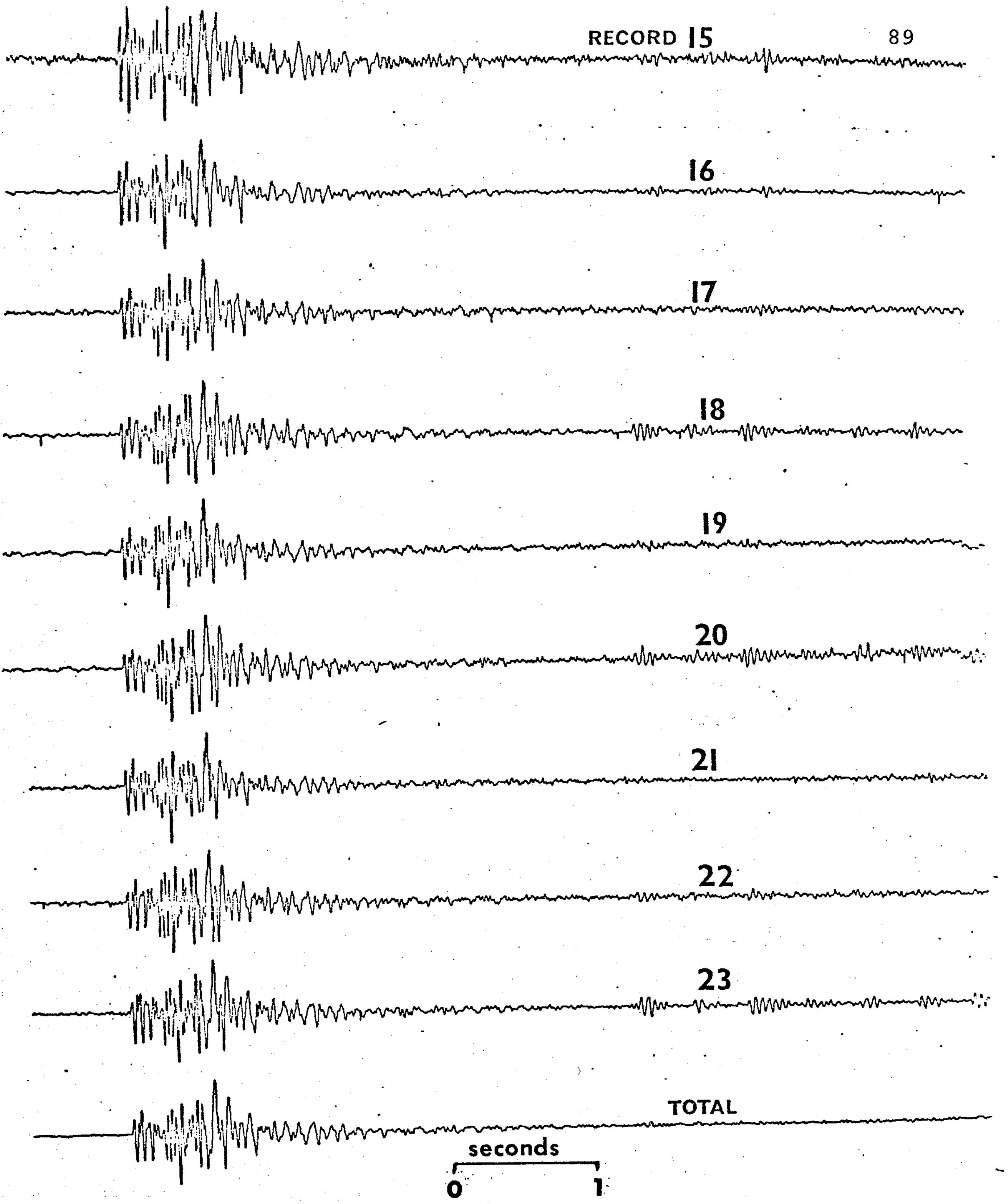


FIG. 4.1 Stack of seismic records. Velocity filter = 6.07 km/sec

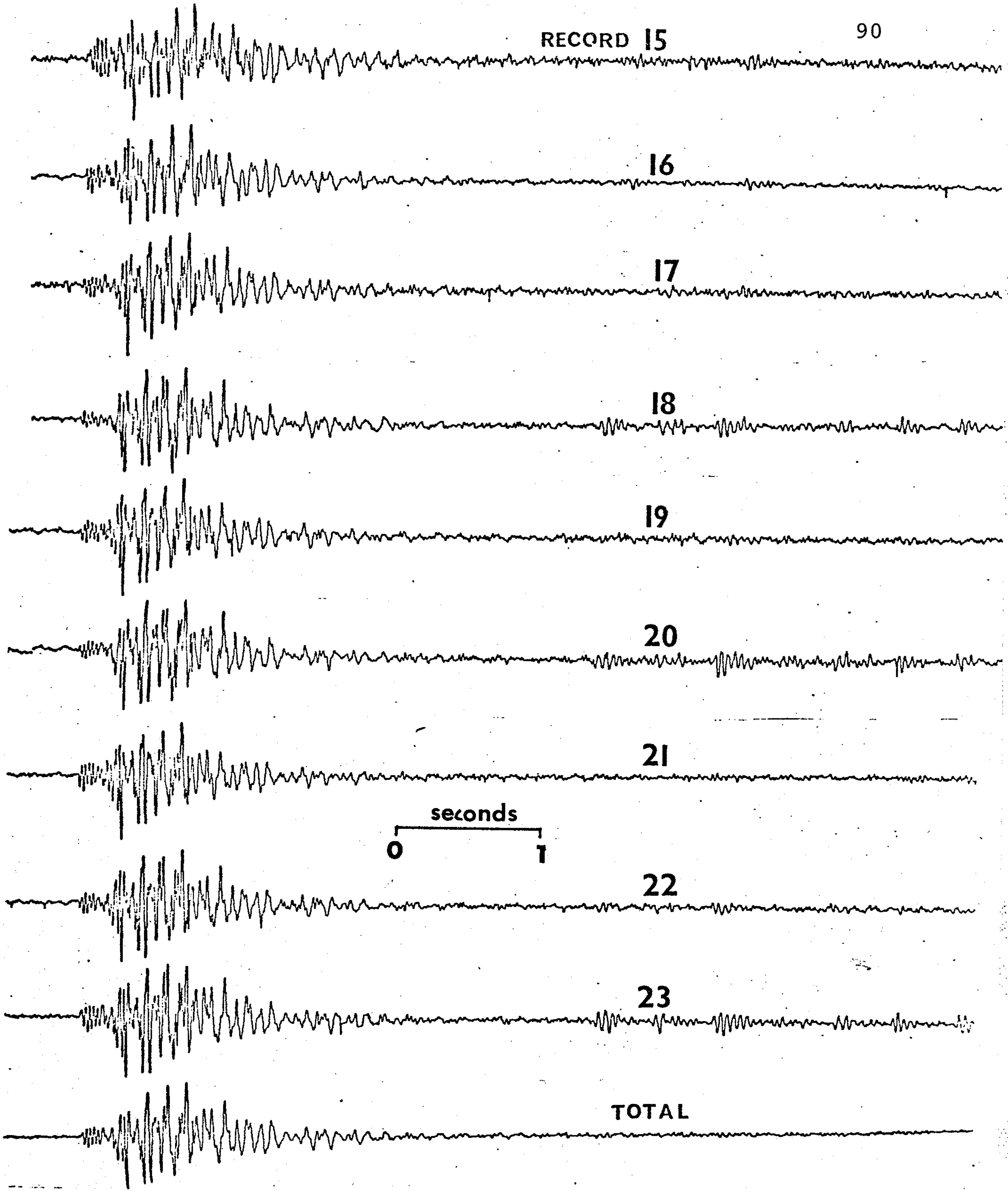


FIG. 4.2 Stack of seismic records. Velocity filter = 0.0 km/sec

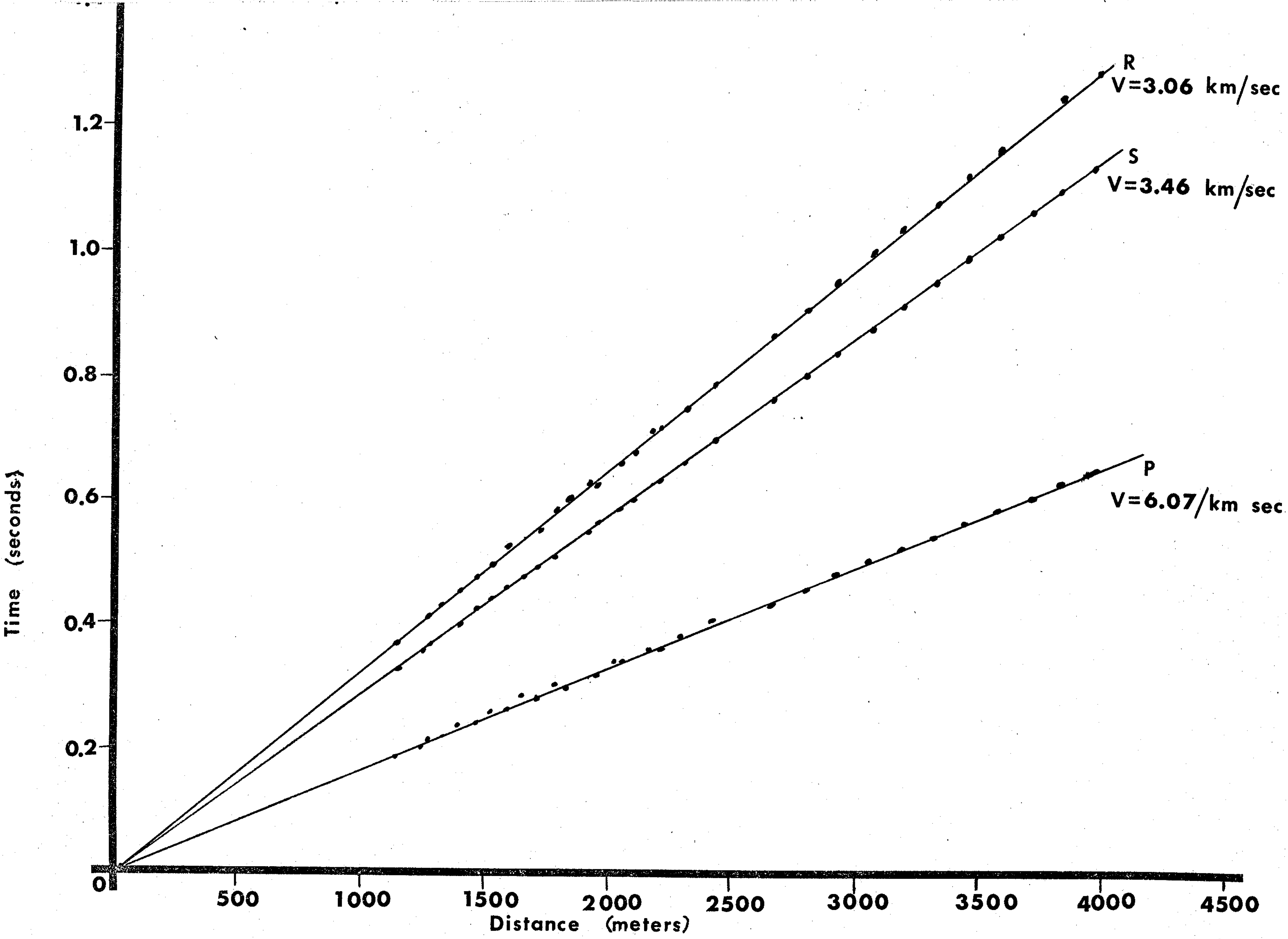


FIG. 4.3 TIME - DISTANCE PLOT OF DIRECT ARRIVALS

CHAPTER 5

CONCLUSIONS

The successful development of a field operational procedure using seismometer arrays to degrade seismic noise relative to seismic signal has been made. The results indicate that the employment of suitable arrays of detectors can yield appreciable increase in the signal-to-noise ratio over a single detector system. There exists a limit, in the length of the spread and the number of detectors of each array, beyond which the manipulation of the arrays becomes difficult and no improvement in the signal-to-noise ratio is observed. In this experiment the arrays consisting of 36 detectors and a 275 meter spread length did not provide any additional reduction in the noise contribution to the seismic records when compared with a 183 meter, 24 seismometer array.

The incorporation of seismometer arrays into the near-vertical reflection method is recommended. The recommendation is based on the attenuation of surface waves and random noise observed when arrays are employed, and the corresponding increase in the signal-to-noise ratio.

The drilling of shot holes with diamond tipped bits was accomplished and the two drill holes used repetitively as the location for the energy source. The mechanism of failure of the shot hole rocks is outlined and an approximate method of calculating the required depth to the bottom of the borehole is outlined. A hole can be used repetitively if the explosive charge is placed at a depth of about 7 times the calculated equivalent radiator.

The drilling of boreholes in the Precambrian is proven to be an acceptable procedure which can be followed to place the site of the seismic sources with some degree of freedom. However, even when the mechanical and physical properties of the shot point medium are known, the failure of the shot-hole rocks cannot be predicted because of the intangibles outlined in Chapter 3, which enter into the largely empirical calculations. Whether or not a chosen site is suitable will be determined largely by a cut-and-try procedure.

Even though boreholes can be used for charge placement, it is recommended that experiments with patterns of air shots be conducted. The additional cost of the larger quantities of explosives, inherent in this method, may be offset by the abandonment of the costly drilling procedure and equipment. Charges of about 160 pounds are suggested as a starting point for experimentation with surface shots, if depths corresponding to the Intermediate Discontinuity are to be investigated.

Velocities of the direct wave arrivals have been determined and reported. The possible layered nature of the shallow crust was not determined as no reflected events were observed. This result can be attributed to the absence of velocity discontinuities in the shallow crust or the insufficient input of energy at the source. A method for determining the approximate charge size is outlined and calculations reveal that 4 individual 20 pound shots placed in boreholes are probably necessary if an Intermediate reflection is to be observed.

Definite final conclusions have not been reached in this early stage of the developing program regarding the use of the near-vertical reflection method for crustal investigation in the Precambrian Shield. However, a number of the questions involving its applicability have been answered. Further experimentation with the method is recommended and the direction of future experimentation outlined.

APPENDIX

DESCRIPTION OF PROGRAM *STACK*

Programmer:	Z. Hajnal, modified by A. Bates and L.A. Homeniuk.
Language:	Fortran IV
Function:	To sum any number of traces and/or records and give one output trace. Each trace is shifted by an amount corresponding to an imput movement.

Operation:

Subroutine SUM; performs actual additions and time shift of seismic traces.

Subroutine IMPUT and NORMEN; normalize each trace included in the process.

Subroutine ENT; finds the required record on the imput tape.

Subroutine SUPUL; locates the starting time of the summation process within an individual record.

Subroutine INI; computes the average value of each trace included in the summation process.

Subroutine STAND; computes the standard deviation of each trace.

Subroutine DAVE; prepares the data for plotting.

Subroutine TPPLT; actual plotting routine.

Imput Parameters:

L - the number of seismic records to be included in the process.

N3 - the total number of digital blocks to be included in the process. Each block corresponds to about 3 seconds of seismic data.

N - the number of traces (channels) of seismic information.

DI - digitizing interval (seconds).

A1 - the number of the first seismic record to be included in the process.

ST - the starting time of each record to be included in the stacking routine.

DT - the time shift (seconds) corresponding to the velocity filter used in the process.

NULL - permits individual traces to be included in or rejected from the stacking process; NULL = 0, indicating that the trace will be excluded.

Operational Requirements:

Space - 170k

Imput Tape - 9 track

Output Tape - 9 track plottape

Storage - 3 disks

Output - imput parameters and a calcomp plot

Time - 0.30 minutes CPU time per block of data

Reference: Hajnal (1970)

```
                C--- THE UNIVERSITY OF MANITOBA
                C--- DEPARTMENT OF EARTH SCIENCE
                C--- GEOPHYSICS DIVISION
                C--- VELOCITY FILTERING PROGRAM
                C--- WRITTEN BY Z.HAJNAL
                C--- MODIFIED BY A.BATES AND L.HOMENIUK
0001                  INTEGER*2 A1(12),MB(12)
0002                  DIMENSION ST(12),NST(12),AV(5,12),NULL(12,12),E(5,12)
                C--- L=THE NUMBER OF RECORDS
                C--- N3=THE TOTAL NUMBER OF BLOCKS(DIGITAL)
0003                  READ(5,10) L,N3
0004             10   FORMAT(2I5)
0005                  ICOUNT=0
0006                  CALL SUM(A1,MB,ST,NST,AV,NULL,E,L,N3,ICOUNT)
0007                  REWIND 8
0008                  CALL EXIT
0009                  END
```

```
      SUBROUTINE SUM(A1,MB,ST,NST,AV,NULL,E,L,N3,ICOUNT)
C---  N=NUMBER OF CHANNELS OF SEISMIC INFORMATION
C---  DI=DIGITIZING INTERVAL(SECONDS)
C---  A1=THE NUMBER OF THE FIRST SEISMIC RECORD TO BE INCLUDED IN THE
C---  STACKING PROCESS
C---  ST=STARTING TIME OF THE STACKING PROCESS(SECONDS)
C---  DT=THE TIME SHIFT TO BE APPLIED TO EACH TRACE(VELOCITY FILTER)
C---  NULL=1,INDICATES THAT THE TRACE WILL BE INCLDED IN THE STACKING
C---  PROCESS,NULL=0,THE TRACE WILL BE EXCLUDED
      INTEGER*2 W(8000),Y(8000),A1(L),MB(L),A,B,LOT(12,70),T(12,1400)
      DIMENSION IT(12),ST(L),DT(12),NST(L),AVR1(12),AV(N3,12),STD(12)
      DIMENSION NULL(L,12),AVR(12),E(N3,12),E2(12)
    1 FORMAT(1H ,'RECORD ',I3,3X,'BLOCK',I3)
    2 FORMAT(1H ,'AVERAGE OF OUTPUT TRACE IS',F10.3)
    3 FORMAT(1H ,'STANDARD DEVIATION / 100 IS',F10.5)
      CALL TPST
      N=12
      M=1400
      DI=0.002448
      HDI=DI*70
      MZ=1260
      MMZ=MZ*N3
      ICOW=0
      TXX=N3*3.5
      READ(5,20) (A1(I),I=1,L)
   20 FORMAT(16I5)
      READ(5,30) (ST(I),I=1,L)
   30 FORMAT(8F10.3)
      READ(5,40) (DT(I),I=1,12)
   40 FORMAT(8F10.6)
      READ(5,50) ((NULL(I,J),J=1,12),I=1,L)
   50 FORMAT(12I1)
      WRITE(6,10) L,N3
      WRITE(6,20) (A1(I),I=1,L)
      WRITE(6,30) (ST(I),I=1,L)
   10 FORMAT(2I5)
      WRITE(6,40) (DT(I),I=1,12)
      WRITE(6,50) ((NULL(I,J),J=1,12),I=1,L)
      DO 51 I=1,L
      MB(I)=ST(I)/HDI
      DZ=ST(I)-(MB(I)*HDI)
      NST(I)=DZ/DI
   51 CONTINUE
      WRITE(6,50) ((MB(I),NST(I)),I=1,L)
      DO 60 I=1,N
      IT(I)=DT(I)/DI
   60 CONTINUE
      WRITE(6,50) (IT(I),I=1,12)
      N1=IT(1)
      N2=IT(2)
      K3=IT(3)
      N4=IT(4)
      N5=IT(5)
      N6=IT(6)
      N7=IT(7)
      N8=IT(8)
      N9=IT(9)
      N10=IT(10)
```

```
      N11=IT(11)
      N12=IT(12)
      MAX=0
      DO 112 IG=1,L
      IF(NST(IG).GT.MAX) MAX=NST(IG)
  112 CONTINUE
      MLO=N3*MZ-MAX
      DO 99 K=1,MLO
   99 W(K)=0
      DO 100 J2=1,L
      CALL ENT(A,B,LOT,A1,J2,L)
      CALL SUPUL(A,B,LOT,MB,J2,L)
      WRITE(6,1) A,B
      CALL INI(A,B,T,N,M,AVR1,AV,AVR,N3)
      CALL STAND(T,AVR1,STD,N,M,N3,E)
      WRITE(6,50) N,M,N3
      NS=1
      DO 200 I=1,N3
      CALL INPUT(T,N,M,AVR1,NS)
      WRITE(6,50) N,M,N3
      CALL NORMEN(M,T,N,STD,NS)
      WRITE(6,50) N,M,N3
      DO 11 J=1,N
      IF(NULL(J2,J).EQ.1) GO TO 12
      DO 13 JP=1,M
   13 T(J,JP)=0
   12 CONTINUE
   11 CONTINUE
      IMZ=(I-1)*MZ
      DO 14 K=1,MZ
      KK=K+IMZ
   14 Y(KK)=T(1,K+N1)+T(2,K+N2)+T(3,K+K3)+T(4,K+N4)+T(5,K+N5)+T(6,K+N6)+
     1T(7,K+N7)+T(8,K+N8)+T(9,K+N9)+T(10,K+N10)+T(11,K+N11)+T(12,K+N12)
      DO 15 IZ=1,12
      DO 15 LZ=1261,M
      MS=LZ-1260
   15 T(IZ,MS)=T(IZ,LZ)
      NS=141
  200 CONTINUE
      REWIND 13
      CALL DAVE(Y,MMZ,ICOUNT,ICOW,TXX)
      ICOW=6
      ICOUNT=ICOUNT+1
C NORMALIZE Y
      STAV=0.0
      DO 300 K=1,MMZ
  300 STAV=STAV+Y(K)
      STAV=STAV/MMZ
      WRITE(6,2) STAV
      SE=0.0
      DO 400 K=1,MMZ
  400 SE=SE+(Y(K)-STAV)*(Y(K)-STAV)
      SE=(SQRT(SE/MMZ))*0.01
      WRITE(6,3) SE
      DO 500 K=1,MMZ
  500 Y(K)=(Y(K)-STAV)/SE
      DO 600 K=1,MLO
      KPP=K+NST(J2)
```

```
0107          600  W(K)=W(K)+Y(KPP)
0108          100  CONTINUE
0109               CALL DAVE(W,MLO,ICOUNT,ICOW,TXX)
0110               CALL TPFIN
0111               RETURN
0112               END
```

```
 0001                SUBROUTINE INPUT(T,N,M,AVR1,NS)
               C---- NORMALIZE EACH TRACE TO BE INCLUDED IN THE STACKING PROCESS
 0002                INTEGER*2 T(N,M)
 0003                DIMENSION AVR1(12)
 0004                DO 18 K=NS,M,70
 0005                L=K+69
 0006                READ(13) ((T(I,J),I=1,12),J=K,L)
 0007          18    CONTINUE
 0008                DO 36 LL=1,N
 0009                DO 37 KK=NS,M
 0010          37    T(LL,KK)=T(LL,KK)-AVR1(LL)
 0011          36    CONTINUE
 0012          60    RETURN
 0013                END
```

```
            SUBROUTINE STAND(T,AVR1,STD,N,M,N3,E)
      C---  COMPUTES THE STANDARD DEVIATION OF EACH TRACE
            DIMENSION E(N3,12),STD(12),AVR1(12),E2(12)
            INTEGER*2 T(N,M)
            WRITE(6,1) N,M,N3
        1   FORMAT(3I5)
            DO 29 I3=1,N3
            DO 17 K=1,M,70
            L=K+69
            READ(13) ((T(I,J),I=1,12),J=K,L)
       17   CONTINUE
            DO 30 L3=1,N
            E(I3,L3)=0.0
            DO 31 KT=1,M
       31   E(I3,L3)=E(I3,L3)+(T(L3,KT)-AVR1(L3))*(T(L3,KT)-AVR1(L3))
       30   CONTINUE
       29   CONTINUE
            DO 32 IS=1,N
            E2(IS)=0.0
            DO 33 LS=1,N3
       33   E2(IS)=E2(IS)+E(LS,IS)
            STD(IS)=SQRT(E2(IS)/(M*N3))*0.01
       32   REWIND 13
            RETURN
            END
```

```
          SUBROUTINE INI(A,B,T,N,M,AVR1,AV,AVR,N3)
    C---  COMPUTES THE AVERAGE VALUE OF EACH SEISMIC TRACE
          INTEGER*2 A,B,T(N,M)
          DIMENSION AV(N3,12),AVR(12),AVR1(12)
          DO 99 LS=1,N3
          DO 18 K=1,M,70
          L=K+69
          READ(8,2) A,B,((T(I,J),I=1,12),J=K,L)
      2   FORMAT(2A2,250A2,250A2,250A2,90A2)
          WRITE(13) ((T(I,J),I=1,12),J=K,L)
     18   CONTINUE
          DO 76 I1=1,N
          AV(LS,I1)=0.0
          DO 77 J1=1,M
     77   AV(LS,I1)=AV(LS,I1)+T(I1,J1)
     76   CONTINUE
     99   CONTINUE
          DO 78 NS=1,12
          AVR(NS)=0.0
          DO 79 MS=1,N3
     79   AVR(NS)=AVR(NS)+AV(MS,NS)
          AVR1(NS)=AVR(NS)/(M*N3)
     78   REWIND 13
          RETURN
          END
```

```
)001                SUBROUTINE ENT(A,B,LOT,A1,J2,L)
              C---- FINDS THE BEGINNING OF THE REQUIRED RECORD ON THE IMPUT TAPE
)002                INTEGER*2 A,B,A1(L),LOT(12,70)
)003                DO 1 MXS=1,6000
)004                READ(8,12) A,B,((LOT(I,J),I=1,12),J=1,70)
)005          12    FORMAT(2A2,250A2,250A2,250A2,90A2)
)006                IF(A.EQ.A1(J2)) GO TO 65
)007           1    CONTINUE
)008          65    BACKSPACE 8
)009                RETURN
)010                END
```

```
            SUBROUTINE SUPUL(A,B,LOT,MB,J2,L)
      C---  LOCATES THE STARTING POINT OF THE STACKING PROCESS WITH IN THE
      C---  INDIVIDUAL RECORD
            INTEGER*2 A,B,LOT(12,70),MB(L)
            II=0
            DO 42 K=1,100
            IF(MB(J2)) 45,45,46
         46 READ(8,5) A,B,((LOT(I,J),I=1,12),J=1,70)
          5 FORMAT(2A2,250A2,250A2,250A2,90A2)
            II=II+1
            IF(II.EQ.MB(J2)) GO TO 45
         42 CONTINUE
         45 RETURN
            END
```

```
 0001                SUBROUTINE NORMEN(M,T,N,STD,NS)
 0002                INTEGER*2 T(N,M)
               C--- NORMALIZE EACH TRACE TO BE INCLUDED IN THE STACKING PROCESS
 0003                DIMENSION STD(N)
 0004                DO 30 I=1,N
 0005                IF(STD(I).EQ.0.)GOTO30
 0006                DO 40 J=NS,M
 0007           40   T(I,J)=T(I,J)/STD(I)
 0008           30   CONTINUE
 0009                RETURN
 0010                END
```

```
 0001               SUBROUTINE DAVE(X,LX,ICOUNT,ICOW,TXX)
              C---  PREPARES DATA FOR PLOTTING
 0002               INTEGER*2 X(LX),XMAX
 0003               XMAX=0
 0004               DO 1 I=1,LX
 0005               M7=X(I)
 0006               IF(M7.GT.XMAX) XMAX=M7
 0007             1 CONTINUE
 0008               FACT=1.0/XMAX
 0009               CALL TPPLT(X,1,LX,0.007344,FACT,2.5,PRNT,ICOUNT,ICOW,TXX)
 0010               RETURN
 0011               END
```

```
      SUBROUTINE TPPLT(Y,NO1,NO2,XSL,YSL,DIST,PRNT,ICOUNT,ICOW,TXX)
C
C---  DEPARTMENT OF GEOLOGY
C---  UNIVERSITY OF MANITOBA
C
C---  INPUT PARAMETERS
C---  INPUT VECTOR Y IN ARGUMENT OF SUBROUTINE
C---  INPUT VECTOR INTEGER*2
C---  NO1 IS FIRST ELEMENT OF VECTOR TO BE PLOTTED
C---  NO2 IS LAST ELEMENT OF VECTOR TO BE PLOTTED
C---  XSL IS XSCALE IN INCHES PER UNIT
C---  YSL IS Y-SCALE IN INCHES PER INTERVAL
C---  DIST IS DISTANCE IN INCHES BETWEEN AJACIENT TRACES
C---  MAX SIZE OF Y .GT. NO1 .GT. 1
C---  MAX SIZE OF Y .GT. NO2 .GT. NO1
      LOGICAL PRNT
      INTEGER*2 Y(1)
      DIMENSION IBUF(5000)
      IF ( PRNT ) PRINT 1,NO1,NO2,XSL,YSL,DIST
1     FORMAT (1H1///' PLOTTING BEGINS AT ELEMENT',I4,' OF Y AND ENDS AT
     XELEMENT',I5,' X-SCALE IS 1 UNIT EQUALS',F7.5,' INCHES',/,'Y-SCALE
     XIS 1 INTERVAL EQUALS',F7.5,' INCHES',/,'DISTANCE BETWEEN TRACES I
     X',F7.2,' INCHES',/,'PLOTTED POINTS ARE '////)
 2    FORMAT (1H  26I5)
      IF ( PRNT )  PRINT 2,(Y(I),I=NO1,NO2)
      IF(ICOW.GE.1)GOTO6
      CALL PLOT(3.,9.,-3)
 6    CONTINUE
      DO 3 I=NO1,NO2
      XD=(I-1)*XSL
      YD=Y(I)*YSL
 3    CALL PLOT(XD,YD,2)
      IF(ICOUNT.EQ.3)GOTO12
      IF(ICOUNT.EQ.6)GOTO12
      IF(ICOUNT.EQ.9)GOTO12
      IF(ICOUNT.EQ.12)GOTO12
      CALL PLOT(0.,-DIST,-3)
      GOTO8
 12   CONTINUE
      DIP=10.0*DIST
      CALL PLOT(0.,0.,3)
      CALL PLOT(TXX,DIP,-3)
 8    CONTINUE
      RETURN
      ENTRY TPST
      CALL PLOTS(IBUF,5000,2)
      RETURN
      ENTRY TPEIN
      CALL PLOT(0.,-DIST,999)
      RETURN
      END
```

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