THE UNIVERSITY OF MANITOBA

DEVELOPMENT OF THE PROCESSING CAPABILITY FOR CRUSTAL EXPLORATION ON THE CANADIAN SHIELD BY THE NEAR VERTICAL REFLECTION TECHNIQUE

by

GEORGE H. FRIESEN

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF EARTH SCIENCES

WINNIPEG, MANITOBA

May, 1974

ABSTRACT

The development of the near vertical reflection seismic technique to the stage where it can be used to map shallow and deep crustal structure has been a goal of the Department of Earth Sciences at the University of Manitoba since 1969. This thesis develops and describes techniques by which this goal can be achieved.

The primary method of improving the quality of data obtained in the field this year was very simple--larger unit charges, and more of them, were used. Thus, the effective charge weights used approximately equaled the theoretical minimum charge size necessary to observe deep crustal reflections. This approach was based on the theoretical estimates produced by Baer (1972).

The use of linear arrays has proven to be successful in attenuating surface waves. However, because of the more difficult terrain in the area of this study, these arrays were not employed. Other methods of overcoming the problems of surface waves were used.

As a further step in the development of the data processing capability of the geophysics group at the University of Manitoba, the existing computer programs were critically assessed and significantly modified in the light of the data obtained in the summer of 1973. Weighted stacking was introduced to do a better job of summing multiple shots; and by proper use of frequency filtering techniques, good quality records were obtained. Velocity filtering routines were further developed so as to improve the S:N ratio of different events, thus aiding in their identification.

The success of this study in obtaining observable reflections indicates that the development of the near vertical reflection technique is now at the stage where it can be used to study the geologic structure of the earth's crust. This thesis does not mark the end of the development processes, but rather the successful start. Continuous effort will be necessary if the maximum amount of information is to be extracted from the data collected.

The 1973 field season was the first in which the Precambrian Centre attempted to obtain near vertical reflection seismic data on or near the Aulneau Dome. The data collected this year was not sufficient to make a complete interpretation, but was used to evaluate and to improve this method for the next four field seasons. The data collected in this five year period (1973-1977) will be used along with other geologic and geophysical information available for this area to answer more questions about the structure and nature of the earth's crust.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. D.H. Hall and Dr. R.J. Brown for their guidance, advice, encouragement and supervision during the course of this study.

Special thanks are given to Mr. O.G. Stephenson for his help in computer programing and processing done this year, and to all the other members of the field crew who worked so hard to collect the data.

I would like to thank the Department of Earth Sciences, the Precambrian Centre and Chevron Standard Limited for their financial support during the course of my studies.

And last but not least, I would like to thank my wife, Sallie, for her understanding, encouragement and help that I needed to complete this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE PAGE

LIST OF TABLES

TABLE PAGE

CHAPTER 1

EVALUATION OF FIELD PROCEDURES

1.1 Introduction:

The Department of Earth Sciences, University of Manitoba has been actively engaged in the study of crustal structure in Manitoba and northwestern Ontario for over a decade. The results have been published in several papers: Hall and Brisbin (1961, 1965), Hall (1964, 1969, 1972), Hajnal (1969, 1970, 1971), Hall and Hajnal (1969, 1973), and Gurbuz (1969, 1970). The primary research method has been refraction seismology including interpretation of wide angle reflections.

The need for the development of a near vertical reflection capability was voiced by Hall and Hajnal (1969) and Wilson (1971). Reasons to believe that the near vertical reflection technique could answer more questions about the structure and nature of the earth's crust have been well documented. Summaries of deep crustal reflections were given by Steinhart and Meyer (1961), Beloussov et al. (1962) and the German Research Group for Explosion Seismology (1964). Other recent results are provided by Robertson (1963), Dix (1965), Khalevin et al. (1966), Kanasewich and Cumming (1965) and Clowes et al. (1968). In response to this need, Hajnal (1970), Homeniuk (1972) and Baer (1972) worked on the development of this method, advancing it to a certain degree.

1.2 Present Project:

The present thesis forms part of a project designed to develop a near vertical reflection technique capable of mapping shallow and deep crustal structure. It must be stressed that the work done this year is developmental in nature and not designed just for mapping a specific structure. However, if this technique is successful, the work done this year will form the starting point for continued exploration of the Aulneau Dome.

The work necessary to achieve this goal can easily be broken up into two distinct areas: 1) Field work, and 2) Lab work. Based on the theoretical and practical experience of the three previous attempts, improvements in both areas are possible and necessary if the end results are to be successful.

1.3 Field Work:

1.3.1 When and where:

The field work was carried out in May 1973 on or near the northeast portion of the Aulneau Dome. Figures 1.1 and 1.2 indicate the area of the survey, and show the locations of the shot point and recording sites occupied this year. Table 1.1 gives the relevant information regarding the exact locations, distances from the shot point, and other related information.

1.3.2 Instrumentation:

The recording equipment was the same unit described by Hall and Hajnal (1969), and Hajnal (1970) with minor modifications to the timing circuits. The time code generator was removed and a filter amplifier called a tone amplifier was added. The tone amplifier was used to amplify and to filter a 475 hertz tone that was received over the radio from the shot point. This tone was then recorded on tape in place of the time code.

The shot point equipment was identical to that described by Hajnal (1970) with the addition of a tone generator called a tone box.

The geophones used were the Hall-Sears, Model H.S.-10-1 seismometers. Eight vertical and four horizontal phones were used.

1.3.3 Shot point procedures:

The shot point was located in an abandoned mine shaft. The shaft had an aperture of approximately 12 by 15 feet, a depth of 100 feet, and contained 25 feet of water when shooting began, dropping to about 8 feet for the last shot.

The explosive agent used was a stable compound designed for underwater detonation called Hydromex. It was purchased in 50-pound cardboard cases containing two plastic bags of Hydromex. Thus, explosive charges of 25, 50 or 75 pounds could easily be used with 25 pounds being the most common.

The procedures used at the shot point stressed safety and efficiency. At a predetermined time, the shaft was loaded with explosives and radio contact was established with the recording crew. At the agreed time, 30 seconds of tone was transmitted over the radio, with the detonation of the charge terminating the tone transmission. Radio contact was again established and the entire cycle was repeated. Multiple shots were fired into each recording location (see Table 1.1 for exact number) with a time interval between shots of fifteen minutes being typical during normal operating conditions.

The exact instant of detonation was also recorded at the shot point if radio communication was poor, by a method documented by Hajnal (1970, page 28).

1.3.4 Recording site procedures:

The spread used consisted of 12 seismometers spaced 220 feet (67.1 meters) apart. Channel 1 was always closest to the shot point. The 1st and 11th seismometers measured the in-line component of horizontal motion. The 2nd and 12th seismometers measured the perpendicular component of horizontal motion, while all other seismometers measured vertical motion. The recording equipment was located in a boat at the center of the spread.

The recording attenuations and frequency settings were recorded in the field book for all shots. However, in general it can be stated that the attenuations were set only high enough to prevent saturation of the system, and the frequency settings were always set at 48 hertz. This allows the maximum amount of information to be recorded.

Once the tone began on the radio, the recording process was started and continued for one minute after the tone cut-off. Regular checks were made of noise conditions and the quality of records obtained, but problems with development of records necessitated doing all playbacks over in the lab.

1.4 Evaluation of Field Procedures:

This year's was the first attempt to take the VLF-2 and tape-recording system away from any roads. The recording equipment was placed in a boat, and all recording locations were chosen along the lake shore. This method extends the amount of freedom available to pick recording sites, but there still exist serious limitations on where the recording spread can be placed. If the cables used allowed end-on recording (all geophones in one direction from the recording equipment) many more locations around the lake shore could be used. However, with such limited mobility, this VLF-2 system is not practical for exploration on the interior of the dome. The new system presently under development by the Physics Department in collaboration with the Precambrian Centre will go a long way towards solving the mobility of recording locations.

The location of the shot point is still the least mobile aspect of this exploration method. Air shots are considered too dangerous in the present study area, if adequate charge sizes are used. Lake shots are generally prohibited by government regulations, and drilling of large enough holes to accommodate adequate charges is too expensive. Mine shafts that contain adequate amounts of water now appear to be the most feasible shot points, but these do not exist in sufficient number in the particular areas of interest to be ideal either. This problem must be solved or circumvented for a study to be feasible.

After solving the problems of where to locate the shot and recording sites, the success of the project depends principally on putting enough energy into the ground in order to get observable reflections. The theory of effective charge weight and the statistical benefits of stacking multiple shots together was documented by Baer (1972). The equation for calculating effective charge weights is

$$W^{2/3} = \sqrt{\frac{t}{r}} \sum_{i=1}^{r} (\mu_i)^{2/3} \qquad (1.1)$$

where W is the effective single charge necessary to achieve the same S:N ratio that could also be achieved by stacking t traces together from r records that were generated by individual charges of μ_i . (See Table 1.1 for effective charge weights for each recording location). In this survey, we have used the largest individual charge weights for near vertical reflection data, used to date by the University of Manitoba, and also increased the number of individual records being stacked. These facts alone give this year's efforts the greatest possibility of success.

As with any seismic survey, the exact determination of shot time relative to the recorded events is critical. The tone break system presently employed by the University of Manitoba is sound in principle, but has certain practical limitations. When radio reception deteriorated, so did the tone break quality. Laboratory examination of the filter response of the tone amplifier showed it to be a relatively poor filter (see Figure 1.3). If the filter were to be improved, the quality of tone break would be improved significantly. The use of better radios would improve this system. The possibility of getting radio antennas higher by the use of balloons should be considered especially since the field work for the present is not near power lines. On the other hand, if the antenna should come in contact with a power line, this would endanger the observers.

Even after considerable effort is put into improving the tone break quality, the need for a back-up system still exists. The equipment described by Hajnal (1970) should be replaced by a magnetic recording of WWV, shot instant and shot generated wave form.

The use of linear arrays as discussed by Homeniuk (1972) was considered, but not employed this year. Linear arrays of adequate length are not available commercially. However, by proper spacing of geophones, the velocity filtering technique could be used to give similar results.

It should be pointed out that the present survey would not, even if successful in yielding recognizable reflections, by itself provide adequate sub-surface data. The major reasons are the wide separation of recording locations and the lack of a reverse profile. However, additional work planned for the next four years should solve this problem.

1.5 Lab Work:

The lab work commenced in July 1973 and continued until the end of the year. The theoretical and practical results obtained in the lab form the basis for the remaining portion of this thesis.

1.6 Sample Calculation of Equivalent Charge Weights:

We had (equation 1.1):

$$W^{2/3} = \sqrt{\frac{t}{r}} \sum_{i=1}^{r} (\mu_i)^{2/3} .$$

We use location 65-9 for the sample calculation. After running the data through the program WTSTACK, $r = 18$, $\mu_i = 25$ pounds for all shots and $t = 1$ because no trace mixing has been done.

$$W^{2/3} = \sqrt{1 \times 18} \quad (25)^{2/3} .$$

$$W = 218.5 \text{ pounds.}$$

After VSTACK, where $t = 8$ because we now mixed eight traces together:

$$W^{2/3} = \sqrt{8 \times 18} \quad (25)^{2/3} .$$

$$W = 1039.25 \text{ pounds.}$$

(See Table 1.1 for all equivalent weights).

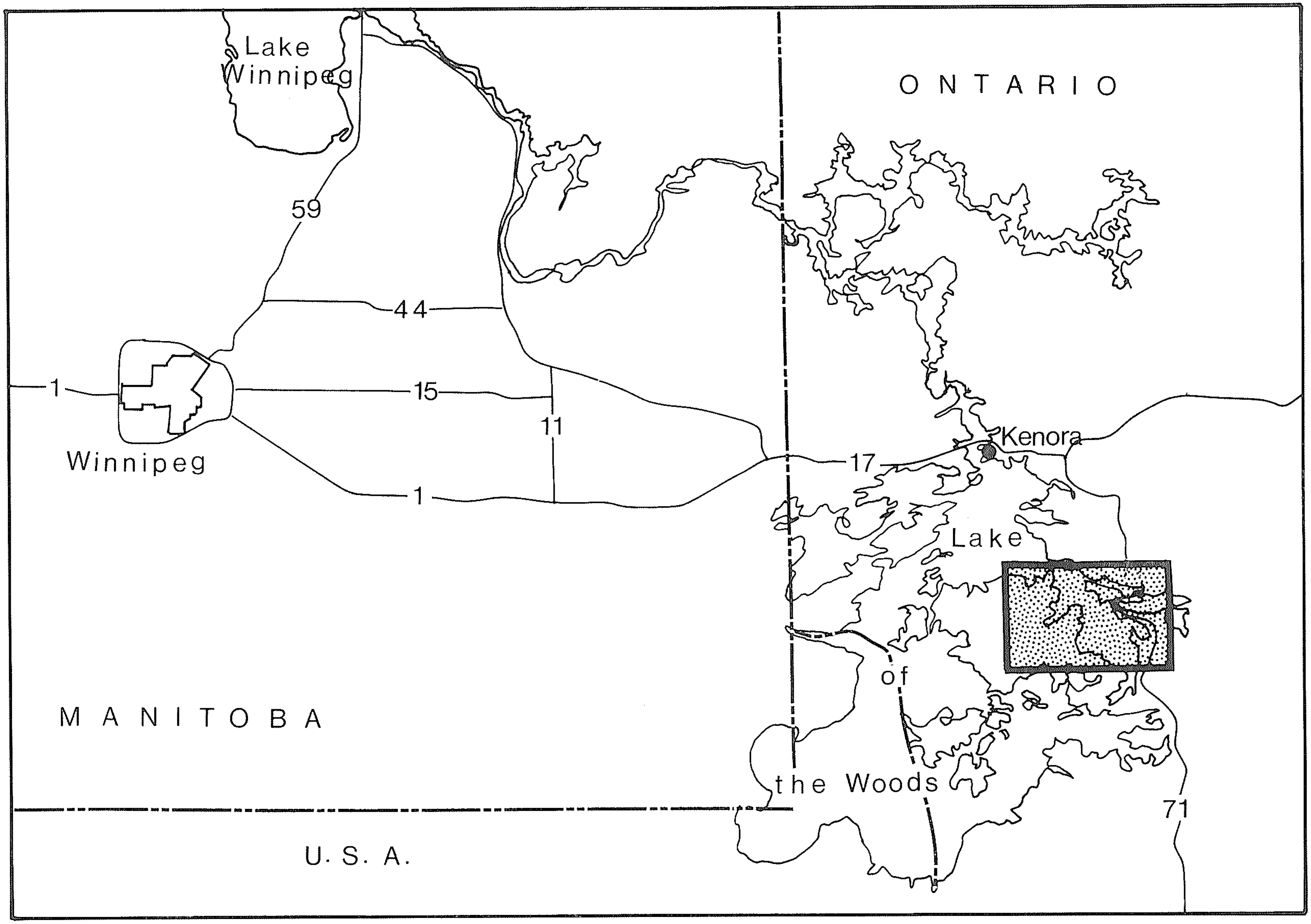

Figure 1.1 Map of Manitoba and northwestern Ontario

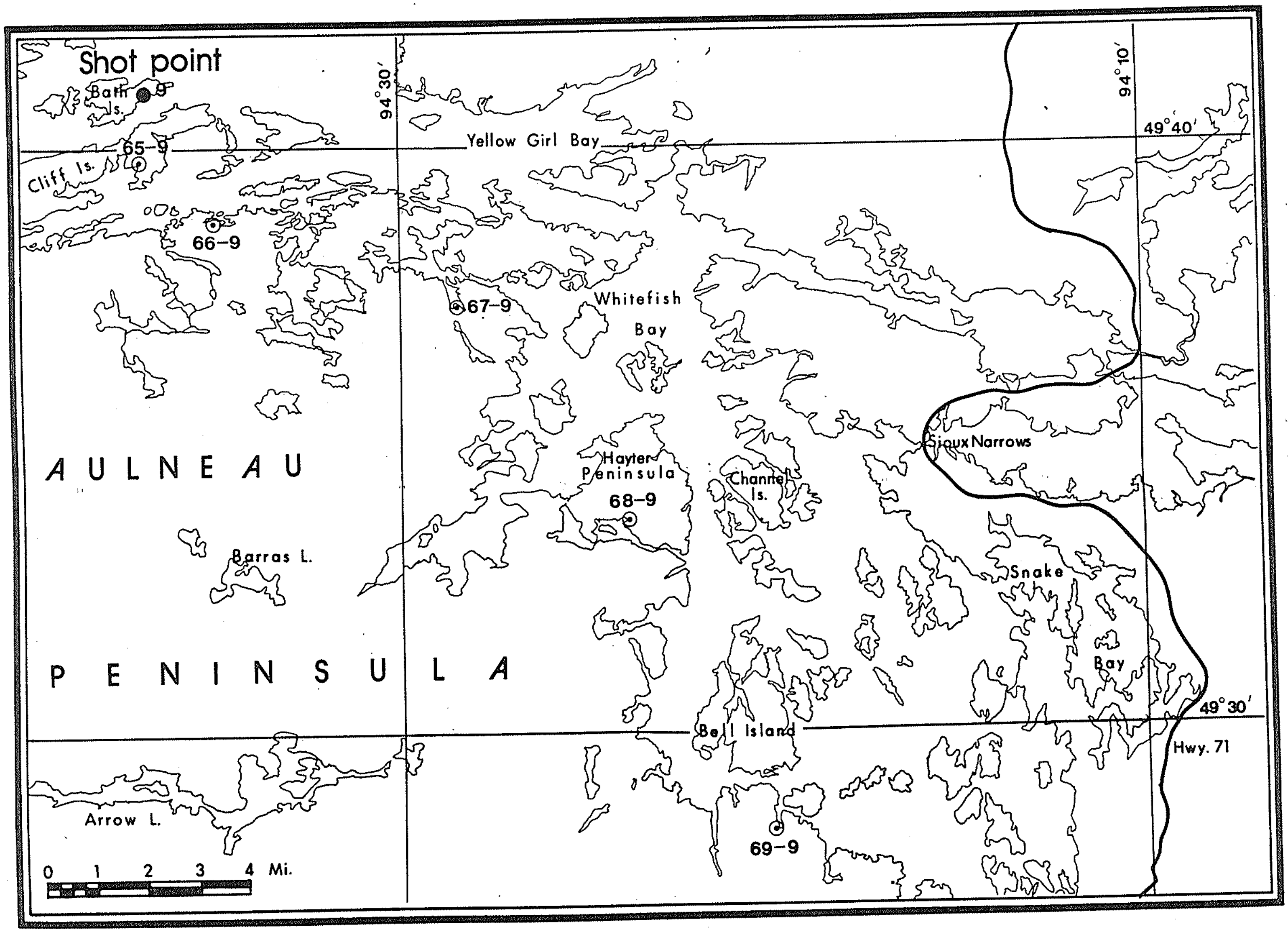

Figure 1.2 Location map of study area

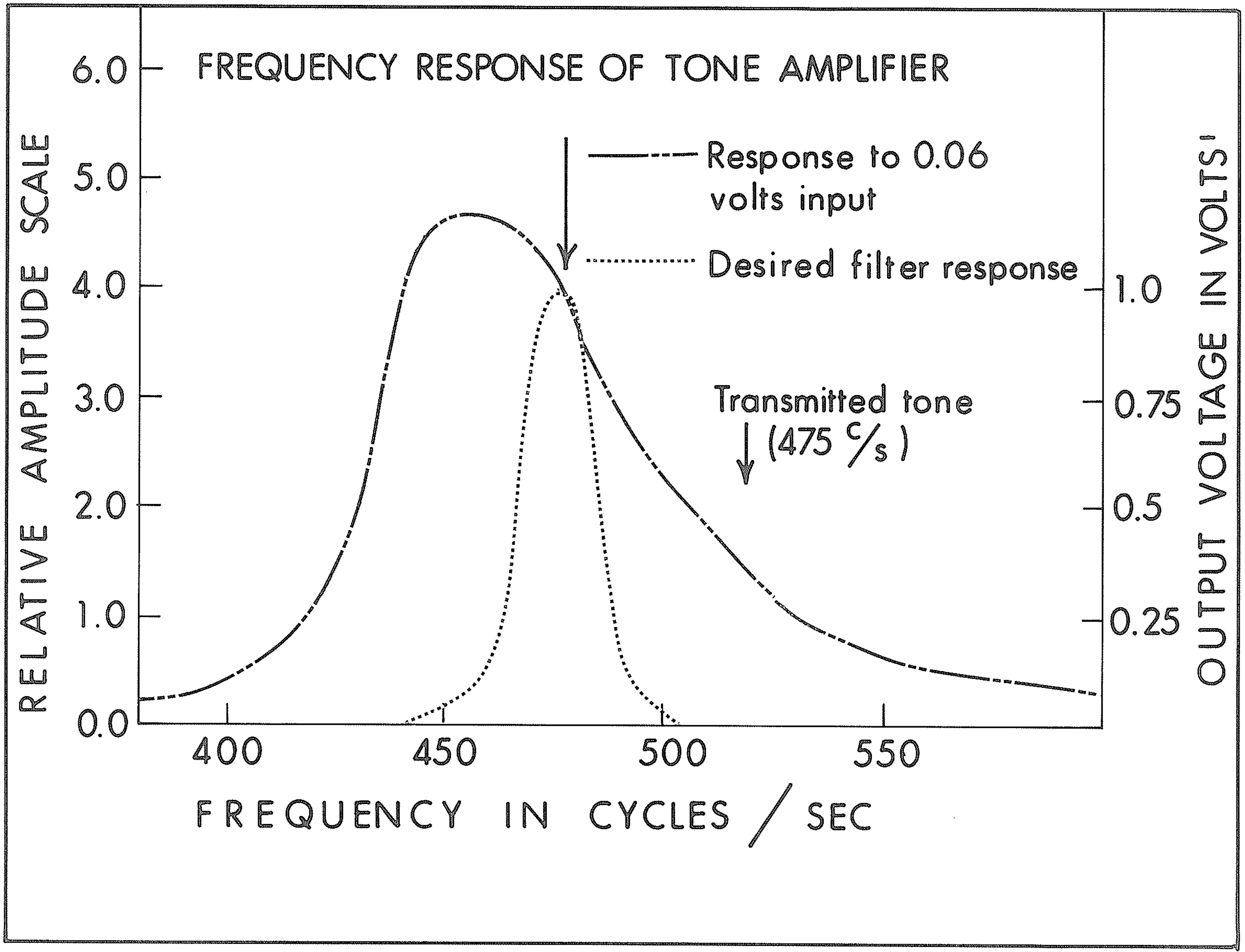

Figure 1.3 Frequency response of tone amplifier

Table 1.1 Table of data regarding shot point and recording locations

Shot Point**	Latitude	Longitude
9	49° 30.93'	94° 26.78'
Recording Location		
65	49° 29.73'	94° 26.88'
66	49° 28.82'	94° 25.17'
67	49° 27.28'	94° 18.53'
68	49° 23.63'	94° 13.92'
69	49° 18.30'	94° 1.10'

Recording Location	Distance from Shot Point 9	No. of Records Stacked	Equivalent Charge Wt. After WTSTACK	Equivalent Charge Wt. After VSTACK
65	2.20 km.	18	218.5 lb.	1039.25 lb.
66	3.81 km.	14	181.0 lb.	861.0 lb.
67	12.04 km.	16	200.0 lb.	951.25 lb.
68	20.50 km.	12	161.25 lb.	767.0 lb.
69	30.93 km.	N.P.*	-	-

*Not processed.

**Shot and recording site numbers follow those of Hall and Hajnal (1973).

CHAPTER 2

STATISTICALLY OPTIMAL STACKING OF SEISMIC DATA

2.1 Introduction

The process of stacking seismic traces together in order to improve the S:N (signal to noise) ratio has been used with varying success for years. Mayne (1962, 1967) and Galbraith and Wiggins (1968) reported success in common depth point stacking techniques applied in the petroleum industry. Whitcomb (1969), Hajnal (1970, 1971), Capon (1972), Baer (1972), Homeniuk (1972), Kanasewich et al. (1973) all used a stacking procedure as a velocity filter in order to improve the S:N ratio of events with specific moveout velocities. Baer (1972) and Homeniuk (1972) also vertically stacked multiple shots with common shot and geophone coordinates.

The theoretical results of stacking n traces together is a $\sqrt{n}$ improvement in the S:N amplitude ratio as documented by Baer (1972). In most cases, the first attempts at stacking traces were based on at least two general assumptions about the input data: 1) the signal amplitudes on all traces being stacked were approximately equal, and 2) the signal to noise amplitude ratios were approximately constant on all traces. Individual traces were assumed to have these characteristics or were normalized in such a way as to impose a relatively consistent amplitude to all input traces (Hajnal, 1970; Baer, 1972).

However, upon closer examination of input data, it is found that these two assumptions are in general, not perfectly valid. Indeed, cases exist in our present data where these assumptions are grossly invalid. Capon et al. (1967), Christoffersson and Jansson (1967) and Robinson (1970) all worked on ways of computing weighting factors to apply to various traces that violate these two assumptions, in order to optimize the output S:N ratio of a stacking procedure.

Since the data recorded in May 1973 by the Department of Earth Sciences, University of Manitoba, was found not to conform to the above-mentioned assumptions, a stacking program (WTSTACK) incorporating weighting factors calculated according to the theory put forward by Robinson (1970) was written. This method allows the stacking of traces with variable signal amplitudes and variable S:N ratio--features which are present in this data. This theory also allows us to calculate the theoretical S:N ratio of the stacked record. (See Appendix A.)

It is interesting to note that when this theory is applied to the sum of n traces that do conform to the above mentioned assumptions, the results are consistent with those predicted by Baer (1972).

2.2 Theoretical Optimum Weighting Factors:

The first step must be the development of a mathematical model of a seismic trace and some criteria on which to evaluate the effectiveness of the stacking procedure.

The model seismic trace presented has a signal and a noise component. The signals are assumed to be identical, with the exception of scale, on all traces that are to be stacked together. The noise on any given trace has zero mean value and is assumed to be statistically independent of the noise on any other trace. The signal and noise components are also statistically independent of each other on all traces. The signal to noise ratio is reasonably constant for each individual trace (at least over the time extent of the windows used). The last requirement put on the seismic trace is that the noise level is constant with respect to time on any individual trace.

The mathematical expression for the j th sample of the i th trace is

$$t_{ij} = a_i(s_j + n_{ij}) \tag{2.1}$$

where a_i is signal amplitude factor of i th trace.

s_j is signal component for the j th sample which is identical on all traces.

n_{ij} is noise component which is in general different for each individual trace and sample.

Also define J as the number of samples in a seismic trace, and I as the number of records to be stacked.

The signal energy (S), noise energy (N_i) and total energy (T_i) of the ith trace are defined as:

$$S \equiv \sum_{j=1}^{J} s_j^2 ; \tag{2.2}$$

$$N_i \equiv \sum_{j=1}^{J} n_{ij}^2 ; \tag{2.3}$$

$$T_i \equiv \sum_{j=1}^{J} t_{ij}^{2} . \tag{2.4}$$

A unique signal to noise power ratio can be defined as:

$$\gamma_i = \frac{S}{N_i} . \tag{2.5}$$

The objective is to determine weighting factors (w_i) to be applied to the i th trace such that the signal to noise energy ratio of the output trace will be a maximum.

In the case of a twofold stack, the weighting factors are determined as follows:

$$t_j^{(2)} = t_{1j} + w_2 t_{2j} . \tag{2.6}$$

Arbitrarily we have set $w_1 = 1$ and $a_1 = 1$. Substituting equation 2.1 in 2.6 and collecting signal terms gives

$$\begin{aligned} t_j^{(2)} &= (1 + a_2 w_2) s_j + n_{1j} + a_2 w_2 n_{2j} \\ &= s_j^{(2)} + n_j^{(2)} . \end{aligned} \tag{2.7}$$

The signal energy of the stacked trace is

$$\begin{aligned} S^{(2)} &= (1 + w_2 a_2)^2 \sum_{j=1}^{J} s_j^{2} \\ &= (1 + w_2 a_2)^2 S . \end{aligned} \tag{2.8}$$

The noise energy of the stacked trace is

$$N^{(2)} = \sum_{j=1}^{J} \left(n_{1j} + a_2 w_2 n_{2j} \right)^2 \tag{2.9}$$

$$= J\,\overline{(n_1 + w_2 a_2 n_2)^2} . \tag{2.10}$$

where the bar indicates mean value for J samples. However, because n_1 and n_2 are statistically independent and have zero mean value, we obtain for the noise energy of the stacked trace

$$N^{(2)} = N_1 + (w_2 a_2)^2 N_2 . \tag{2.11}$$

(See Lee, 1960, equation 5.82.)

By substituting equation 2.8 and 2.11 into equation 2.5, we find the signal to noise energy or power ratio as

$$\gamma^{(2)} = \frac{(1 + w_2 a_2)^2 S}{N_1 + (w_2 a_2)^2 N_2} . \tag{2.12}$$

By setting $\dfrac{\partial \gamma^{(2)}}{\partial w_2} = 0$ and solving for w_2, we find that

a) $$w_2 = -\frac{1}{a_2} \tag{2.13}$$

or

b) $$w_2 = \frac{N_1}{a_2 N_2} . \tag{2.14}$$

Clearly solution a) minimizes the signal to noise power ratio and solution b) maximizes the power ratio.

Thus the twofold optimum stack becomes

$$\left\{ t_j^{(2)} \right\}_{opt} = t_{1j} + \frac{N_1}{a_2 N_2} t_{2j} . \tag{2.15}$$

The output can be normalized to any value by multiplying $\left\{ t_j^{(2)} \right\}_{opt}$ by some constant. At this time it is convenient to choose S/N_1 as such a constant. As a result

$$\left\{t_j^{(2)}\right\}_{opt} = \frac{S}{N_1} t_{1j} + \frac{S}{a_2 N_2} t_{2j}$$

$$= \frac{\gamma_1}{a_1} t_{1j} + \frac{\gamma_2}{a_2} t_{2j} \, . \tag{2.16}$$

Recall that $a_1 = 1$.

Stated in words: the optimum stack is effected by first equalizing the scale factors on each trace, then weighting the resulting traces with their respective signal to noise energy ratios, and finally, stacking the traces together.

If we substitute equation 2.14 into equation 2.12 we find that

$$\gamma^{(2)} = \gamma_1 + \gamma_2 \, . \tag{2.17}$$

Thus the optimum signal to noise power ratio of the stacked trace is equal to the sum of the individual signal to noise power ratios.

By an iterative method using $\left\{t_j^{(2)}\right\}_{opt}$ in the place of t_{1j} we can extend this procedure to the sum of I traces.

$$\left\{t_j^{(I)}\right\}_{opt} = \frac{1}{C} \sum_{i=1}^{I} \left(\frac{\gamma_i}{a_i}\right) t_{ij} \tag{2.18}$$

where C is a normalizing factor.

Also we find that

$$\left\{\gamma^{(I)}\right\}_{opt} = \sum_{i=1}^{I} \gamma_i \, . \tag{2.19}$$

Thus if we can, by some method, measure γ_i and a_i for all our input traces, we can determine

$$\omega_i = \frac{\gamma_i}{a_i} \tag{2.20}$$

and we can also estimate the expected signal to noise power ratio of the stacked trace.

2.3 <u>Practical Calculation of Weighting Factors</u>:

In order to calculate the weighting factors for each trace, we first must calculate the power of the seismic trace in two windows. The first window is selected before the first-break energy. In this we will measure the noise energy level (T_i') of the ith trace. Under our assumption that the noise level is constant with respect to time over the entire trace, the noise level measured in the first window is representative of the noise level over the entire trace. The total energy in the first window (just noise) is then

$$T_i' = \sum_{j=1}^{J} t_{ij}^2 = \sum_{j=1}^{J} (a_i n_{ij})^2 = a_i^2 N_i . \tag{2.21}$$

The second window is centered over a strong arrival. The signal to noise power ratio in this window will represent γ_i for this trace. Clearly changing the position of the second window will change γ_i . However, it is the relative magnitude of each γ_i which is of importance in designing weighting factors and not the actual magnitudes. The total energy in the second window (T_i) on the i th trace is

$$T_i = \sum_{j=1}^{J} \left\{ a_i (s_j + n_{ij}) \right\}^2$$

$$= a_i^2 J \overline{(s_j + n_{ij})^2} \quad .$$

(2.22)

By the same argument that was used to derive equation 2.11, we claim that

$$T_i = a_i^2 (S + N_i) . \qquad (2.23)$$

Up to this point, both windows have been J samples long. In practice, WTSTACK divides both T_i' and T_i by the number of samples in the first and second windows respectively. As a result, the windows are not restricted to being of equal length.

We now have enough information to calculate the signal to noise power ratio of this trace.

$$\gamma_i = \frac{S}{N_i} = \frac{T_i - T_i'}{T_i'} . \qquad (2.24)$$

By looking at the signal energies of the different traces relative to trace 1 we can calculate the scaling factor a_i as

$$a_i = \left\{ \frac{T_i - T_i'}{T_1 - T_1'} \right\}^{1/2} . \qquad (2.25)$$

The quantities T_i' and T_i are measured directly from the input data for all traces. We could proceed to substitute equations 2.24 and 2.25 into 2.20 and directly calculate the appropriate weighting factors. Or we can look at the overall expression for ω_i and simplify it slightly.

$$\omega_i = \frac{\gamma_i}{a_i} = \frac{T_i - T_i'}{T_i'} \cdot \left\{ \frac{T_1 - T_1'}{T_i - T_i'} \right\}^{1/2} . \qquad (2.26)$$

We can multiply these weights by any constant we desire in order to normalize the output trace. The constant we use is $k/\sqrt{T_1 - T_1'}$ where k is determined in such a way that

$$\sum_{i=1}^{I} w_i = 10 , \qquad (2.27)$$

This is done to ensure that the maximum amplitude of the output record is always less than 20470. Thus the final form of the weighting factors used by the subroutine WEIGHT is

$$w_i = \frac{k\sqrt{T_i - T_i'}}{T_i'} . \qquad (2.28)$$

(see Appendix A.)

2.4 Evaluation of Weighted Stacking:

The evaluation of weighted stacking will be approached in two ways. Method 1 will be a direct comparison of the output of STACKER and WTSTACK. Method 2 will be based on statistical measurements performed on the input and output data.

The data recorded at location 67-9 is considered typical. This is the center location of the five recording locations for the 1973 field season and is at the intermediate distance of 12.04 km. from the shot point. The number of records going into the stack (16) was only one more than the average of fifteen. The performance of STACKER and WTSTACK on all the different locations is adequately represented by 67-9.

Method 1:

The relevant data appear in Figures 2.1 and 2.2. Each plot consists of 2.15 sec. of data. Figure 2.1 is the result of sixteen input records stacked by STACKER. Figure 2.2 shows the identical input records stacked by WTSTACK. Neither record has had any further processing except that each trace is normalized by PLOTMOD so that the first-break amplitude is ½ inch. Thus the relative amplitudes of the data, trace to trace and also record to record, give a comparative indication of the output signal to noise amplitude ratios.

For all traces, it becomes obvious from looking at this comparison that WTSTACK has done a much better job than STACKER.

Method 2:

Although WTSTACK did a superior job to STACKER, some measure of how well WTSTACK approaches its theoretical potential is also desirable.

In order to do this evaluation, we may use the subroutine WEIGHT to measure the signal to noise amplitude ratios of the data. Figure 2.3 is a plot of the S:N amplitude ratios of all the individual traces recorded at location 67-9. Also plotted is the average S:N amplitude ratio. By using equation 2.10 we calculate the expected S:N amplitude ratio that WTSTACK would produce. This is also plotted in Figure 2.3 along with the actual S:N amplitude ratios of WTSTACK and STACKER. By using the expected S:N amplitude ratio as the optimum output, we can calculate the percentage efficiency of WTSTACK and STACKER. This is plotted in Figure 2.4.

By studying these two graphs and the two plots, a number of interesting points appear:

1) By comparing Figures 2.1 and 2.2 with Figure 2.3 we can see that the statistical method for measuring S:N amplitude ratio does give a consistent picture of data quality, i.e.: the best trace from Figure 2.2 is also the best in Figure 2.3. This adds some degree of confidence to the method of measuring γ_i .

2) The very large variation in S:N amplitude ratios of the input data stands out. This is in fact the main justification for using a weighted stack.

3) Some of the individual traces have a very high S:N amplitude ratio. In general, these traces have an extremely low background noise level measured before the first breaks. This low noise level is not usually representative of the noise over the entire record. For this reason, these traces are not consistent with the model seismic trace as specified in Section 2.2. Improvements in measuring S:N ratios would help here.

4) Figure 2.3 clearly shows the benefits of WTSTACK over STACKER. This is firm evidence that we are moving in the right direction, but it also indicates that some overall improvement in the theoretical or practical aspects are needed to bring estimated and actual S:N amplitude ratios closer together.

5) Figure 2.4 indicates the relative efficiencies of WTSTACK at $55\pm17\%$ and STACKER at $24\pm17\%$. These levels of efficiency are typical of all locations.

6) The short-fall in actual WTSTACK output S:N ratio must be attri-

buted to the degree to which our model seismic trace does not fit our data or to errors in estimating γ_i and a_i from our data. The 5% of the individual traces that have individual S:N ratios higher than the output trace indicate that the theory does in fact, not apply exactly. However, the S:N ratio on STACKER output was below the S:N ratio on 32% of the input traces.

2.5 Conclusions:

WTSTACK represents a considerable step forward over previously used methods in the processing of multiple shot data.

New and, hopefully, better ways should be found of evaluating γ_i and a_i from the input data.

Other theoretical methods of optimizing the stacking procedure should be looked into in the future.

2.6 General Comment:

The algorithm used by WTSTACK attempts to maximize the S:N power ratio. Inherent in this method is a definition of signal energy. Signal energy is considered to be all shot-generated energy measured at the recording location and includes such arrivals as Rayleigh waves. It will be left to other means than stacking multiple shots to enhance reflections with respect to surface waves or other types of shot-generated noise.

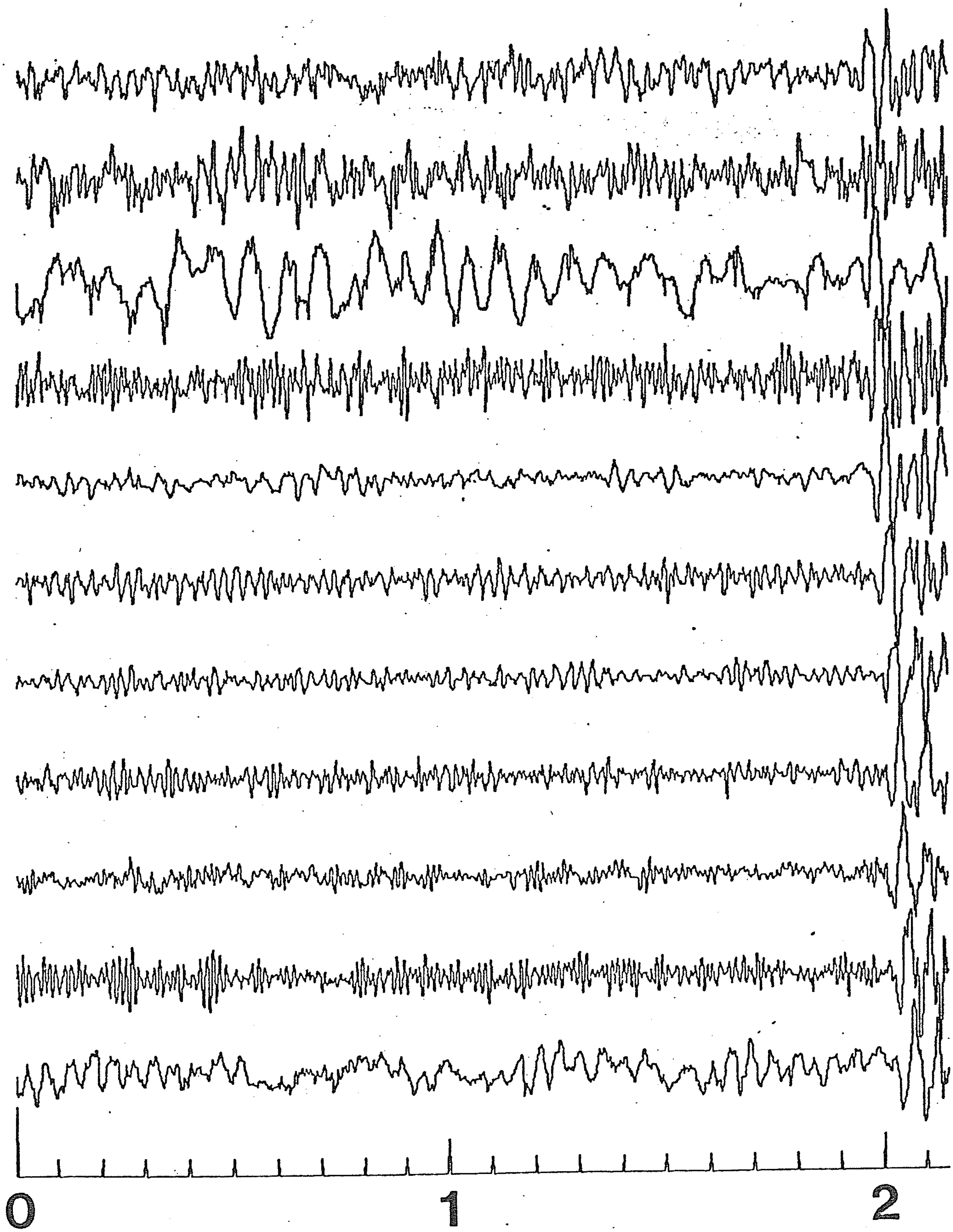

Figure 2.1 67-9 after STACKER (2.15 sec.)

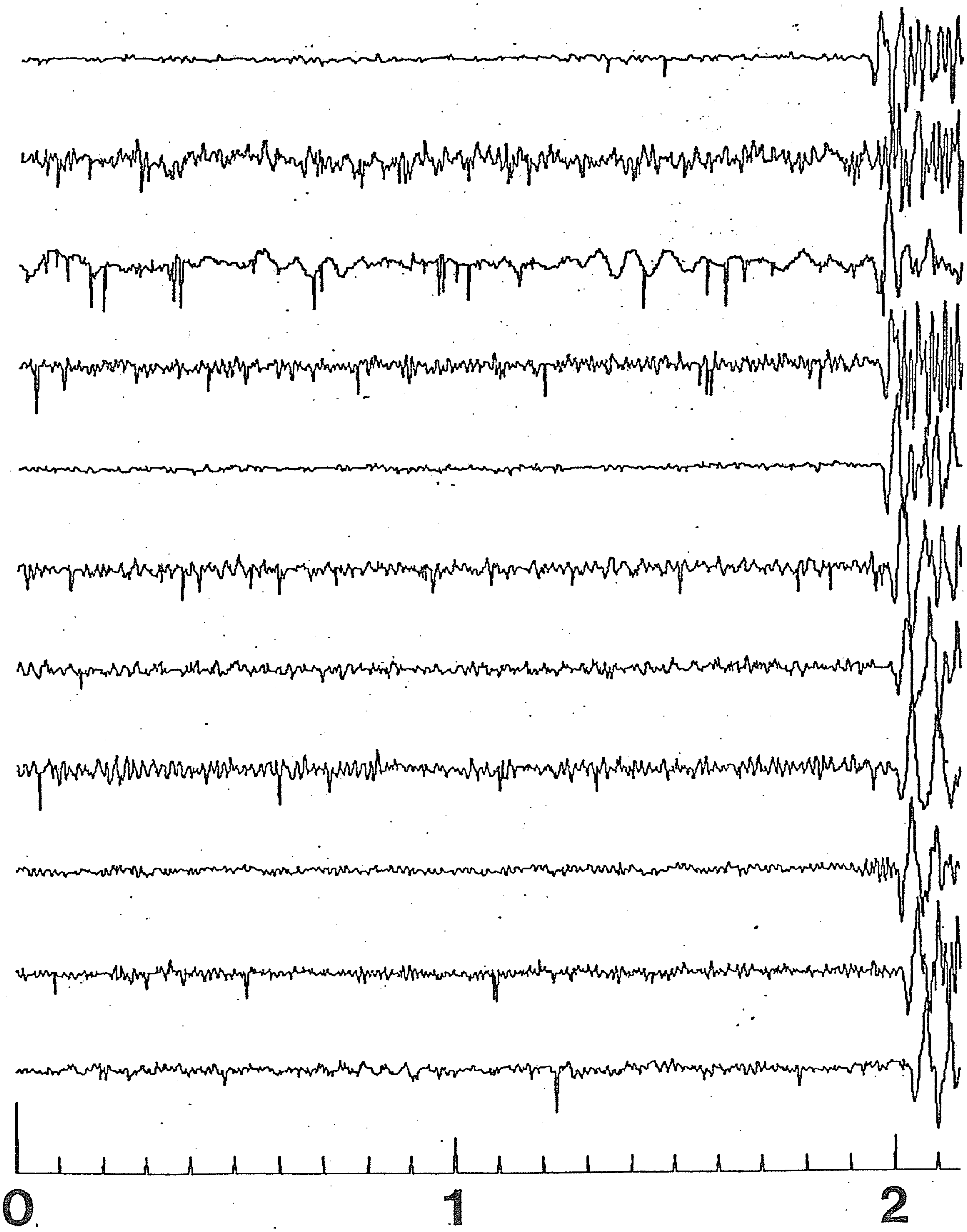

Figure 2.2 67-9 after WTSTACK (2.15 sec.)

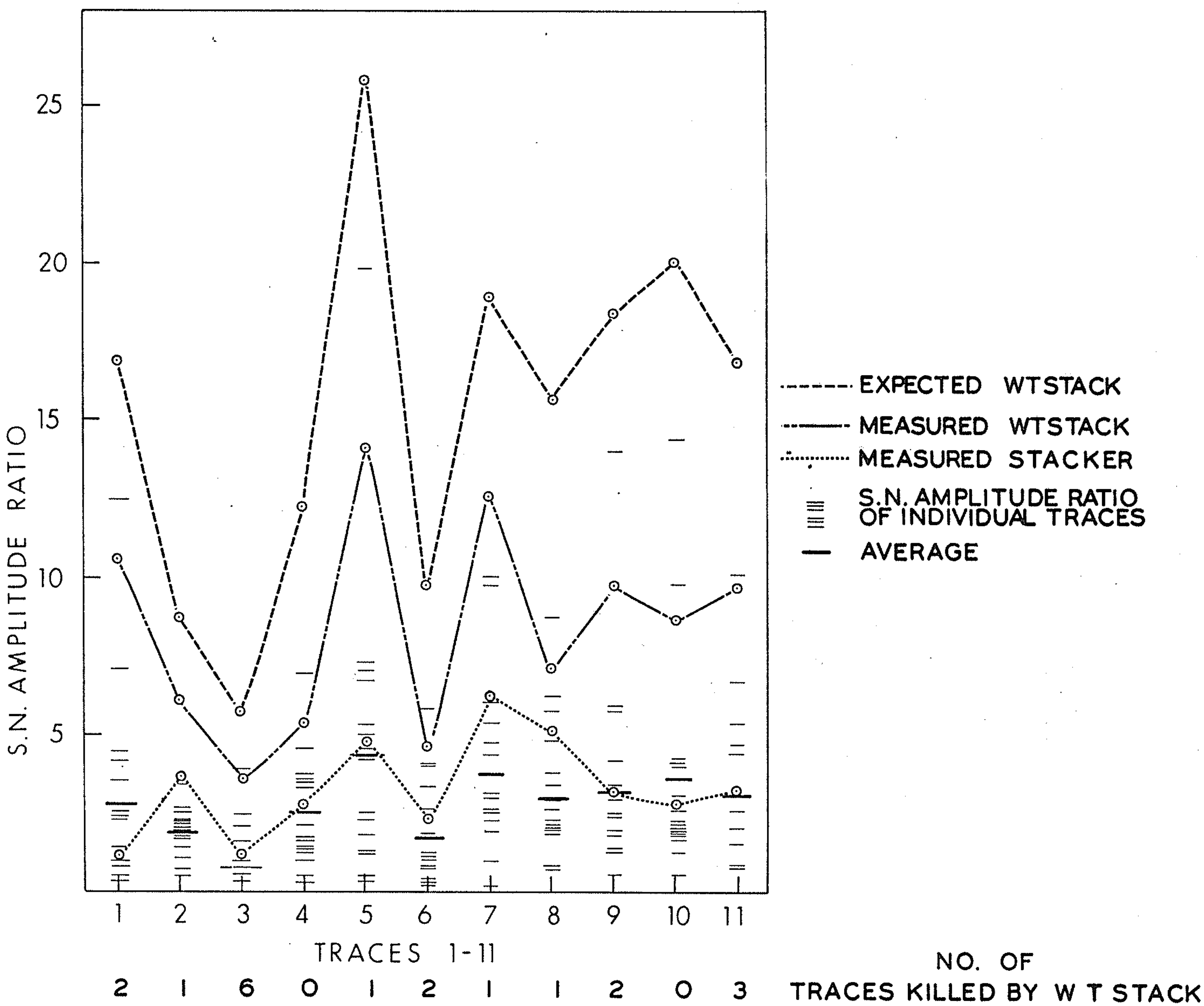

Figure 2.3 Plot of S:N amplitude ratios

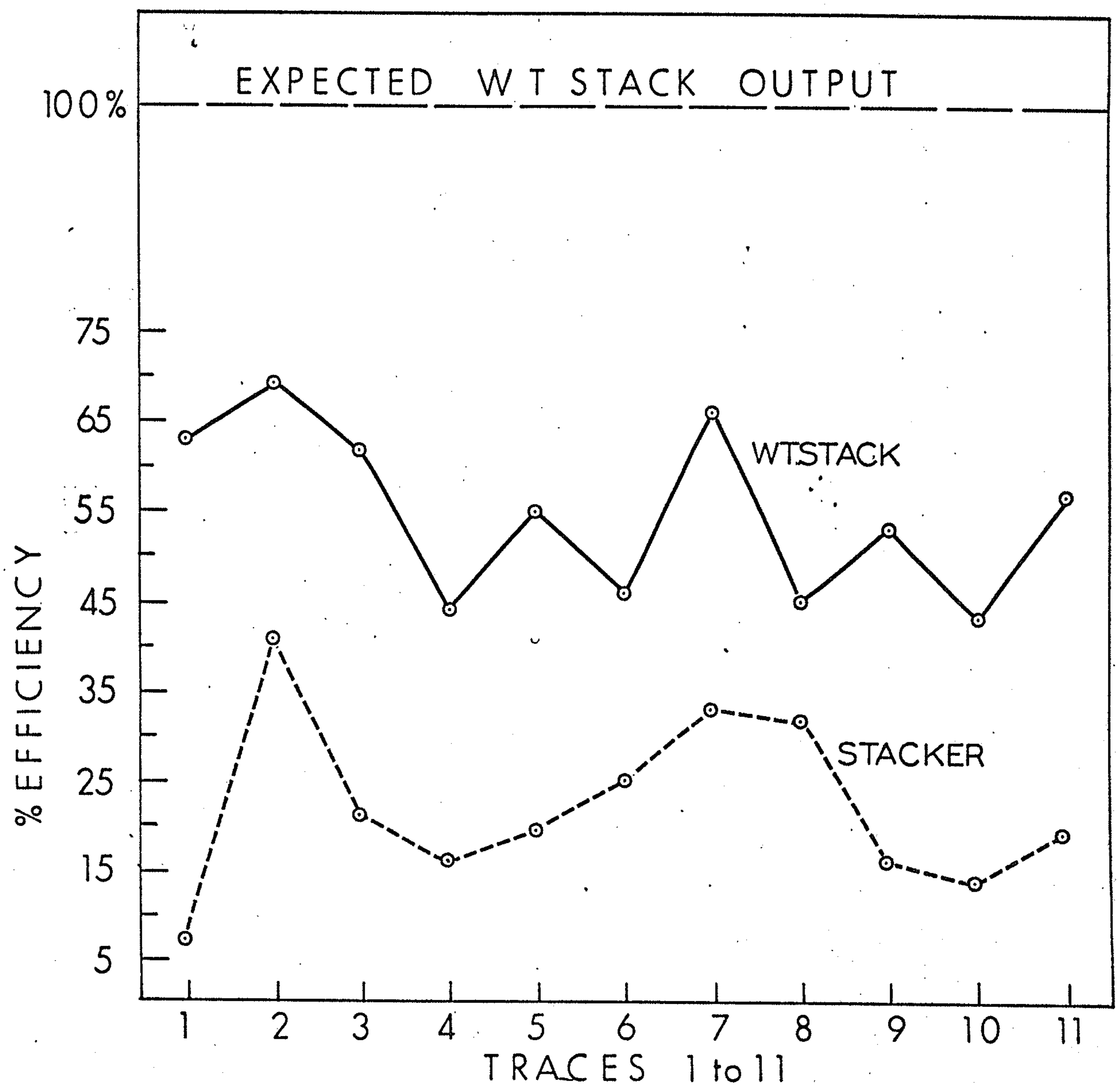

Figure 2.4 Plot of % efficiency of WTSTACK and STACKER

CHAPTER 3

EVALUATION OF PROCESSING ABILITY, PAST AND PRESENT

3.1 Introduction:

A considerable amount of time, energy, and money was spent this year on seismic data processing. The solutions of problems that arose and some initial concepts on how data should be processed formed the basis of a processing philosophy. The more important aspects of this philosophy and the evolutionary history of the programs developed this year constitute an important segment in the development of the near vertical reflection technique as an exploration and research tool on the Canadian Shield.

3.2 Processing Philosophy:

The processing philosophy developed for the handling of seismic data can best be described by stating it in six propositions, as follows:

1) Exact shot time must be present on BINBIN's (see Section 3.3.1) output tape. This information is absolutely essential in poor quality data in order to allow stacking to be used.

2) All programs after BINBIN should maintain absolute timing information on the output tapes, i.e. the first sample of the output should represent zero time. Exact timing information can then be plotted on output displays simply by counting samples.

3) Careful manipulation of the integer data values is essential if a significant amount of information is not to be lost.

4) Each program should print out as much information about the data as possible.

5) Processing efficiency should be reviewed regularly.

6) Critical studies should be made on the quality of data out of each processing step. Program deficiencies, poor parameter selection and input errors will not necessarily stop execution and eliminate the output from the various programs. When the output was not up to expected standards, it was often due to some unsolved problems.

These propositions are to be upheld at all stages and in all programs used in the processing sequence if possible. They outline technical requirements that have to be built into every program as well as outlining methods that should be used in processing data.

3.3 Program Evolution:

The programs used this year fall into five main categories: 1) Utility programs, 2) Stacking programs, 3) Filtering programs, 4) Gain adjustment programs, and 5) Velocity filtering programs. Significant programing changes were made in all these areas.

3.3.1 Utility programs:

The principal program in this area was BINBIN, as documented by Hajnal (1970). Its main function was to perform a data conversion from a 7 to a 9 track tape. The program was written in COBAL and is very difficult to modify, because of a general lack of familiarity with this language at the present time. Serious attempts were made, although unsuccessful, to modify BINBIN so that 13 channels could be processed. (The tone channel was processed in channel 12, making it necessary to omit one seismic trace.) BINBIN's strongest point is its efficiency, and because of this consideration, no attempts were made to completely replace it.

However, as of December 15, 1973, BINBIN ceases to be of use, because of changes in the computer facilities at the University of Manitoba. The exact form of its replacement is not yet certain.

Another utility program, READER, was written to perform the printout operations in place of BINBIN. It is efficient and allows much greater freedom in choosing exactly what blocks should be printed.

PLOTMOD is another utility program used extensively. This program will produce a calcomp plot of a seismic record from a 9 track tape. This program now counts output samples and plots timing marks in place of channel 12.

3.3.2 Stacking programs:

The evolution of the programs that perform the stacking operation has to be considered the greatest single area of improvement. The program that existed, COSPS (or VERTS) as documented by Baer (1972), was modified in several minor ways to make the output consistent with proposition 2. Some changes in read formats made it slightly more efficient. The program STACKER was written as a more efficient substitute. It performed exactly the same operations as COSPS with the exception of normalizing the output traces. The signal to noise amplitude ratios of input and output data were measured by a routine that later evolved to become WEIGHT.

The wide variation in signal to noise amplitude ratios, and the poor performance of STACKER provided the incentive for evaluating the benefits of weighted stacking. The result was WTSTACK which was not only a theoretical improvement, but was more efficient time-wise and did a much better job of handling the integer data.

A more complete write-up of the theory of weighted stacking and a critical evaluation of WTSTACK is found in Chapter 2. The actual production data is in Chapter 4, while the program listing and additional comments can be found in Appendix A.

3.3.3 Filtering programs:

The program that existed was CONVOLV as documented by Hajnal (1970). Attempts were made to make this program conform to the concept of absolute time, but this proved infeasible. The program was modified to include in its output the timing error it introduced. Allowances for this error could be made in PLOTMOD so that the output record would have proper timing information plotted in place of channel 12. CONVOLV's efficiency was questionable and certain round-off errors in the algorithm indicated improvements could be made in the overall processing system if CONVOLV was replaced.

FILTER was written to do the frequency filtering process, and was used to produce all data displays where filtering had taken place.

3.3.4 Gain adjustment programs:

The problem of large amplitude surface waves (Rayleigh waves) has not been dealt with yet. Geophone arrays were not used in the field and the result is evident in Figure 4.9. PLOTMOD normalized each trace such that the maximum amplitude is ½ inch. The result is that reflections, that are arriving after Rayleigh waves have passed, are plotted at a scale so small that they cannot be seen. Some method of balancing the relative amplitudes of the trace with time and yet still maintain wave forms is considered necessary. McClure (1973) used a method of normalizing data over different windows on a single trace to balance the amplitudes of different events. This was tried in the present study with limited success and other methods were considered.

The method finally adopted is similar to that used in the petroleum industry in the past. The resulting program written to achieve this gain adjustment was AGC. The theory and algorithm used are explained in Appendix B. The data processed through this program is displayed in Figures 4.13 and 4.14.

3.3.5 Velocity filtering programs:

STACK was the previously existing velocity filtering program written by Hajnal (1970). It was working, but modifications desired in the output posed more of a problem than writing a new program (VSTACK).

VSTACK incorporates all the advantages and efficiency that the processing experience to date has taught us. The output of VSTACK is a series of traces (up to 8) each with a different Δt shift applied to data before stacking. The traces are all normalized to a constant value and plotted versus the time of the event on trace 6 of input data.

The data processed by this program are displayed in Chapter 4.

3.4 Evaluation of Processing Capability:

It can be seen that the present processing capability of the University of Manitoba is the result of a continuous evolutionary process in which programs are used, critically assessed, modified and/or replaced. This process has been going on for five years now, and must continue if the maximum amount of information is to be extracted from the data.

The introduction of weighted stacking, improvements in frequency filtering techniques, the automatic gain control (AGC) program, and the new display after velocity filtering, have added much to the processing capability of the University of Manitoba. However, it is premature to claim that the better processing is the principal reason for the significant improvement in data quality obtained this year. The larger effective charges used this year have also helped.

In order to evaluate better the overall improvements in the processing ability, it is recommended that the data collected by Baer (1972) and Homeniuk (1972) be processed according to the revised models.

CHAPTER 4

FINAL PROCESSING MIX

4.1 Introduction:

The final processing mix is outlined in Figure 4.1. This procedure for processing near vertical reflection data yields what appears to be acceptable records. These steps and the final data displays will be explained in this chapter.

4.2 Analog to Digital Conversion:

The conversion process was carried out exactly as described by Gurbuz (1969) and Hajnal (1970) with one modification. The tone channel was digitized on channel 12 in place of the seismic trace. This was done because of limitations in BINBIN and because of the importance of having exact shot time information.

4.3 BINBIN, READER:

All digitized tapes were processed through BINBIN with the 12th channel being the tone break. READER was used to print out the appropriate blocks from each record. The block and sample where the tone cut off is picked at this stage, and is used to program WTSTACK. Record quality was checked at this stage by first plotting a selected number of records output from BINBIN, then by filtering and plotting these records, thus giving a direct comparison to the analog playback records. These records should be identical.

4.4 WTSTACK:

All the records were then processed through WTSTACK thus reducing 60 individual records to 4 stacked records. Record 68-9 is plotted in Figure 4.2 and is representative in both character and quality to the other three locations. The top trace represents the first geophone and the bottom seismic trace represents the 11th geophone. The 12th trace now represents time and is graduated in tenths of seconds with the second marks being larger.

4.5 FILTER:

4.5.1 Tests:

In order to decide on the optimum bandpass filter to use on the stacked records, filter tests were performed on all stacked records. The operators used for these tests, 179 points in length, allowed a 10-hertz wide bandpass of frequencies centered on 5, 15, 25, and 35 hertz. Figure 4.3 indicates the amplitude responses of these operators with the 20-30 bandpass being identical in shape to the 10-20 and 30-40 filter operators. The filter slices for 67-9 are displayed in Figures 4.4 to 4.7.

Filter slices of frequencies up to 100 hertz were evaluated for location 65-9 and although large amounts of energy are present in the high frequencies, these frequencies do not improve the S:N amplitude ratio of any "events" when included in the final filtered record.

4.5.2 Final filtered records:

The final filter chosen for locations 65-9 and 66-9 was a 5-25 bandpass while locations 67-9 and 68-9 were filtered with a 2-25 bandpass. Figure 4.8 indicates the amplitude response of these two filters. Because of the wider bandpass used here than in the filter tests, the operator length was shortened to 99 points. The filtered records are displayed in Figures 4.9 to 4.12.

These records have a higher equivalent charge weight (see Table 1.1) than the individual records and the improvement in data quality is evident.

4.6 AGC:

Only records 65-9 and 66-9 were processed through AGC. An operator length of 1 second was used in both cases and the results are plotted in Figure 4.13 and Figure 4.14. It is important to note the variable noise level before the first breaks on record 66-9 (Figure 4.14) and to realize this can also happen later in the record. For this reason, the decision was made to process both the AGC records and the non-AGC records for location 65-9 and 66-9 through VSTACK.

4.7 VSTACK:

The output displays from VSTACK (Figures 4.15 to 4.19) are different from the other plots. Each output trace now represents the sum of eight vertical seismometer traces. A different time shift has been applied for each output trace in order to enhance events with specific apparent horizontal velocities. These velocities can be determined by this equation:

$$V = (d \cos \theta)/\{\delta t(I-1)\}. \tag{4.1}$$

where V is apparent horizontal velocity, d is the geophone separation, θ is the acute angle between the recording spread and the line of sight to the shot point, δt is the sampling interval and I is the trace number counting from the top of VSTACK display. The relative amplitudes of events, trace to trace, are retained in this display. The time of the event on VSTACK output will agree with the time of the same event on trace 6 of the input record. By looking at the input record at this time, and considering the specific velocity filtered, it is easy to line up the exact portions of each event that have been summed together. Figures 4.15 to 4.19 contain the VSTACK output for all 4 locations.

4.8 Summary:

The programs in this processing mix give the University of Manitoba the processing capability to extract detailed information from near vertical reflection data. Each and every program is essential and performs a function critical to the ultimate success of the processing.

The data presented in this chapter is now part of the data file of the Department of Earth Sciences, University of Manitoba. This data will be used along with more data that will be collected in the future to gain additional information about the structure and nature of the earth's crust. The resulting interpretations will be published at a later date.

4.9 Additional Processing Possibilities:

The only additional processing planned at present is to modify VSTACK to perform an Nth root velocity stack as explained by Kanasewich et al. (1973). This should aid in the selection of possible events.

All the output data of previous processing steps has been retained on 9 track magnetic tape so that additional processing may be done at any time in the future. This will depend on new or better programs being developed to extract more information from the data.

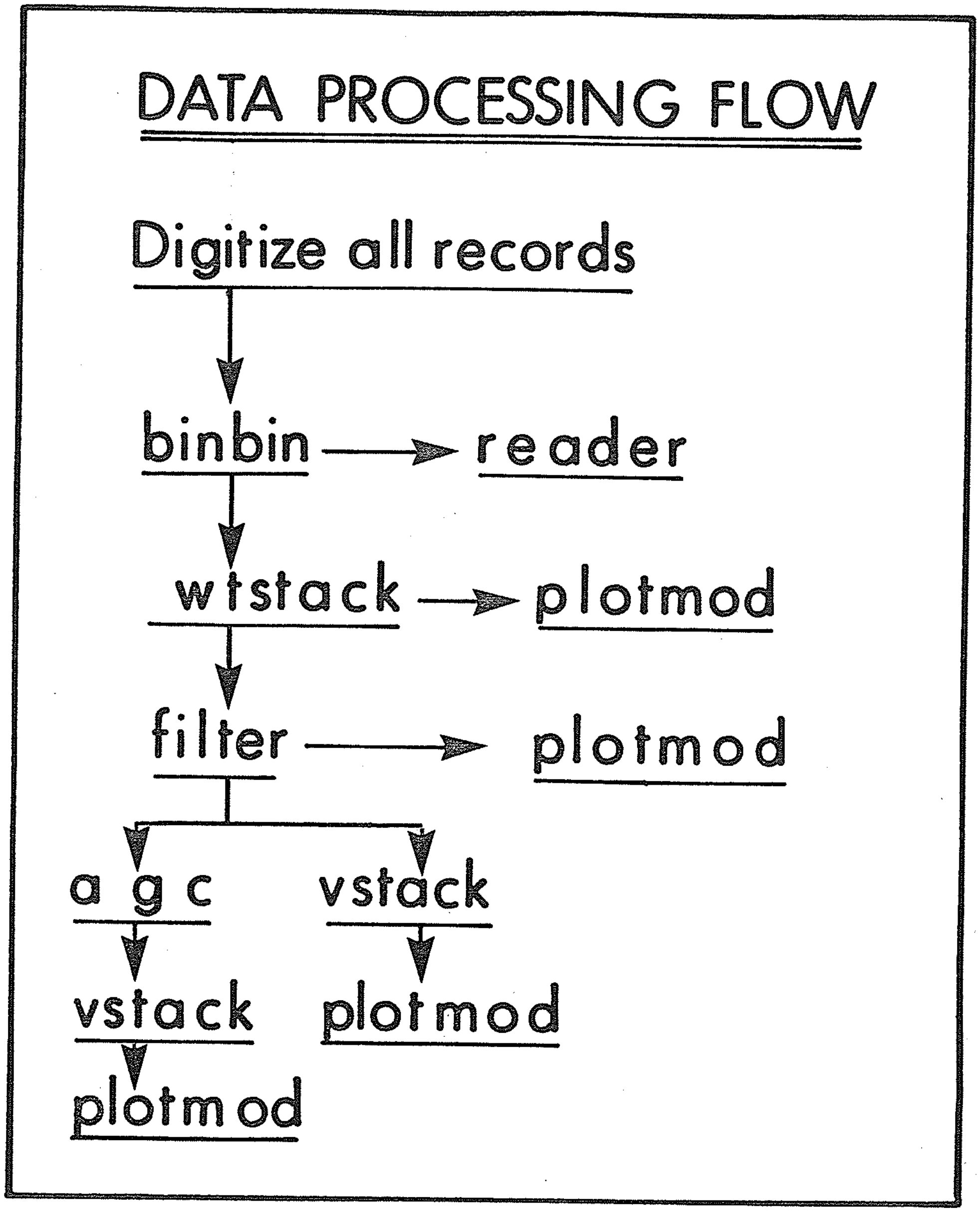

Figure 4.1 Flow chart of data processing

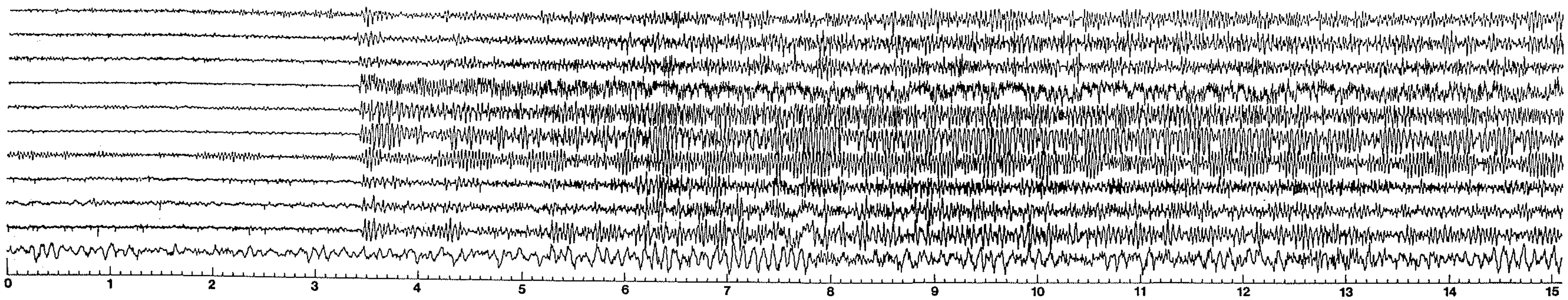

Figure 4.2 68-9 after WTSTACK (15 sec.)

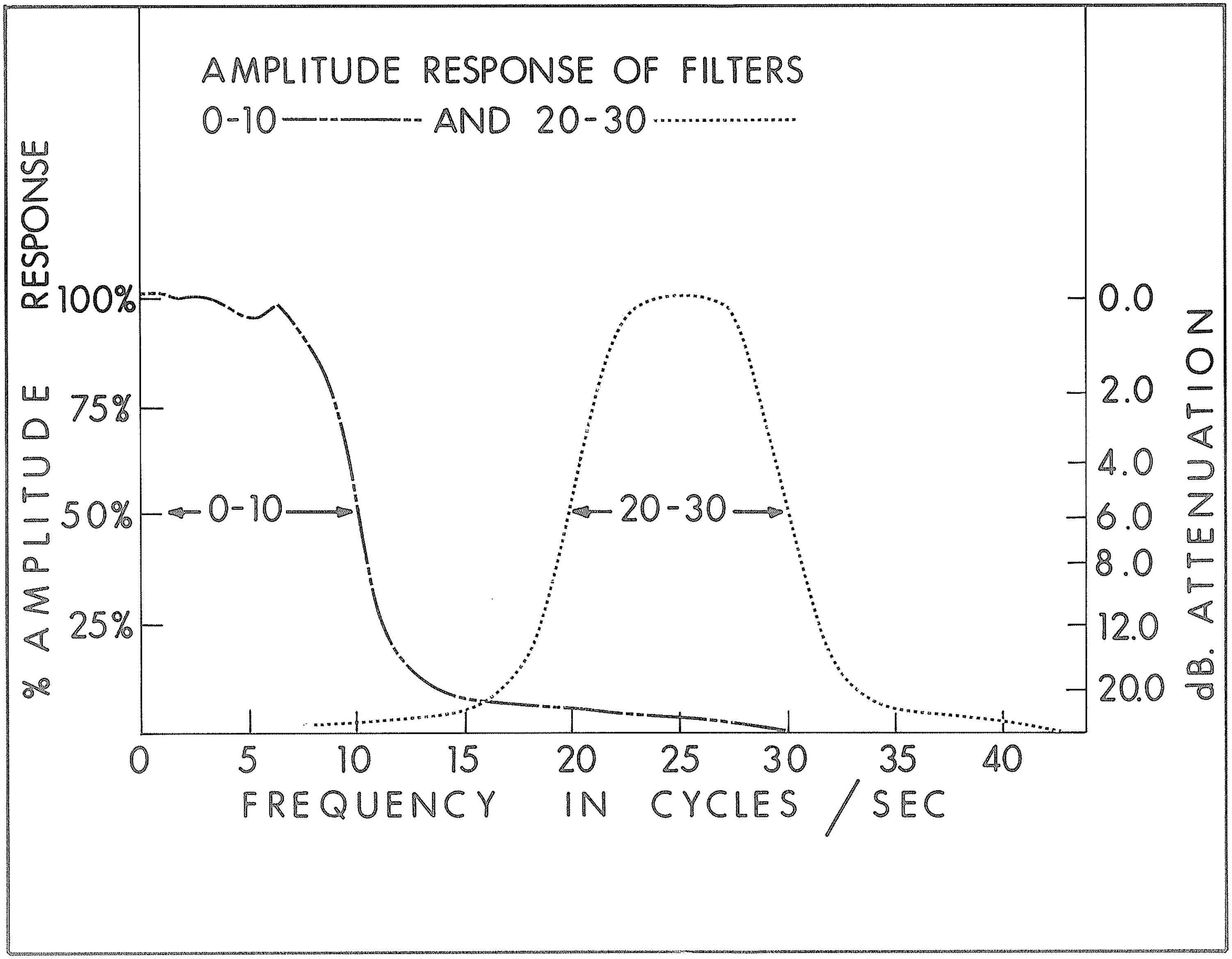

Figure 4.3 Amplitude response of filter test operators

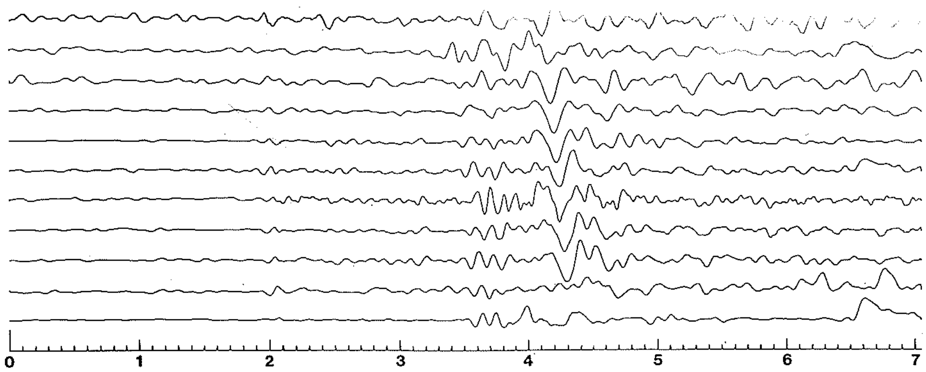

Figure 4.4   67-9 after FILTER (0-10)

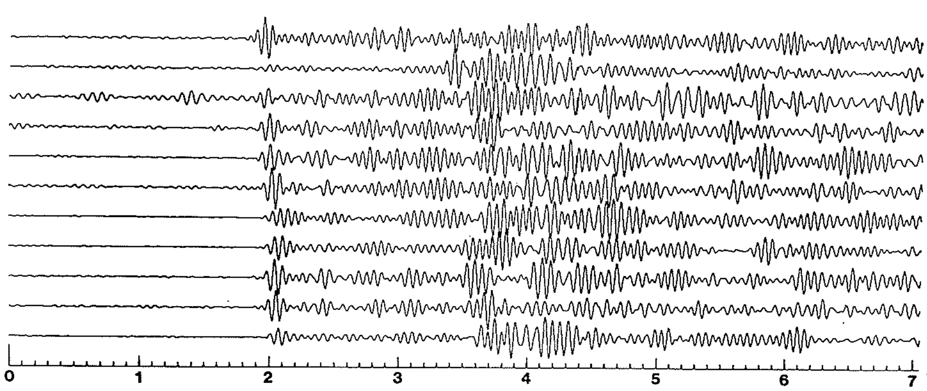

Figure 4.5   67-9 after FILTER (10-20)

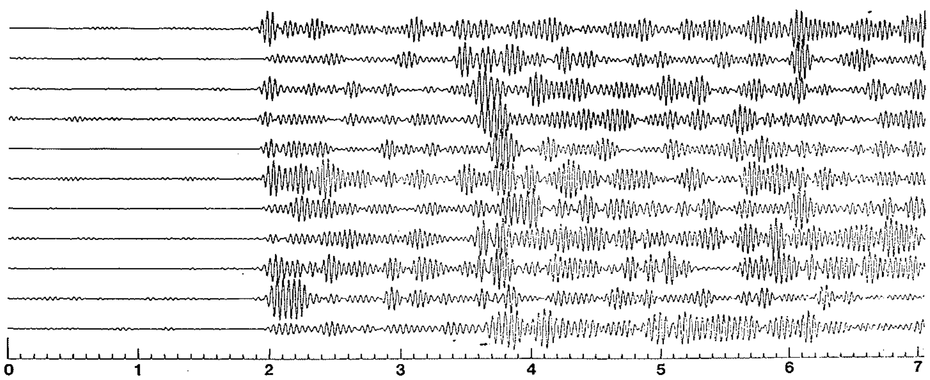

Figure 4.6 67-9 after FILTER (20-30)

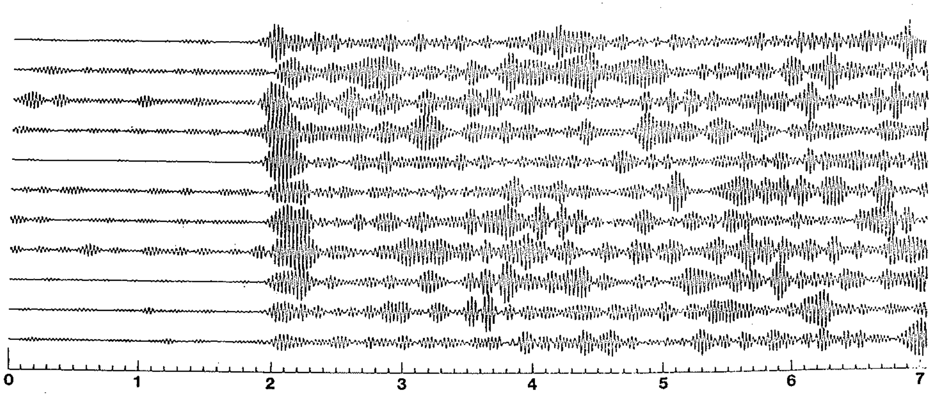

Figure 4.7 67-9 after FILTER (30-40)

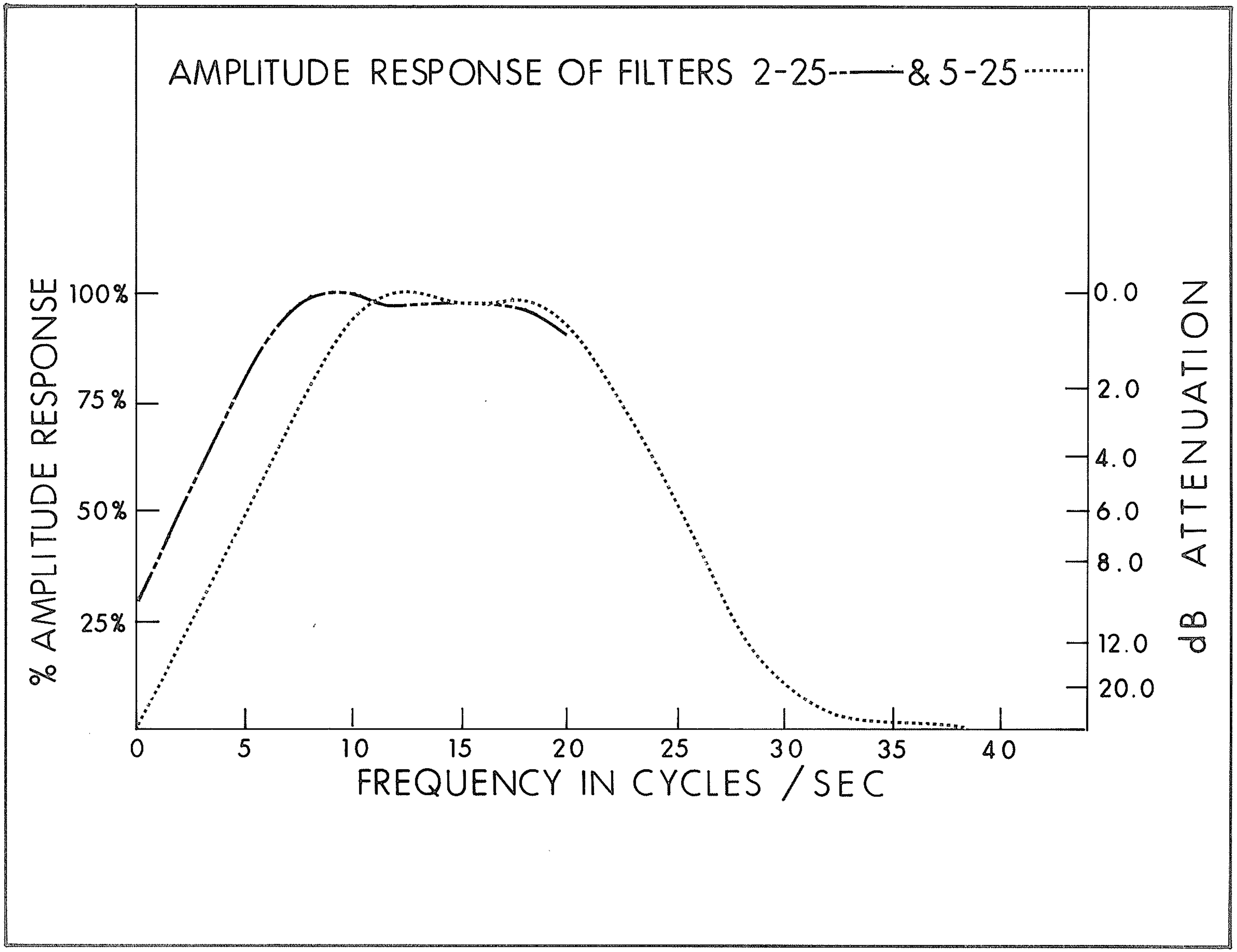

Figure 4.8 Amplitude response of final filters

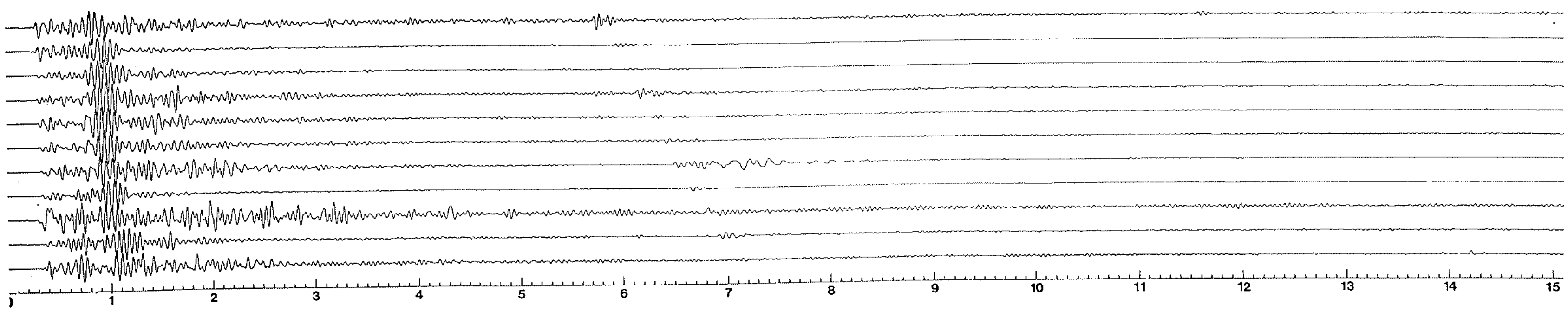

Figure 4.9   65-9 after FILTER (5-25)

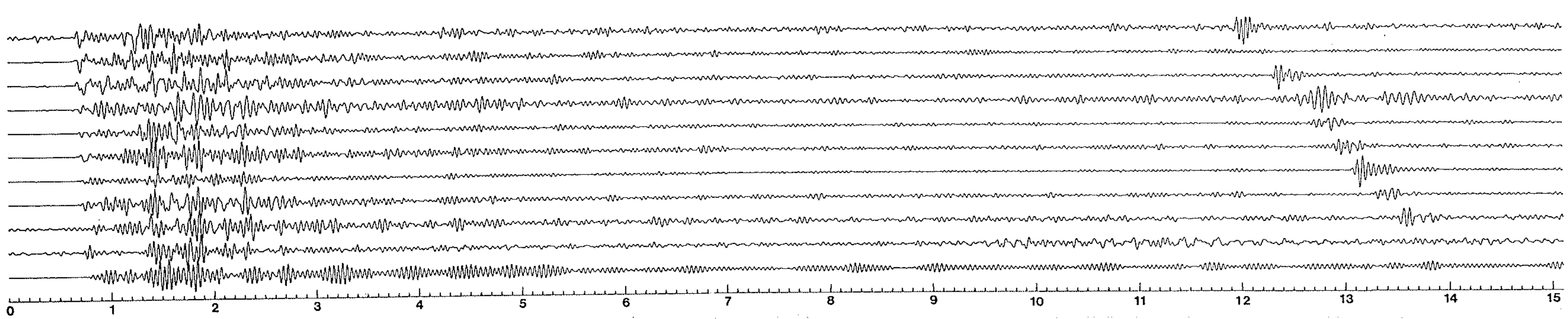

Figure 4.10   66-9 after FILTER (5-25)

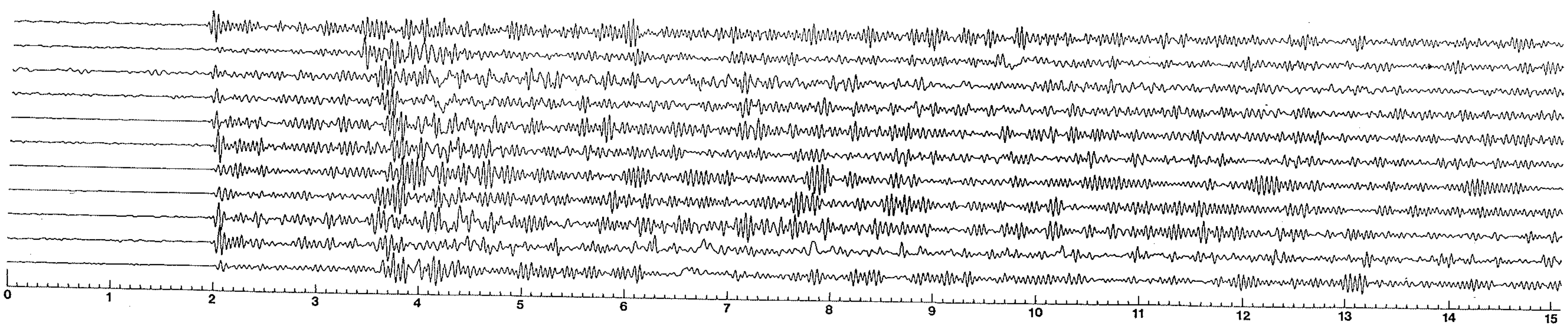

Figure 4.11   67-9 after FILTER (2-25)

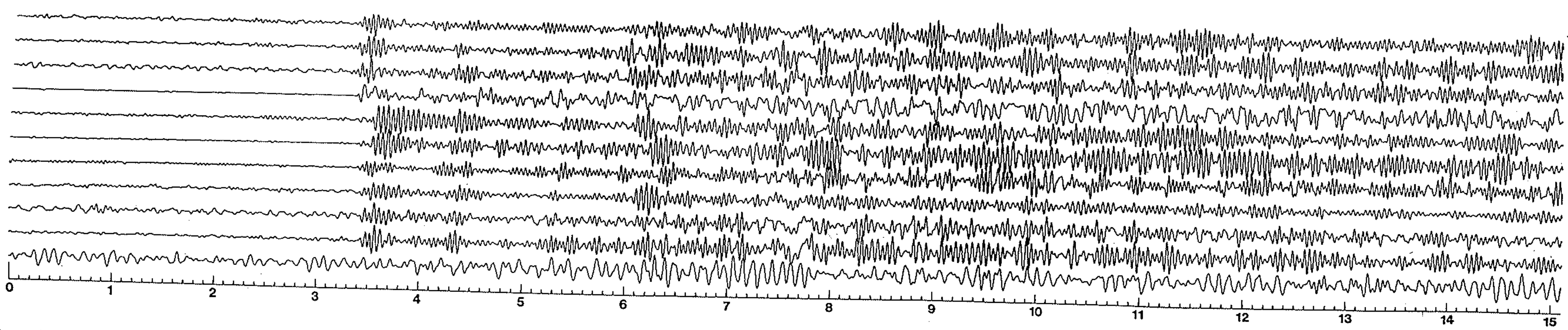

Figure 4.12   68-9 after FILTER (2-25)

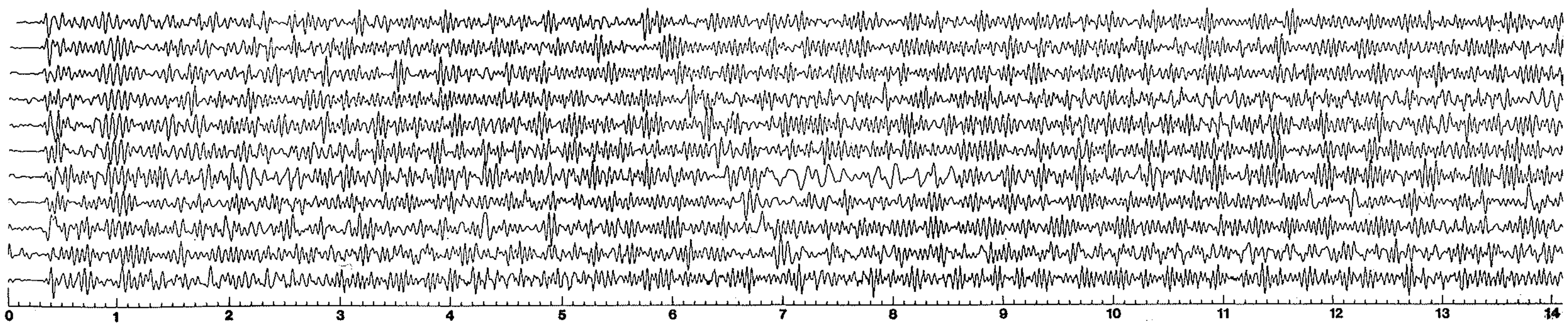

Figure 4.13   65-9 after AGC

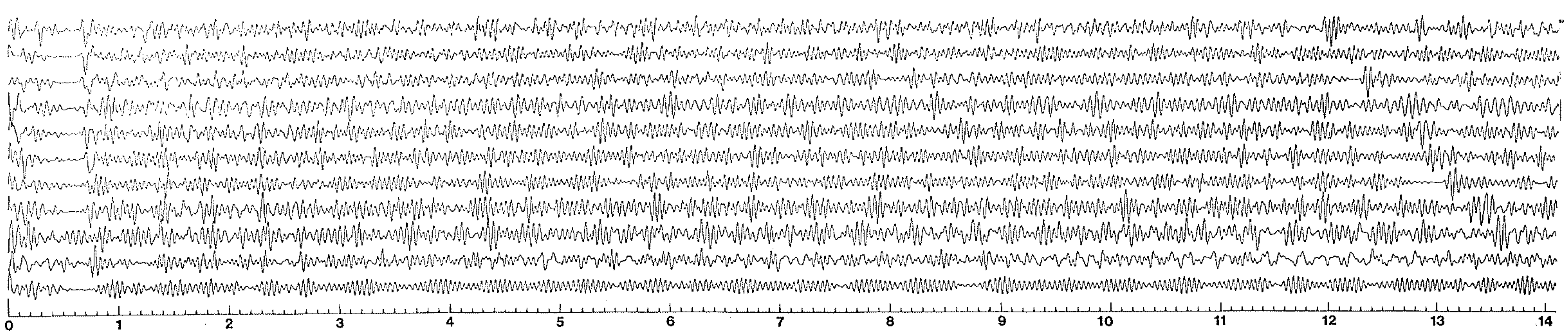

Figure 4.14   66-9 after AGC

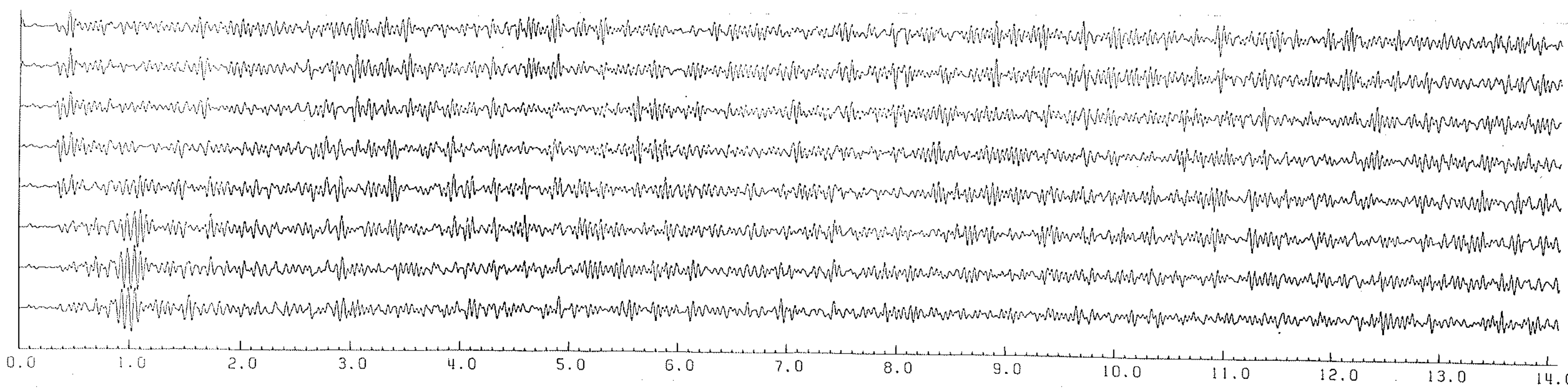

Figure 4.15 65-9 VSTACK after AGC

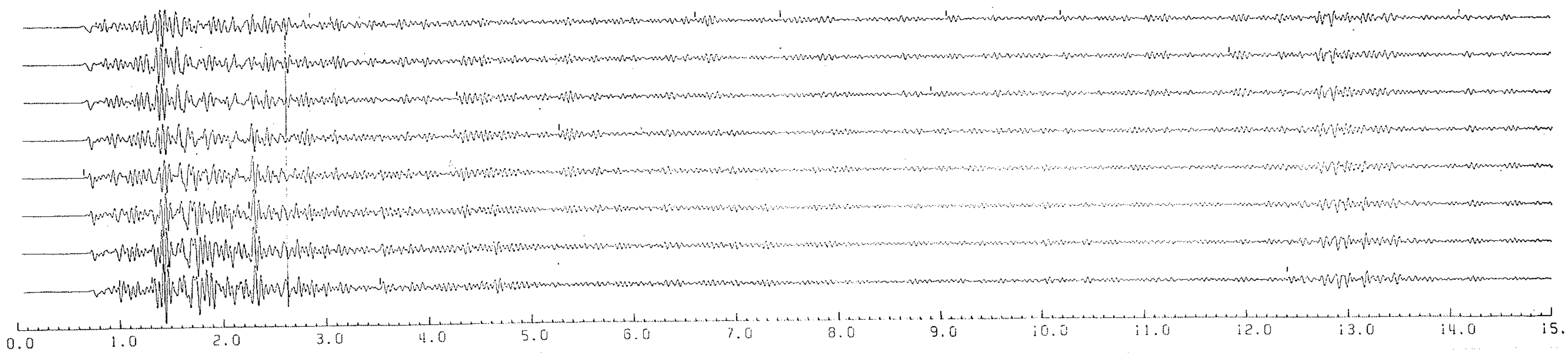

Figure 4.16 66-9 VSTACK after FILTER

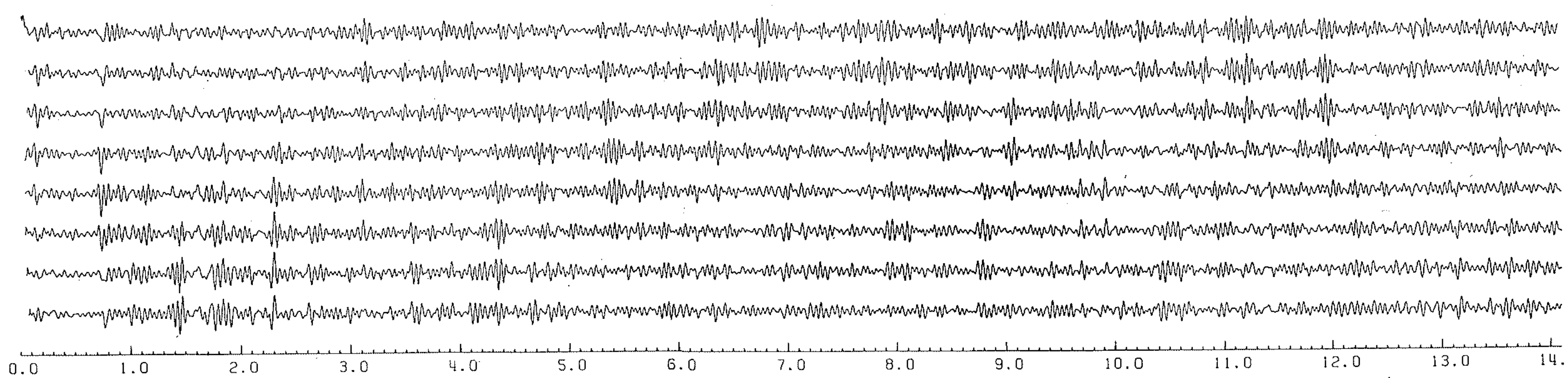

Figure 4.17 66-9 VSTACK after AGC

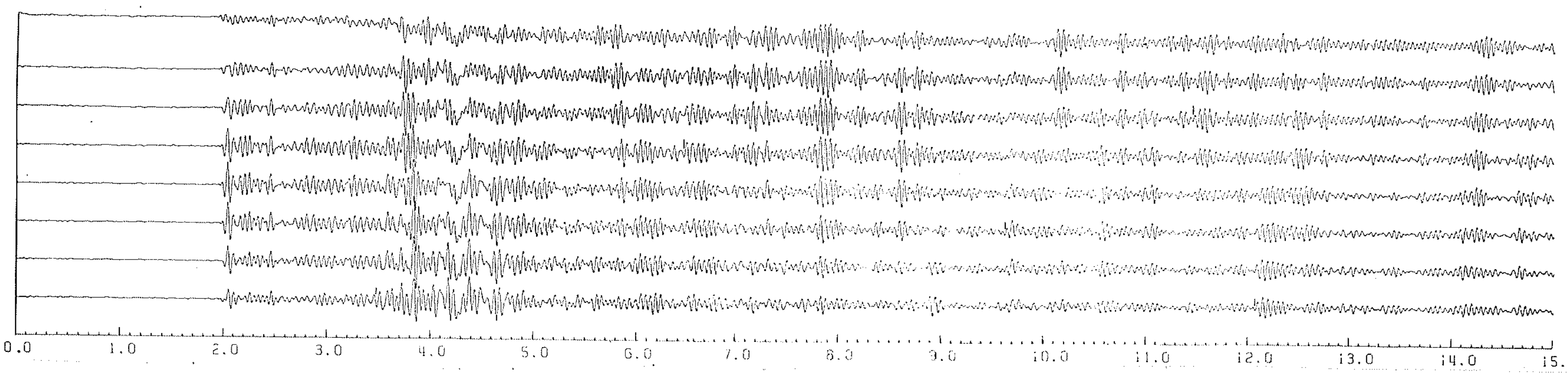

Figure 4.18 67-9 VSTACK after FILTER

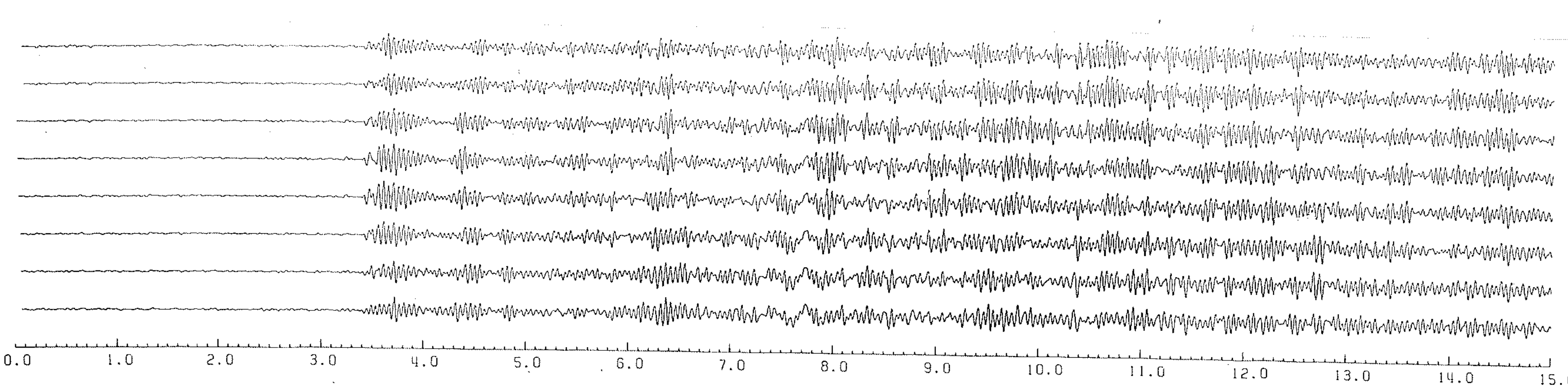

Figure 4.19 68-9 VSTACK after FILTER

CHAPTER 5

CONCLUSIONS

The data presented in Chapter 4 exemplifies the stage to which the development of the near vertical reflection method has progressed. The appearance of events that could represent possible reflections from deep in the earth's crust suggests that this method is approaching a stage where it can be considered a viable exploration and research tool on the Precambrian Shield.

Modifications of the field equipment as suggested in Chapter 1 will make the system more usable. By closer spacing of the recording sites, the correlations of events on the output records will be much easier, thus allowing different reflecting horizons to be mapped.

Further processing of this data, as well as other data collected by a similar method, will be necessary to establish the minimum unit charges and minimum effective charge weights that can be used successfully. This study indicates that 25-pound unit charges and effective charge weights of just over 760 pounds will give what appear to be good results. However, it is recommended that larger unit charges and larger effective charge weights be used in order to improve the output data quality.

Weighted stacking has proven to be a more effective method of putting multiple shot records together than conventional stacking techniques. However, additional effort should be spent looking into theoretical and practical improvements in methods to calculate the weighting factors.

The processing capability of the University of Manitoba now must rate as very acceptable. It is probably not as efficient as possible, but it does the job required of it. These programs should not be used without careful study and modifications should be made if ways can be found to make them more efficient or to make them do a better job on the data.

APPENDIX A

Program WTSTACK:

This program was written by O.G. Stephenson and G.H. Friesen. It performs a weighted vertical stack designed to optimize the output signal to noise power ratio.

The program requires only a limited number of input parameters. These parameters and the appropriate input formats are listed in the program. The subroutine WEIGHT was designed to calculate the optimum weighting factors. (See Chapter 2.)

The four parameters that require some judgements based on actual input data are W1, W1L, W2 and W2L. These parameters specify the two windows used in calculating the weighting factors. The first window should be located entirely before, but ending close to the first break energy. A gap of 0.2 sec. is required between windows. The second window should be centered over some strong signal energy, usually the strongest energy on the record. The lengths of the two windows can vary. The program normalizes the energy measured in each window by dividing by the number of samples in the window. It is recommended that the windows be between one and two sec. in length in order to achieve the best results.

The subroutine WEIGHT will automatically kill any trace on which the energy in the second window is less than the energy in the first window. For this reason, caution is recommended when stacking data of extremely poor quality. Modifications might be in order if this is found to be a serious problem.

On a technical side, this program requires 350 K of core, 15,000 I/O counts, and 14 minutes CPU time to stack 16 records and output 25 sec. of data on an IBM 360/65. There is, at present, a limitation of approximately 30 sec. of data that can be output. However, by enlarging the appropriate arrays, disk storage and core requirements, longer records can be processed.

A list of the program, including comment cards, follows.

```
      C
      C
      C     THIS PROGRAM DOES A VERTICAL STACK OF SEISMIC RECORDINGS WITH THE
      C     SAME SHOT AND RECORDING POINT LOCATIONS.  AN ENTIRE RECORD IS READ
      C     IN AT ONE TIME WHICH IMPOSES A LIMIT OF 30 SECONDS TO THE LENGTH
      C     OF DATA TO BE STACKED.
      C        INPUT TO THE PROGRAM IS FROM A 9-TRACK TAPE ON UNIT 8.  DATA ON
      C     THIS TAPE MUST BE IN BLOCKED FORM (LRECL=BLKSIZE=1684) WITH THE
      C     FIRST FOUR BYTES REPRESENTING RECORD NUMBER AND BLOCK NUMBER IE.
      C     THE SAME AS THE OUTPUT FROM 'BINBIN' WITH THE DIGITIZER ON LOW
      C     DENSITY, AND WITH 12 CHANNELS OF INFORMATION.  IF THE HIGH DENSITY
      C     OR A DIFFERENT NUMBER OF CHANNELS IS USED THE PROGRAM WILL
      C     REQUIRE A GREAT DEAL OF MODIFICATION.
      C        A WEIGHTING FACTOR IS APPLIED TO EACH TRACE OF EACH RECORD.
      C     THIS FACTOR IS A FUNCTION OF THE ENERGY IN THE 'NOISE' AND THE
      C     ENERGY IN THE 'SIGNAL' AS DETERMINED BY TWO WINDOWS. THESE WINDOWS
      C     MUST BE SPECIFIED AS TO THEIR START TIME AND LENGTH IN SECONDS IN
      C     THE INPUT PARAMETERS.  THE NOISE WINDOW SHOULD COVER THAT PORTION
      C     OF THE TRACE BEFORE FIRST BREAKS. THE SIGNAL
      C     WINDOW SHOULD COVER ANY PORTION OF THE TRACE WHICH CONTAINS SOME
      C     STRONG SIGNAL.
      C
      C
      C     INPUT PARAMETERS
      C
      C        PARAMETERS READ IN ON CARDS ARE AS FOLLOWS,
      C
      C     ON THE 1ST CARD IN I4 , F8.3
      C        PROFNO=NUMBER OF OUTPUT PROFILE (ARBITRARY)
      C        SST=NUMBER OF SECONDS OF DATA TO STACK
      C     ON THE 2ND CARD IN I4 , 4 F8.3
      C        NRST=NUMBER OF RECORDS TO STACK
      C        W1=START TIME OF NOISE WINDOW ( NEG. VALUES ALLOWED )
      C        W1L=LENGTH OF NOISE WINDOW
      C               NOTE  ( (W1 + W1L ) .LT. ( W2 - 0.2 )  )
      C        W2=START TIME OF SIGNAL WINDOW
      C        W2L=LENGTH OF SIGNAL WINDOW
      C
      C        THE FOLLOWING CARDS CONTAIN THE PARAMETERS FOR EACH RECORD TO
      C     BE STACKED, ONE CARD FOR EACH RECORD (SEE FORMAT 20).
      C
      C        IR(-)=RECORD NUMBER
      C        IB(-)=BLOCK CONTAINING TIME OF START OF THE STACKING PROCESS.
      C        IS(-)=SAMPLE WITHIN STARTING BLOCK AT WHICH THE STACK IS TO
      C        BEGIN.
      C        NILL(-,-)=1 IF THE TRACE IS TO BE INCLUDED, =0 IF IT IS TO BE
      C        KILLED (KILLED TRACES ARE ZEROED AND ARE NOT PROCESSED)
      C
      C
      C     OUTPUT
      C
      C     OUTPUT OF SUBROUTINE WEIGHT
      C
      C       OUTPUT ON THE LINE PRINTER FOR EACH RECORD IS THE AVERAGE
      C     VALUE AND A WEIGHTING FACTOR FOR EACH TRACE, AND WHICH TRACES, IF
      C     ANY, ARE KILLED.
      C
```

```
C        THE STACKED RECORD IS CUPUT ON 9-TRACK TAPE (UNIT 9) IN THE
C     SAME FORMAT (BLOCK SIZE, LOGICAL RECORD LENGTH, ETC.) AS THE
C     INPUT TAPE, TO BE COMPATABLE WITH EXISTING PLOT PROGRAMS.
C
C
C        A DISK (UNIT 13) IS USED DURING EXECUTION OF THE PROGRAM TO
C     STORE DATA TEMPORARILY.  THE SIZE OF STORAGE REQUIRED IS DETERMIN-
C     ED BY THE FIRST PARAMETER INSIDE THE BRACKETS OF THE 'DEFINE FILE'
C     STATEMENT IMMEADIATELY FOLLOWING THE FORMAT SPECIFICATIONS.  THIS
C     NUMBER MUST BE EQUAL TO OR LARGER THAN THE NUMBER OF BLOCKS IN
C     THE OUTPUT RECORD.     ( .GT. ( SST / 0.171 )  )
C
C
      INTEGER*2 DATA(12,10650)          ,PROFNO,NBLKST,TEMP(12,70),
     1A,B,ICR,IDUM1,IDUM2,ITB,IR(20),IB(20),IS(20)
      INTEGER NULL(12,25)
      REAL NORM(25,12)
   20 FORMAT(3I4,2X,12I1)
   30 FORMAT(250A2,250A2,250A2,92A2)
   31 FORMAT('-','RECORD',I6,'  IS STACKED BEGINNING AT BLOCK',I4,', SAM
     1PLE',I4/)
   32 FORMAT('-',I4,' RECORDS ARE STACKED FOR A LENGTH OF',F8.3,'  SECON
     1DS, AND ARE OUTPUT AS RECORD NUMBER',I5)
   33 FORMAT('1')
  108 FORMAT(' ','TRACE',I3,' IS KILLED')
  130 FORMAT(' ','TRACE',I3,'     AVERAGE =',F6.1,'     WEIGHTING FACTOR =
     1',F7.3)
      DEFINE FILE 13 (160,1688,L,INT)
      WRITE(6,33)
C
C     READS AND CALCULATES PARAMETERS.
C
      INT=1
      ND=1
      DI=.002449
      READ ( 5,11 ) PROFNO , SST
   10 FORMAT ( I4 , 4F8.3 )
      READ (5,10 ) NRST,W1,W1L,W2,W2L
   11 FORMAT ( I4 , F8.3 )
C
C     NBLKST=NUMBER OF BLOCKS OF DATA TO STACK
C
      NBLKST=(SST/DI)/70
      DO 40 IU=1,NRST
   40 READ(5,20) IR(IU),IB(IU),IS(IU),(NULL(I,IU),I=1,12)
      CALL WEIGHT (NRST,W1,W1L,W2,W2L,IR,IB,IS,NULL,NORM)
      WRITE (6,32) NRST,SST,PROFNO
C
C     PERFORMS THIS LOOP ONCE FOR EVERY RECORD IN THE STACK.
C
      DO 500 IRA=1,NRST
C
C     SEARCHES FOR THE APPROPRIATE RECORD AND BLOCK AND READS IT INTO
C     MEMORY.  (THE SAMPLES FOLLOWING THE 'IS' SAMPLE IN THE 'IB'
C     BLOCK ARE TRANSFERRED TO THE FRONT OF THE ARRAY AND 'NBLKST'
C     BLOCKS ARE THEN READ INTO THE REMAINDER OF THE ARRAY).
C
      DO 50 IRB=1,8000
```

```
      READ(8,30) A,B
      IF(A.EQ.IR(IRA).AND.B.EQ.(IB(IRA)-1)) GO TO 60
   50 CONTINUE
   60 READ(8,30) IDUM1,IDUM2,((DATA(I,J),I=1,12),J=1,70)
      WRITE(6,31) IDUM1,IDUM2,IS(IRA)
   70 IRD=70-IS(IRA)
      DO 80 IRE=1,IRD
      IRJ=IS(IRA)+IRE
      DO 80 IRF=1,12
   80 DATA(IRF,IRE)=DATA(IRF,IRJ)
      NSX=IRD+70
      IRD=IRD+1
      DO 100 IRG=1,NBLKST
      READ(8,30) IDUM1,IDUM2,((DATA(I,J),I=1,12),J=IRD,NSX)
      IRD=IRD+70
  100 NSX=NSX+70
C
C     II=TOTAL NUMBER OF SAMPLES PER TRACE
C
      II=70-IS(IRA)+70*NBLKST
C
C     PERFORMS THIS LOOP FOR EACH TRACE
C
      DO 170 IP=1,12
C
C     ZEROES TRACES TO BE KILLED
C
      IF(NULL(IP,IRA)) 105,105,110
  105 DO 107 IQ=1,II
  107 DATA(IP,IQ)=0
      WRITE(6,108) IP
      GO TO 170
C
C     CALCULATES THE AVERAGE OF THE TRACE
C
  110 SUMIT=0.
      DO 120 IQ=1,II
  120 SUMIT=SUMIT+DATA(IP,IQ)
      AVRG=SUMIT/II
C
C     SUBTRACTS THE AVERAGE AND MULTIPLIES BY THE WEIGHTING FACTOR
C
      STA=NORM(IRA,IP)
      DO 140 IQ=1,II
  140 DATA(IP,IQ)=(DATA(IP,IQ)-AVRG)*STA
      WRITE(6,130) IP,AVRG,STA
  170 CONTINUE
      IF(IRA.EQ.1) GO TO 240
C
C     READS DATA FROM DISK AND ADDS RECORD BEING PROCESSED TO PREVIOUS-
C     LY STACKED RECORDS.
C
  200 DO 230 IBC=1,NBLKST
      READ(13' INT    ) A,B,((TEMP(I,J),I=1,12),J=1,70)
      DO 230 IP=1,12
      IX=IBC*70-69
      DO 230 IQ=1,70
      DATA(IP,IX)=DATA(IP,IX)+TEMP(IP,IQ)
```

```
230     IX=IX+1
240     IF(IRA.EQ.NRST) GO TO 600
C
C       WRITES THE DATA ON DISK
C
        INT=1
        DO 260 IBC=1,NBLKST
        IX=IBC*70-69
        NSY=IX+69
260     WRITE(13' INT    ) IDUM1,IDUM2,((DATA(I,IZ),I=1,12),IZ=IX,NSY)
500     INT=1
C
C       OUTPUTS STACKED RECORD
C
600     IX=1
        NSY=70
        ITB=0
        DO 650 ITA=1,NBLKST
        ITB=ITB+1
        WRITE(9,30) PRCFNC,ITB,((DATA(I,IZ),I=1,12),IZ=IX,NSY)
        IX=IX+70
650     NSY=NSY+70
        STOP
        END
```

```
      SUBROUTINE WEIGHT (NOREC,SEC1,DSEC1,SEC2,DSEC2,IR,MB,NST,NULL,WT)
C
C
C     SUBROUTINE WEIGHT WRITEN BY G.H.FRIESEN , OCT. / 73
C
C        DESIGNED CN THEORY OF J.C.RCBINSCN PUBLISHED IN GEOPHYSICE
C        VOL. 35 , # 3 , JUNE 1970
C
C        ' STATISTICAL OPTIMAL STACKING OF SEISMIC DATA '
C
C
      INTEGER*2 IT(12,70),IRR,IER,IR(NOREC),MB(NOREC),NST(NOREC)
      INTEGER NULL( 12,25 )
      DIMENSICN POWER(25,12) , SN(25,12)  , SS(25,12)
      DIMENSION SWT(12)
      DIMENSION WT(25,12)
      REAL SUM (25) , STDN(25),STDS(25),STCN(25)
      DI = 0.002449
      HDI = DI * 70
      DSEC = DSEC 1
      IB4 = SEC1 / HDI
      H4 = SEC1 -IB4 * HDI
      M4 = H4 / DI
      IB5 = SEC2 / HDI
      H5 = SEC2 - IB5 * HDI
      M5 = H5 / DI
      SREC = 0.0
      DO 100 KA=1,NOREC
      IB1 = MB(KA) + IB4
      MM = NST(KA) + M4
      IF ( MM.LT.70 ) GO TO 207
      IB1 = IB1 + 1
      MM = MM - 70
  207 CCNTINUE
      IF ( MM.GT. 0 ) GO TO 208
      IF ( MM.EQ. 0 ) GC TO 208
      IB1 = IB1 - 1
      MM = 70 + MM
  208 CCNTINUE
      NS1 = MM
      IB2 = MB(KA) + IB5
      MM = NST(KA) + M5
  209 IF ( MM.LT. 70 ) GO TO 210
      IB2 = IB2 + 1
      MM = MM - 70
  210 CCNTINUE
      NS2 = MM
      IB = IB1
      IO = IR(KA)
      IST = NS1
      IK2 = NS1
      DO 15 IX=1,7000
      READ(8,10) IRR,IBR
   10 FORMAT(2A2,250A2,250A2,250A2,250A2)
      IF(IRR.EQ.IO.AND.IBR.EQ.(IB  )) GO TO 12
      GC TO 15
   12 DO 99 I = 1 , 12
   99 SUM(I) = 0.0
```

```
      BACKSPACE 8
      NB = DSEC / HDI
      H6 = DSEC - NB * HDI
      M6 = H6 / DI
      N = NB * 70 + M6
      IF ( M6 .EQ. 0 ) NB = NB - 1
      IK2 = IK2 + M6
      IF ( IK2 .GT. 70 ) NB = NB + 1
      NB = NB + 1
      IEND = 70
      DO 30 IJ = 1,NB
      READ(8,10,END=15,ERR=15)   IRR,IBR,((IT(I,J),I=1,12),J=1,70)
      DO 101 I = 1,12
      DO 101 J = IST , IEND
101   SUM(I) = SUM(I) + IT(I,J) * IT(I,J)
      IST = 1
      IF ( IJ .EC. ( NB - 1 ) ) IEND = M6
30    CONTINUE
      IF ( IB.EQ.IB2 ) GO TO 119
      DO 120 I = 1,11
120   STDN(I) = SUM(I) / N
      IK2 = NS2
      IB = IB2
      F1 = SEC1
      F2 = SEC1 + DSEC1
      DSEC = DSEC2
      IST = NS2
      GC TC 15
119   DO 122 I = 1,11
122   STDS(I) = SUM(I) / N
      F3 = SEC2
      F4 = SEC2 + DSEC2
      DSEC = DSEC1
      GO TO 129
15    CONTINUE
129   ASTCN= 0.0
      WRITE ( 6,333)
333   FORMAT ( /////,1X )
      WRITE ( 6,114 ) IRR
114   FORMAT (     //,1X,'RECCRD NO. =  ',I4 ,20X, 3I4 )
      WRITE (6,300) F1,F2,F3,F4
300   FORMAT ( /,1X, ' POWER WINDOWS ARE FROM ',F8.3,2X,' TO ',
     1    F8.3,2X,'AND FRCM',F8.3,2X,'TO ', F8.3,2X,
     1      ' SECCNDS CN THES RECORD ' )
      KK=0
      DO 244 I = 1,11
      SS(KA,I) = STDS(I) - STDN(I)
      STON(I) = SS(KA,I) / STCN(I)
      IF ( STON(I).GT.0 ) GO TO 239
      SS(KA,I) = 0.0
      STON(I) = 0.0
      POWER(KA,I) = 0.0
      NULL(I,KA) = 0
      WRITE ( 6,204 ) I
204   FORMAT (/,1X, ' NEGATIVE VALUE IN TRACE ' , I4 )
      GO TC 123
239   CONTINUE
      POWER(KA,I) = STCN(I)
```

```
      STON(I) = SQRT ( STON(I) )
 123  ASTCN = ASTCN + STON(I)
 244  WT(KA,I)=STON(I)
      ASTON = ASTON / ( 11 - KK )
      DO 125 I = 1,11
      STDN(I) = SQRT ( STDN(I) )
      STDS(I) = SQRT ( STDS(I) )
 125  SN(KA,I) = STDN(I)
      WRITE (6,115 )
 115  FORMAT (/,1X,'TRACE  STD NOISE  STD SIGNAL  SIGNAL : NOISE RATIO')
      DO 135 I = 1,11
      WRITE (6,116 ) I,STDN(I),STDS(I),STON(I)
 135  CCNTINUE
 116  FORMAT (1X,I4,3X,F9.2,2X,F9.2,7X,F7.2 )
      SREC = SREC + ASTON
      WRITE(6,117 ) ASTCN
 117  FORMAT ( 50X ,'AVERAGE SIGNAL TC NOISE RATIO = ', F7.2 )
 100  CONTINUE
      SREC = SREC / NOREC
      WRITE ( 6,9 ) SREC
 9    FORMAT ( / , 50X , ' AVERAGE AVERAGE = ' , F 7.2 )
      WRITE ( 6,900 )
 900  FORMAT ( /,1X,I4 )
      REWIND 8
      DO 192 I = 1,NOREC
 192  WT(I,12 ) = 0.0
      WRITE ( 6, 2 )
 2    FORMAT ( ///,1X, ' NULL ARRAY PASSED TO MAIN PROGRAM ' )
      WRITE ( 6,663 ) ( ( NULL(J,I),J=1,12 ),I= 1, NOREC )
 998  FORMAT ( 12 F 10.2 )
      WRITE ( 6, 1 )
 1    FORMAT ( ///,1X,' SIGNAL TO NCISE AMPLITUDE RATIO ' )
      WRITE(6,998 ) ( ( WT(I,J),J=1,12 ) , I = 1,NOREC )
      DO 6 J = 1 , 11
      SWT(J) = 0.0
      DO 5 I = 1 , NOREC
 5    SWT(J) = SWT(J) + WT(I,J )
 6    SWT(J) = SWT(J) / NOREC
      WRITE ( 6,8)
 8    FORMAT ( 1X, ' TRACE AVERAGES ' )
      WRITE ( 6,998 ) ( SWT(J) , J=1,11 )
      DO 301  I = 1,11
      SUN = 0.0
      DO 303 KA = 1,NOREC
 303  SUN = SUN + POWER(KA,I)
 301  SWT(I) = SQRT ( SUN )
      WRITE (6,302 )
 302  FORMAT(1X,'EXPECTED SIGNAL TO NOISE AMPLITUDE RATIO CF WTSTACK')
      WRITE (6,998 ) ( SWT(I) , I= 1 , 11 )
      WRITE ( 6, 3 )
 3    FORMAT ( ///,1X, ' STANDARD DEVIATICN OF THE NOISE ' )
      WRITE (6,50 )((SN(I,J),J=1,11),I=1,NOREC)
 663  FORMAT ( 10X,12I2   )
      DO 40 J = 1,11
      E1 =0.0
      DO 20 I = 1,NOREC
      SN(I,J) = 1 / SN(I,J)
      WT(I,J) = WT(I,J) * SN(I,J) * NULL(J,I)
```

```
   20  E1 = E1 + WT(I,J)
       F1 = 10.0 / E1
       DO 31 I = 1 , NOREC
   31  WT ( I,J ) = WT(I,J) * E1
   40  CONTINUE
       WRITE ( 6, 4 )
  4    FORMAT ( ///,1X , ' WEIGHT ARRAY PASSED TO MAIN PROGRAM ' )
       WRITE (6,50 )((WT(I,J),J=1,11),I=1,NOREC)
   50  FORMAT ( 11 F10.2 )
       RETURN
       END
```

APPENDIX B

Program AGC:

This program was written by O.G. Stephenson, and is based on an algorithm supplied by G.H. Friesen. The program is designed to apply a time variable amplification to seismic data on a trace by trace basis.

This program should only be used to solve a specific problem that occurs on near vertical reflection seismic records with shot to geophone distances of less than 5 km. Record 65-9 in Figure 4.9 best typifies the problem of very large amplitudes over a short time period and large time segments with amplitudes so low that possible events cannot be picked. This program will balance the amplitudes over the entire trace leading to a better portrayal of wave forms, thus aiding interpretation. This program will also create a variable noise level on each trace. Relative amplitudes of events are maintained only to a partial degree over short segments of the trace, approximately ¼ the length of the operator used.

The input parameters and the appropriate formats are listed in the program. The critical parameter is the operator length. The larger the shot-geophone distance, the longer the operator should be for best results. Operators of one second or more in length are recommended.

The program designs a triangular shaped operator, $OP(j)$, symmetric about the center point $j = 0$ where it has a maximum value of 1 and dropping to zero at $j = \pm t$. This operator is used to calculate an envelope for each trace. The ith sample of the envelope $[ENV(i)]$ is

$$ENV(i) = \sum_{j=-t}^{+t} OP(j) \cdot X(i+j)$$

where $X(i)$ are the input data. The maximum value of the envelope (ENVMAX) is found and used to calculate the output data $[Y(i)]$ in the following way:

$$Y(i) = X(i) \cdot \frac{ENVMAX}{ENV(i)}$$

It is clear that the amplification will always be greater than or equal to one.

On a technical side, this program requires 150 K of core, approximately 36000 I/O counts and 20 minutes CPU time on the IBM 360/65 to process 15 sec. of data on 11 traces with an operator length of 1 sec. Longer operators will substantially increase the CPU time required.

A list of the program follows.

```
C
C
C       PRCGRAM 'AGC' WRITTEN BY C. G. STEPHENSCN FROM AN ALGORITHM BY
C       G. H. FRIESEN
C
C
C
C       PROGRAM DESCRIPTICN-
C          THIS PROGRAM APPLIES A TIME VARIANT AMPLIFICATION TO SEISMIC
C          DATA CN A TRACE BY TRACE BASIS.  IT CCES THIS BY CALCULATING
C          A TRACE ENVELOPE, AND NORMALIZING THIS ENLELOPE TO 1 AND THEN
C          DIVIDING THE TRACE VALUE BY THE NORMALIZED ENVELOPE TO GIVE THE
C          OUTPUT DATA VALUE.
C
C
C       PRCGRAM USES-
C          THE PROGRAM IS USEFUL IN EVENING OUT THE AMPLITUDES OF THE
C          TRACE WITH TIME.  RECCMENDED USE IS FCR RECORDS RECORDED LESS
C          THAN 5.0 KILCMETERS FRCM THE SHOT.
C
C
C       INPUT PARAMETERS-
C          FIRST CARC (SEE FORMAT 5)
C          NOREC = THE NUMBER OF RECORDS TO PROCESS
C          SECS = THE LENGTH CF OPERATOR USED TC CALCULATE THE ENVELOPE
C
C          SECCND CARD  (SEE FORMAT 10 IN SUBROUTINE 'SEARCH')
C          IR = THE INPUT RECCRD NUMBER
C          IB = THE BLOCK IN 'IR' CONTAINING ZERC TIME (OR THE TIME AT
C          WHICH PROCESSING IS TO BEGIN)
C          IS = THE SAMPLE IN THE 'IB' BLOCK AT WHICH PROCESSING IS TO
C          BEGIN
C          SECSDA = THE NUMBER CF SECCNDS OF DATA TO BE PROCESSED
C          PROFNO = THE OUTPUT RECORD NUMBER (ARBITRARY)
C
C
        INTEGER*2 TRACE(11000),DATA(12,700),A,B,JAK,IS
        INTEGER*2 PRCFNO
        DIMENSICN CPERAT(700),ENVEL(11000)
        DEFINE FILE 13 (192,1404,L,INT)
  30    FORMAT(250A2,250A2,250A2,250A2)
        DI=.C02449
        READ (5,5 ) NOREC , SECS
   5    FORMAT ( I4, F8.3 )
C
C       LENGTH = THE CPERATOR LENGTH (IN SAMPLES)
C
        LENGTH=SECS/DI-2
        IF((LENGTH/2)*2.EQ.LENGTH) LENGTH=LENGTH+1
        WRITE(6,1) SECS,LENGTH
   1    FORMAT('1',//' ','OPERATOR LENGTH = ',F4.2,' SECCNDS   ( ',I2,' SAM
       1PLES)')
        LEN=LENGTH/2
        LEN1=LEN+1
C
C       THIS PCRTION OF THE PROGRAM CALCULATES AND PRINTS OUT THE SYMETRIC
C       TRIANGULAR-SHAPED OPERATOR
C
        DO 110 M=1,LEN
```

```
      OPERAT(M)=FLCAT(M)/LEN1
110   OPERAT(2*LEN+2-M)=OPERAT(M)
      OPERAT(LEN1)=1.
      WRITE(6,21) (CPERAT(I),I=1,LENGTH)
21    FORMAT('-',20X,'OPERATOR VALUES ARE'/'0',(10F10.3))
      WRITE(6,2)
2     FORMAT('-')
C
C     THIS LOOP IS PERFORMED FOR EVERY RECORD TO BE PROCESSED
C
      DO 705 LII=1,NOREC
      CALL SEARCH (IS,SECSCA,PRCFNO)
C
C     II = THE NUMBER OF DATA POINTS TO PROCESS
C
      II=SECSCA/DI+.5
      NBLKS=II/700+1
C
C     THIS PORTION READS THE CATA FROM TAPE IN TRACE PARALLEL FORMAT,
C     SORTS  INTO LARGER BLOCKS AND WRITES IT ON DISK IN TRACE
C     SEQUENTIAL FORMAT.  THE FIRST TRACE IS RETAINED IN THE 'TRACE'
C     ARRAY AND IS PROCESSED FIRST.  ALL THE CATA IS PROCESSED TRACE BY
C     TRACE.
C
      DO 100 M=1,NBLKS
      IX=1
      DO 10 L=1,10
      IZ=IX+69
      READ(8,30) A,B,((DATA(I,J),I=1,12),J=IX,IZ)
10    IX=IX+70
      MM=700*(M-1)
      DO 50 NY=1,700
50    TRACE(MM+NY)=DATA(1,NY)
      DO 60 K=2,11
      INT=15*(K-1)+M
60    WRITE(13' INT   ) (DATA(K,J),J=1,700)
100   CONTINUE
      IF(IS.EQ.0) GO TO 106
      DO 105 LI=1,II
105   TRACE(LI)=TRACE(LI+IS)
106   KTRACE=1
115   EMAX=0.
      LEN=LENGTH/2
      LEN2=LEN1
      NEL=LEN
C
C     THIS PORTION PERFORMS THE CONVOLUTION ON THE FIRST HALF-OPERATOR
C     LENGTH OF DATA,  IE HALF THE OPERATOR IS USED TO DETERMINE THE
C     ENVELOPE VALUE FOR THE FIRST DATA POINT.  THE SECOND ENVELOPE
C     VALUE IS DETERMINED USING HALF THE OPERATOR PLUS ONE POINT, AND
C     SO ON UNTIL THE OPERATOR IS MOVED COMPLETELY INTO THE CATA.
C
      DO 150 L=1,LEN
      SUM=0.
      DO 120 M=1,LEN2
      CK=TRACE(M)
      IF(CK.LT.0.) CK=-CK
120   SUM=SUM+OPERAT(NEL+M)*CK
```

```
      NEL=NEL-1
      ENVEL(L)=SUM
      IF(SUM-EMAX) 150,150,140
140   EMAX=SUM
150   LEN2=LEN2+1
      III=II-LEN
C
C     ONCE THE OPERATOR IS ENTIRELY INTO THE DATA THIS PORTION OF THE
C     PROGRAM CONTINUES THE CONVOLUTION UNTIL THE LAST HALF-OPERATOR
C     LENGTH OF DATA IS ENCOUNTERED.
C
      DO 250 IB=LEN1,III
      MS=IB-LEN1
      SUM=0.
      DO 200 JS=1,LENGTH
      CK=TRACE(MS+JS)
      IF(CK.LT.0.) CK=-CK
200   SUM=SUM+OPERAT(JS)*CK
      IF(SUM-EMAX) 250,250,240
240   EMAX=SUM
250   ENVEL(IB)=SUM
      NEL=LENGTH-1
      LEN=LENGTH/2
      LEN2=LEN2-1
C
C     THIS PORTION CONVOLVES THE LAST HALF-OPERATOR LENGTH OF DATA IN
C     THE SAME MANNER AS THE FIRST, USING LESS AND LESS OF THE OPERATOR
C     UNTIL, FOR THE LAST ENVELOPE VALUE, ONLY THE FRONT HALF OF THE
C     OPERATOR IS USED.
C
      DO 350 L=1,LEN
      SUM=0.
      DO 320 M=1,LEN2
      CK=TRACE(II-NEL+M)
      IF(CK.LT.0.) CK=-CK
320   SUM=SUM+OPERAT(M)*CK
      IF(SUM-EMAX) 330,330,340
340   EMAX=SUM
330   NEL=NEL-1
      ENVEL(III+L)=SUM
350   LEN2=LEN2-1
C
C     THE MAXIMUM ENVELOPE VALUE DETERMINED IN ONE OF THE ABOVE THREE
C     PORTIONS (AS 'EMAX') IS USED TO NORMALIZE THE ENVELOPE TO A
C     MAXIMUM VALUE OF 1 IN THE FOLLOWING PORTION OF THE PROGRAM.
C
      EMAX=1./EMAX
      DO 400 I=1,II
400   ENVEL(I)=ENVEL(I)*EMAX
      IA=700
C
C     THE TRACE VALUES ARE MULTIPLIED BY THE NORMALIZED ENVELOPE AND ARE
C     THEN STORED TEMPORARILY ON DISK.
C     THE NEXT TRACE TO BE PROCESSED IS READ FROM DISK AND CONTROL IS
C     TRANSFERRED BACK TO STATEMENT 115.
C
      DO 500 I=1,NBLKS
      IW=700*(I-1)+1
```

```
      INT=15*(KTRACE-1)+I
      IF(I.EQ.NBLKS) IA=II-(NBLKS-1)*700
      DO 550 IQ=1,IA
      IY=IW+IQ-1
      LK=TRACE(IY)
      ND=1
      IF(LK.LT.0.) ND=-1
      IF(ENVEL(IY).EQ.0.) GO TO 540
      TRACE(IY)=LK/ENVEL(IY)+.5*ND
      GO TO 550
540   TRACE(IY)=0
550   CONTINUE
      IWW=IW+699
500   WRITE(13' INT    ) (TRACE(IH),IH=IW,IWW)
      IF(KTRACE.EQ.11) GO TO 700
      KTRACE=KTRACE+1
      INT=15*(KTRACE-1)+1
      DO 600 M=1,NBLKS
      IW=700*(M-1)+1
      IWW=IW+699
600   READ(13'INT    )(TRACE(IY),IY=IW,IWW)
      IF(IS.EQ.0) GO TO 615
      DO 610 LI=1,II
610   TRACE(LI)=TRACE(LI+IS)
615   GO TO 115
700   JAK=1
C
C     ONCE THE LAST TRACE HAS BEEN PROCESSED IT IS RETAINED. THE OTHER
C     TRACES ARE READ FROM THE DISK, BLOCK BY BLOCK, AND THE DATA IS
C     OUTPUT ONTO MAGNETIC TAPE IN TRACE PARALLEL FORMAT.
C
      DO 705 M=1,NBLKS
      IX=1
      DO 704 MM=1,700
      MMM=700*(M-1)+MM
704   DATA(11,MM )=TRACE(MMM)
      DO 710 I=1,10
      INT=(I-1)*15+M
710   READ(13' INT    ) (DATA(I,J),J=1,700)
      DO 705 IH=1,10
      IZ=IX+69
      WRITE(9,30) PRCENC,JAK,((DATA(K,L),K=1,12),L=IX,IZ)
      IX=IX+70
705   JAK=JAK+1
      STOP
      END
```

```
      SUBROUTINE SEARCH (IS,SECSDA,PROFNO )
C
C     THIS SUBROUTINE READS IN INFORMATION REGARDING THE INPUT RECORD
C     AND POSITIONS THE INPUT TAPE FOR THE MAIN PROGRAM.
C
      INTEGER*2 PROFNO
      INTEGER*2 A,B,IR,IB,IS
      READ(5,10) IR,IB,IS,SECSDA , PROFNO
 10   FORMAT(3I4,F8.3,I4 )
      DO 100 I=1,7000
      READ(8,30) A,B
 30   FORMAT(2A2)
      IF(A.EQ.IR.AND.B.EQ.IB) GO TO 15
 100  CONTINUE
 15   BACKSPACE 8
      ISS=IS
      WRITE(6,20) A,SECSDA,B,IS, PROFNO
 20   FORMAT(' ','RECORD ',I3,' IS PROCESSED OVER A LENGTH OF ',F4.1,'
     1ECONDS, BEGINNING AT BLOCK',I3,' , SAMPLE',I3,'OUTPUT AS',I4 )
      RETURN
      END
```

LIST OF REFERENCES

Baer, D.W.
1972. A developmental near-vertical reflection seismic study of the upper crust in the Canadian Shield near Kenora. Unpubl. M.Sc. Thesis, University of Manitoba.

Beloussov, V.G., Volvovsky, B.S., Volvovsky, I.S. and Riaboi, V.Z.
1962. Experimental investigation of the recording of deep reflected waves. Izv. Acad. Sci. U.S.S.R., (Geophys. Ser., English Translation), No. 8, pp. 662-669.

Capon, J.
1972. Long-period signal processing results for LASA, NORSAR and ALPA. Geophys. J.R. astr. Soc., V. 31, pp. 279-296.

Capon, J., Greenfield, R.J. and Kolker, R.J.
1967. Multidimensional maximum likelihood processing of a large aperture seismic array. Proc. IEEE, V. 55, pp. 192-211.

Christoffersson, A. and Jansson, B.
1967. Maximum-likelihood estimation of an unknown signal in multiple Gaussian noise with known covariance matrix. Unpubl. manuscript, Uppsala Statistics Inst., 12 pp.

Clowes, R.M., Kanasewich, E.R. and Cumming, G.L.
1968. Deep crustal seismic reflections at near-vertical incidence. Geophysics, V. 33, pp. 441-451.

Dix, C.H.
1965. Reflection seismic crustal studies. Geophysics, V. 30, pp. 1068-1084.

Galbraith, J.N. and Wiggins, R.A.
1968. Characteristics of optimum multichannel stacking filters. Geophysics, V. 33, pp. 36-48.

German Research Group for Explosion Seismology.
1964. Crustal structure in western Germany. Z. Geophys., V. 30, pp. 209-234.

Gurbuz, B.M.
1969. Structure of the earth's crust and upper mantle under a portion of Canadian Shield deduced from travel-times and spectral amplitudes of body waves using data from Project Early Rise. Unpubl. Ph.D. Thesis, University of Manitoba, 166 pp.

Gurbuz, B.M.
1970. A study of the earth's crust and upper mantle using travel-times and spectrum characteristics of body waves. Bull. Seism. Soc., V. 60, pp. 1921-1935.

Hajnal, Z.
1968. A two-layer model for the earth's crust under Hudson Bay in: Earth Science Symposium on Hudson Bay. Hood (ed.), Geol. Surv. Can., Paper 68-53, pp. 326-336.

1970. A continuous deep-crustal seismic refraction and near-vertical reflection profile in the Canadian Shield interpreted by digital processing techniques. Unpubl. Ph.D. Thesis, University of Manitoba, 280 pp.

1971. Detailed seismic studies of the earth's crust in eastern Manitoba in: Geology and Geophysics of the Rice Lake Region, Southeastern Manitoba. McRitchie and Weber (ed.), Manitoba Mines Branch Publ. 71-1, pp. 417-425.

Hall, D.H.
1964. Converted waves in refraction surveys over markers with variable depth. Geophysics, V. 29, pp. 733-744.

1968. A seismic-isostatic analysis of crustal data from Hudson Bay in: Earth Science Symposium on Hudson Bay. Hood (ed), Geol. Surv. Can., Paper 68-53, pp. 337-364.

1971 Geophysical determination of deep crustal structure in Manitoba in: Geoscience Studies in Manitoba. Turnock (ed.), Geol. Assoc. Can., Special Paper No. 9, pp. 83-88.

Hall, D.H. and Brisbin, W.C.
1961. A study of the Mohorovicic discontinuity near Flin Flon, Manitoba. Final Report, Geophy. Directorate, Air Force, Cambridge Res. Lab., U.S. Dept. Comm., Office of Technical Service, Washington, D.C.

1965. Crustal structure from converted head waves in central western Manitoba. Geophysics, V. 30, pp. 1053-1067.

Hall, D.H. and Hajnal, Z.
1969. Crustal structure of northwestern Ontario: refraction seismology. Can. J. Earth Sci., V. 6, pp. 81-99.

1973. Deep seismic crustal studies in Manitoba. Bull. Seism. Soc. Am., V. 63, pp. 885-910.

Homeniuk, L.A.
1972. A near-vertical-incidence reflection survey conducted over the Precambrian Shield of southeastern Manitoba. Unpubl. M.Sc. Thesis, University of Manitoba.

Kanasewich, E.R. and Cumming, G.L.
1965. Near-vertical-incidence seismic reflections from the 'Conrad' discontinuity. J. Geoph. Res., V. 70, pp. 3441-3446.

Kanasewich, E.R., Hemmings, C.D. and Alpaslan, T.
1973. Nth-root stack nonlinear multichannel filter. Geophysics, V. 38, pp. 327-338.

Khalevin, N.I., Druzhinin, V.S., Rybalka, V.M., Nezolenova, E.A. and Chudakova, L.N.
1966. The results of deep seismic sounding of the earth's crust in the middle Urals. Izv. Acad. Sci. U.S.S.R., (Physics of the Solid Earth), No. 4, pp. 226-232.

Lee, Y.W.
1960. Statistical Theory of Communication. John Wiley and Sons, Inc., New York.

Mayne, W.H.
1962. Common reflection point horizontal data stacking techniques. Geophysics, V. 27, pp. 927-938.

1967. Practical considerations in the use of common reflection point techniques. Geophysics, V. 32, pp. 225-229.

McClure, J.E.
1973. A seismic investigation of the Yorkton area of Saskatchewan. Unpubl. M.Sc. Thesis, University of Saskatchewan, (Saskatoon).

Robertson, G.
1963. Intrabasement reflections in southwestern Alberta. Geophysics, V. 28, pp. 910-915.

Robinson, J.C.
1970. Statistically optimal stacking of seismic data. Geophysics, V. 35, pp. 436-446.

Steinhart, J.S. and Meyer.
1961. Explosion studies of continental structure. Carnegie Inst. Washington, Publication 622, 409 pp.

Whitcomb, J.H.
1969. Array data processing techniques applied to long-period shear waves at Fennoscandian seismograph stations. Bull. Seism. Soc. Am., V. 59, pp. 1863-1887.

Wilson, H.D.B.
1971. Assessment of the project in: Geology and Geophysics of the Rice Lake Region, Southeastern Manitoba, McRitchie and Weber (ed.), Manitoba Mines Branch Publ. 71-1, pp. 427-430.