THE UNIVERSITY OF CALGARY

DESIGN AND APPLICATIONS OF A DIVERSITY STACK COMPUTER PROGRAM

by

DENIS DUFRESNE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF

GEOLOGY AND GEOPHYSICS

CALGARY, ALBERTA

NOVEMBER, 1987

ISBN 0-315-42468-0

THE UNIVERSITY OF CALGARY

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "Design and applications of a diversity stack computer program" submitted by Denis Dufresne in partial fulfillment of the requirements for the degree of Master of Science.

Supervisor,

Dr. Frederick A. Cook

Dept. of Geology and Geophysics

Dr. Don C. Lawton

Dept. of Geology and Geophysics

Dr. Patrick Wu

Dept. of Geology and Geophysics

Dr. Peter Lancaster

Dept. of Mathematics and Statistics

November, 2nd, 1987

ABSTRACT

The objective of this research project was to develop a processing technique which will provide an efficient means of eliminating a specific type of coherent noise present on an experimental deep seismic reflection data set recorded by the Lithoprobe group. The solution was effected by the design and development of a diversity stack computer program.

The data set was the result of a pilot experiment conducted over the Kapuskasing Zone of northern Ontario during the summer of 1984. The quality of the recorded data was greatly deteriorated by the presence of high amplitude coherent noise. A likely source of this noise was atmospheric discharges into the receivers' connecting cable. The developed diversity stack computer program proved very efficient in the elimination of noise of this sort as well as noise which has the characteristics of being temporally random and of higher amplitude than the normal signal and background noise amplitude levels.

Granulite facies metamorphic rocks exposed in the Kapuskasing Zone of northern Ontario are thought to represent a fragment of the lower crust (20 to 25 km deep) which was brought to the surface along crustal scale thrust faults. The validity of this interpretation depends upon the structural geometry of the crust at depth. The purpose of the pilot seismic reflection survey was to test the

feasibility of recording reflection surfaces from this crystalline environment and consequently to demonstrate the possibility of imaging the crustal geometry.

Results obtained from the complete processing of the data confirmed the presence of reflection surfaces in the 10 to 15 kilometers depth range. These results are in partial agreement with the ones drawn from a previous processing of this data set by Cook (1984) in which no diversity stack was done. Disparities consist essentially in a different imagery of reflection surfaces.

TABLE OF CONTENTS

LIST OF TABLES

page

LIST OF FIGURES

page

INTRODUCTION

The Kapuskasing Zone of northern Ontario represents a segment of the Precambrian shield in which granulite facies metamorphic rocks are exposed. Percival and Card (1983) have suggested these rocks have been brought to the surface along crustal scale thrust faults, and thus that the high grade rocks, which were originally buried to depths of 20 to 25 kilometers, may represent a fragment of the lower crust now at the surface. The validity of this interpretation depends upon the structural geometry of the crust at depth. For this reason, the Lithoprobe(1) group has targeted the area for a major effort focused on understanding the crustal structure of the area. One facet of the effort will be the acquisition, processing and interpretation of an extensive (300 to 400 kilometers) seismic reflection survey.

In an effort to obtain essential information on logistical problems of data acquisition and reduction, a pilot reflection seismic survey was recorded over the Kapuskasing Zone during the summer of 1984 (Cook, 1984). Preliminary results were encouraging in that they indicated the presence of reflection surfaces in the 15 to 20 kilometers depth range. However, the quality of the recorded data was greatly deteriorated by the presence of high amplitude coherent noise. A likely source of this noise was atmospheric discharge into the receivers' connecting cable as a direct result of the anomalously high electrical resistivity of the Precambrian basement rocks. The primary objective of this research project was to develop a processing technique which would provide an efficient means of eliminating this coherent noise from the shot records.

The solution to the coherent noise problem was effected by the development of a diversity stack computer program. The diversity stack method is a weighting and stacking technique which operates on shot records (Kirk, 1981). Noise which is of higher amplitude than normal signal and background noise and that occurs randomly with respect to time will be efficiently eliminated using this technique. In the next chapters, development and theoretical aspects of the diversity stack method will be thoroughly described. The performance of the method will be compared with other standard noise reduction techniques and optimum utilization of the method will be studied.

A second objective of this research project was the reprocessing of the pilot seismic reflection survey using the diversity stacked shot records. In a previous processing of this data set, Cook (1984) was able to identify two major groups of reflections on the stack section. One group was composed of near horizontal reflection surfaces at times of 3.0 to 4.0 seconds. The second group of reflections was seen at shallower times (1.8 to 3.0 seconds) and displayed a significant dip to the northwest. Cook (1984) interpreted this last group as the thrust fault which has been postulated in Percival and Card's (1983) crustal model. To reduce the coherent noise, Cook (1984) applied an automatic gain control scaling to the data prior to doing a vertical sum. Thus the reprocessing of this same data set using the diversity stack program will allow a comparison between the two results.

The reprocessing of the Kapuskasing data also highlighted several aspects of the acquisition procedure and processing flow that can be improved upon during the large scale seismic reflection survey in 1987. These problems will be briefly discussed along with proposed solutions.

1- Lithoprobe is a coordinated geoscience project which involves Canadian universities, industries and the federal government. It has, as its objective, the delineation of the structure, composition and evolution of the continental lithosphere of Canada.

CHAPTER 1 STATEMENT OF THE PROBLEM

The Kapuskasing Zone extends for some 600 kilometers in a northeast direction from Chapleau, Ontario, to the south of Aminiski Island in James Bay (Figure 1; Gibb, 1978; Percival and Card, 1983). The high grade metamorphic rocks that comprise the Kapuskasing Zone have northeast structural trends and crosscut the east-west grain defined by the low grade metamorphic rocks of the Superior province (Figure 1). Recent work by Percival and Card (1983) suggests that the rocks from the Kapuskasing Zone originated some 15 to 25 kilometers deep into the crust and were uplifted to the surface along a northeast-striking northwest-dipping crustal scale thrust fault. The fault is thought to bound the Kapuskasing Zone to the east at the contact with the Abitibi subprovince.

A pilot seismic reflection profile was recorded over the Kapuskasing Zone by the Lithoprobe group in an effort to determine any logistical problems prior to the expenditure of a large scale survey. The seismic reflection data recorded over the Kapuskasing Zone were afflicted by serious noise problems. Noise surges (Figure 2) on the shot records were so numerous and variable in character and amplitude that they could not be efficiently eliminated using standard processing techniques and thus hindered the realization of a good seismic stack section. As an example, Figure 3 shows

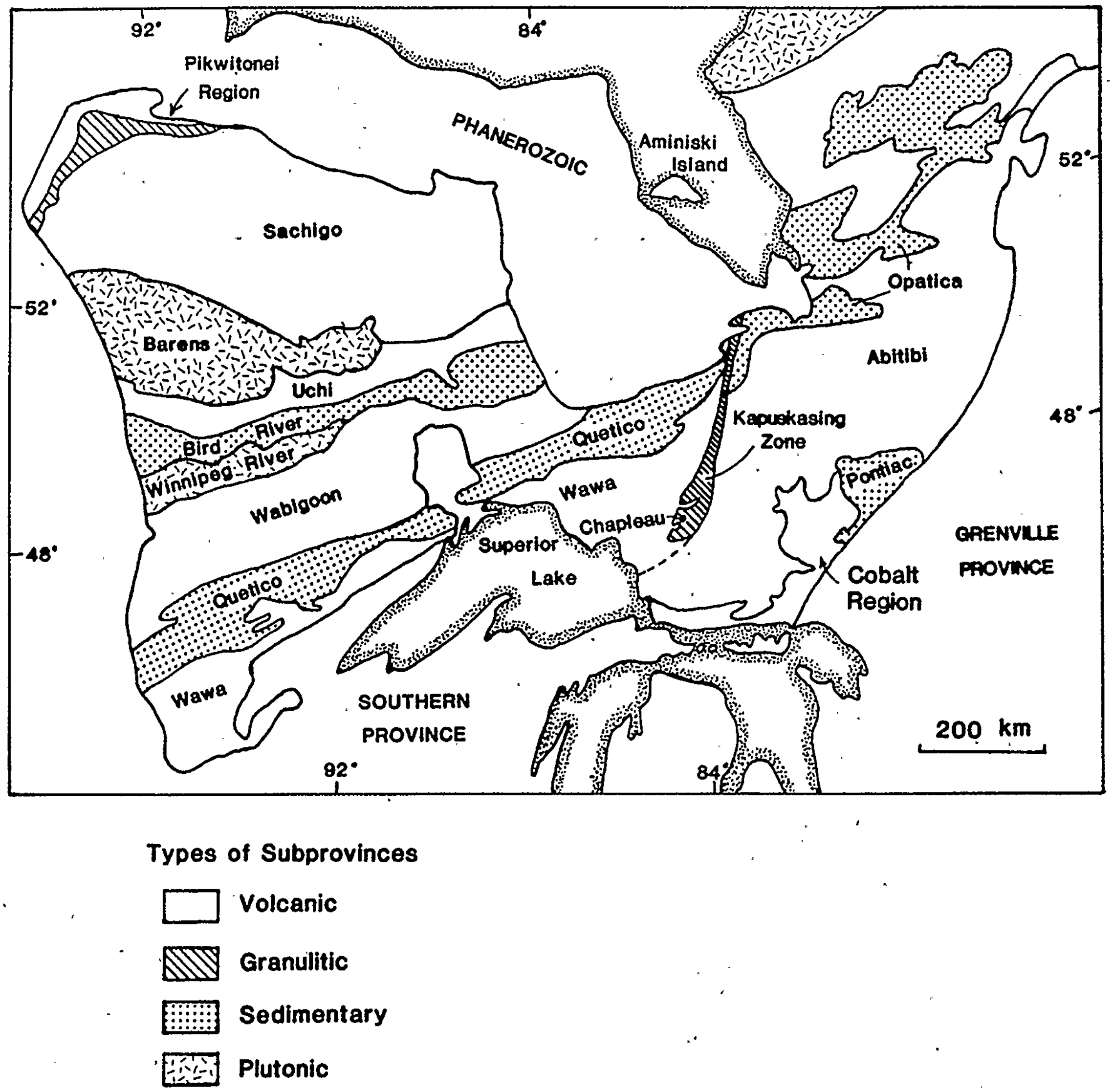
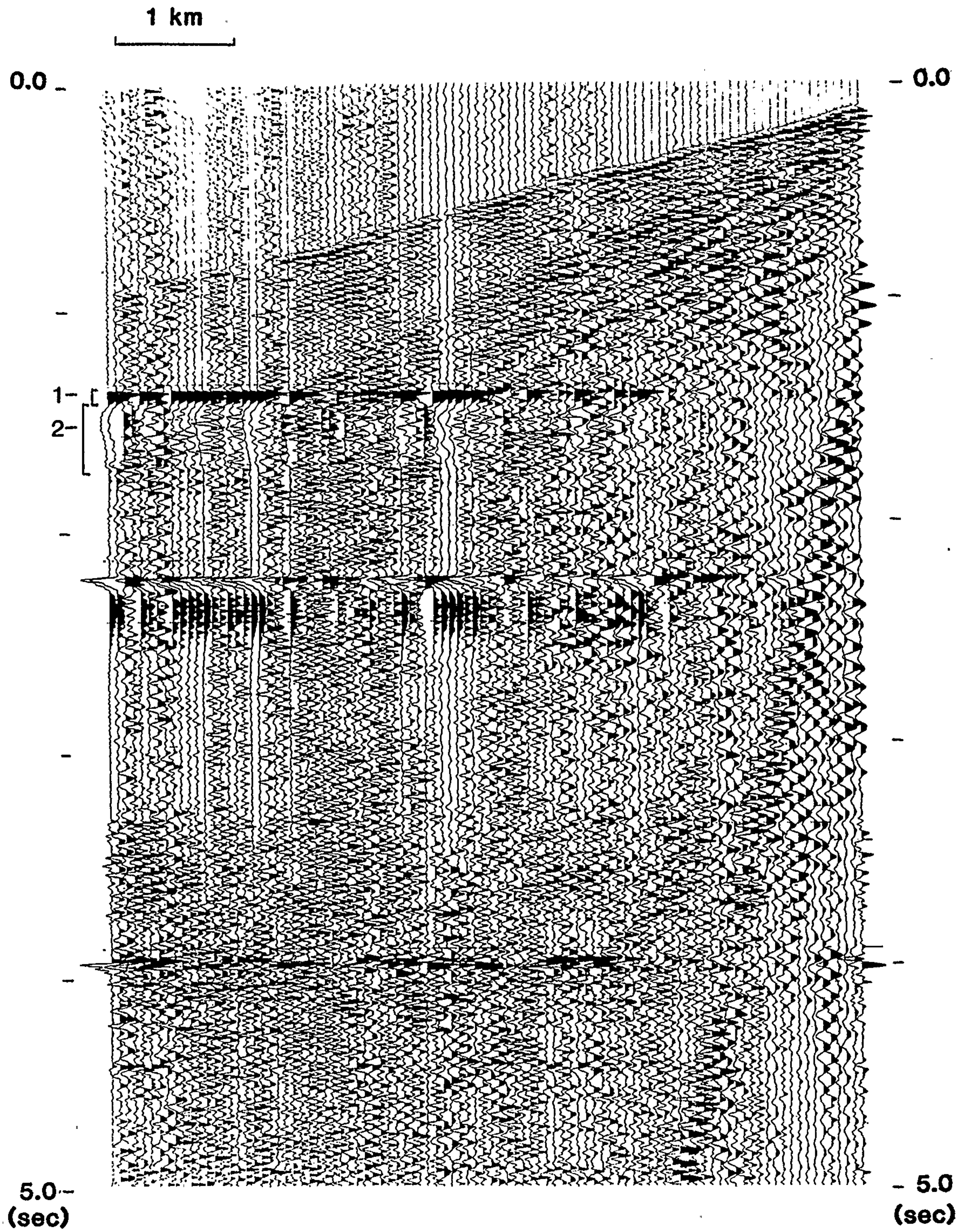


Figure 1, The Kapuskasing Zone and the subprovinces of the Superior province (modified from Ciesielski, 1986).



1- Electrostatic discharge

2- Impulse response

Figure 2, High amplitude coherent noise on record 857 at shot 181.

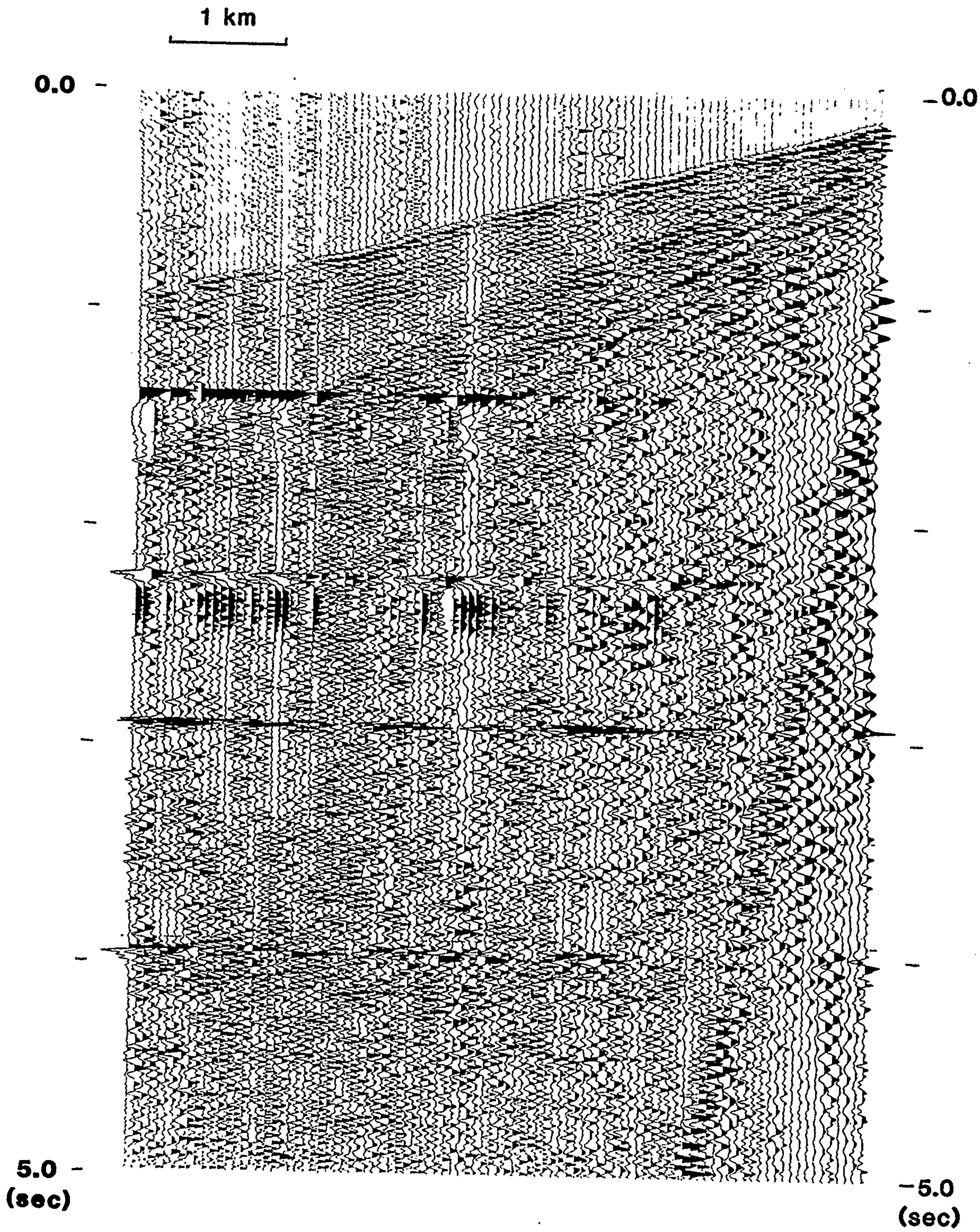


Figure 3, Example of the vertical stack of two shot records, shot 181.

the result of doing a simple sum (vertical stack) of two shot records. The high amplitude noise is still clearly visible.

The characteristics of the noise present on the Kapuskasing data are well illustrated in Figure 2. As the noise can be followed across several traces, it is seen to be spatially coherent. However, the noise is random with respect to time. For simplicity, this special type of noise will be referred to as "the coherent noise" in the remainder of the text. The coherent noise does not show any increase in time with increase of offset distance (normal move-out), as it is always horizontal on a shot record. Its form and amplitude vary from trace to trace and from surge to surge. The duration of individual noise surges vary from 5 milliseconds up to about 50 milliseconds, and their amplitudes can exceed the normal amplitude of the signal and background noise by more than a 100 times. Often when the electrostatic discharges are very strong they literally saturate the recording system, and in reaction the system generates its impulse response. This combination, energy surge/impulse response can be clearly seen on Figure 2 at 1.3 and 2.2 seconds. The coherent noise appears predominantly on the traces which are situated farthest from the shot point; the true signal is much lower in amplitude there than at receivers located closer to the shot point. Only the very high amplitude surges fill all channels; most coherent noise surges affect about 75 percent of all channels across a shot record.

The occurrence of coherent noise was likely a consequence of the high electric resistance of the Precambrian crystalline basement rocks in the study area, and was aggravated by the very humid atmospheric conditions that prevailed during data acquisition. The noise was probably caused by electrostatic discharges from the atmosphere which were not attenuated by the resistive surface lithologies and were thus preferentially discharged into the 6.6 kilometers long recording cable. The recording cable acted as an antenna which received the discharges. As the speed of the discharges in the cable approached the speed of light, there would be no move-out.

The primary objective of this research project addresses the coherent noise problem on the Kapuskasing data. The data were processed on the Perkin-Elmer computer in the department of Geology and Geophysics at the University of Calgary using software developed by Teknica Resources Development Ltd. of Calgary. The software contains the programs normally required to process seismic reflection data and obtain stack sections from field records. However, it proved difficult to achieve a satisfactory cancellation of the coherent noise using any of the existing programs and it was necessary to develop a new approach to this problem.

The solution was effected by the development and implementation of a processing technique called the "diversity stack method" (Kirk, 1981). This technique takes advantage of the fact that several shots were triggered at each shot location. With the use of this particular summation process only the best segments of each trace are selected from all shot records for summation into a single shot record free of the coherent noise.

CHAPTER 2 GEOLOGICAL SETTING

The Superior province of the Canadian shield was a stable craton by the end of the Archean era (2480 Ma). Several subprovinces divide it into volcanic-rich, sedimentary-rich and gneiss-rich belts (Figure 1). The lithologic and structural regional trends in all these belts as well as their associated regional gravity and aeromagnetic anomalies strike in an east-west direction.

In Ontario, the east-west structural trend of the Superior province is crosscut in a northeast direction by the Kapuskasing Zone (Figures 1 and 4). The Kapuskasing Zone is less than 50 kilometers wide and extends for some 600 kilometers from south of Aminiski Island in James Bay to Chapleau (Gibb, 1978; Percival and Card, 1983). Faults along the Kapuskasing Zone bring granulite facies metamorphic rocks into juxtaposition with low grade metamorphic rocks of the Abitibi and Opatica subprovinces to the east and the Wawa and Quetico subprovinces to the west (Percival and McGrath, 1986). Farther to the north, the Kapuskasing Zone is hidden under the Paleozoic cover; its extent can only be inferred from gravity anomalies (Gibb, 1978).

The Kapuskasing Zone is composed of paragneiss, mafic and tonalitic orthogneiss plus the members of the Shawmere anorthosite complex to the south (Percival and Coe, 1980),

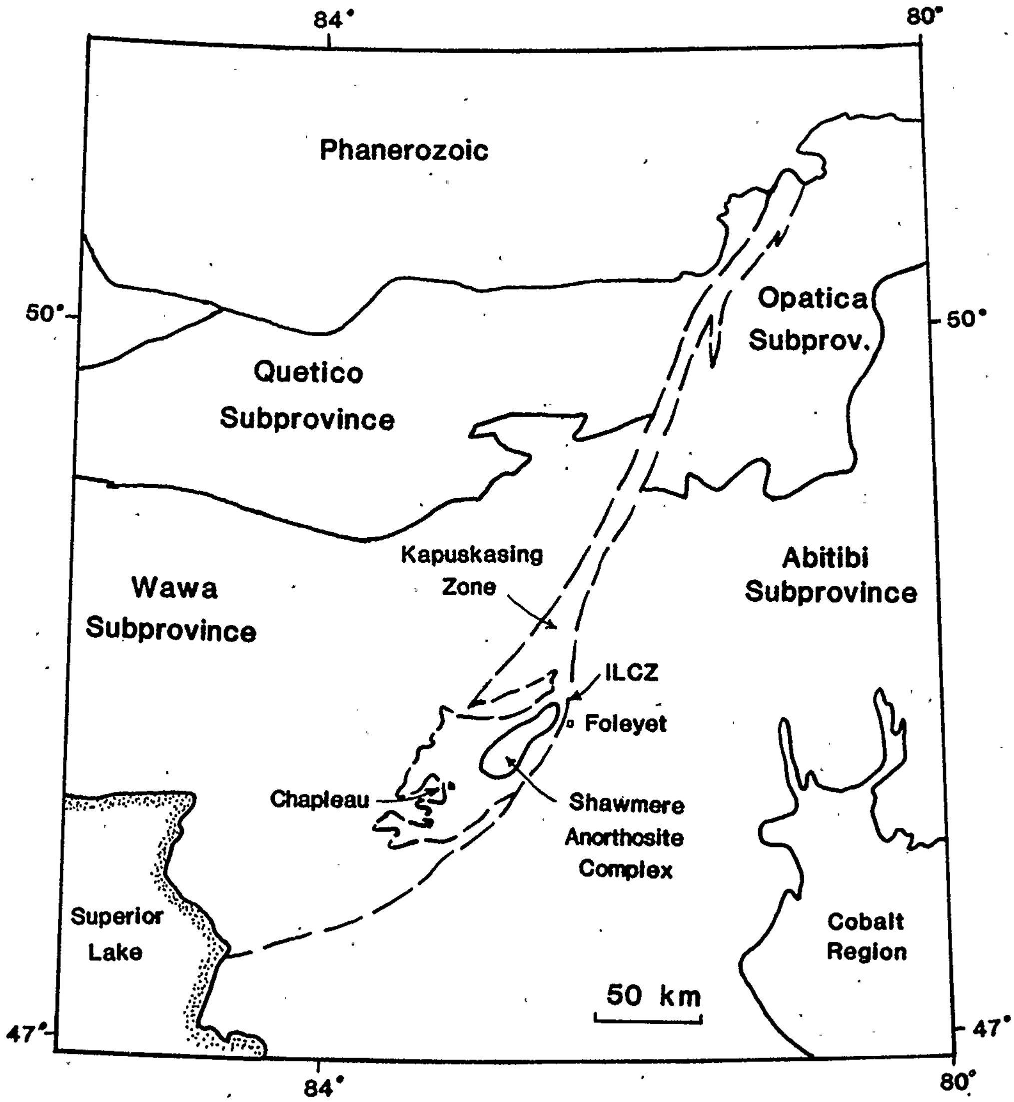


Figure 4, The Kapuskasing Zone (modified from Percival and Card, 1985).

all of Archean age. Metamorphic facies are upper amphibolite to granulite. Lithologies and gneissosity strike northeast and north-northeast and dip 20 to 40 degrees to the northwest.

Within 2 kilometers of the Kapuskasing Zone, to the east of the Shawmere anorthosite complex (Figures 4 and 5), are sporadic occurrences of blastomylonites, pseudotachylites and cataclasite veinlets (Percival and Krogh, 1983). These rocks are the surface expression of a fault zone and are designated as the Ivanhoe Lake Cataclastic Zone (ILCZ on Figures 4 and 5). Aeromagnetic anomalies allowed Percival and McGrath (1986) to extend the fault Zone several tens of kilometers to the north and to the south.

To the east of the ILCZ is the Abitibi subprovince, in which mafic metavolcanics and volcaniclastics form narrow, vertically dipping, east-west belts. Late- to post tectonic massive batholiths of felsic composition intruded the supracrustal rocks and the felsic gneiss which form the terranes between the supracrustal rocks. Metamorphic facies in the supracrustal rocks are sub-greenschist to greenschist and locally lower amphibolite where in contact with intrusions.

Very similar geologic assemblages, structures and metamorphic facies to the Abitibi subprovince can be found in the Wawa subprovince to the west of the Kapuskasing Zone. However the contact between these two areas is not as clearly defined as to the east. The geologic

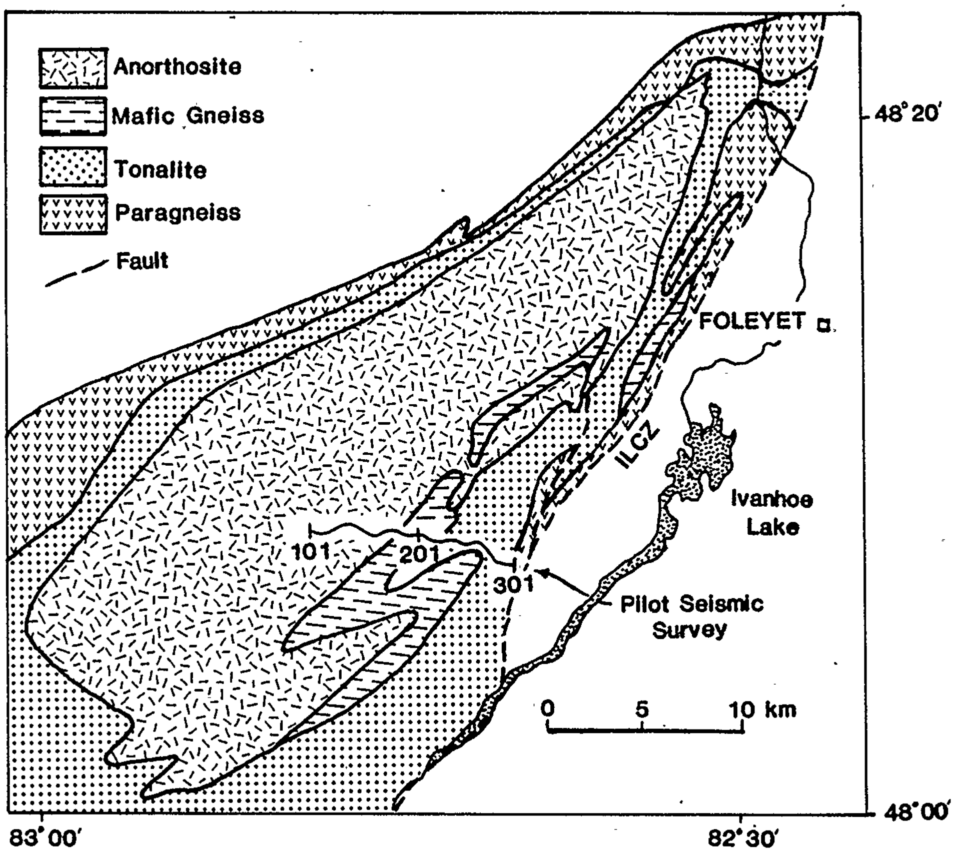


Figure 5, The Shawmere anorthosite complex and the location of the pilot seismic reflection survey (from Cook, 1984).

characteristics change gradually over some 20 kilometers from the Kapuskasing Zone into the Wawa subprovince (Percival and Card, 1983).

To the north, the Kapuskasing Zone transects the east-west striking paragneiss, felsic gneiss and migmatites of the Quetico and Opatica subprovinces. Metamorphic facies in these metasediment-rich subprovinces vary from lower to upper amphibolite.

A positive gravity anomaly is associated with the Kapuskasing Zone. However, this anomaly does not correlate with the surface geology. It is offset by some 20 kilometers to the west relative to the trace of the Kapuskasing Zone, suggesting a deep origin for the anomaly (Garland, 1950, Innes, 1960). The aeromagnetic anomalies on the other hand closely follow the surface geology (Gaucher, 1967).

After many years of study, considerable uncertainty still remains with respect to the causes of this positive gravity anomaly and the structural, lithological and metamorphic contrasts observed between the Kapuskasing Zone and the surrounding subprovinces. Several models have been proposed to explain these phenomena. For example, Garland (1950) interpreted the gravity high as being caused by a rise of the Conrad discontinuity at depth. A rift model, in which associated faults would have permitted the rise of high density material at depth, was proposed by Innes (1960) to explain the gravity anomaly. Innes *et al* (1967), Goodwin

(1972) and Gibb (1978) also supported this interpretation. Burke and Dewey (1973b) further suggested the rift was a failed arm of a triple point junction.

Bennett *et al* (1967) proposed a horst model to explain the different metamorphic facies observed at the surface in conjunction with the gravity anomaly. Stockwell *et al* (1970), Thurston *et al* (1974, 1977) and Jolly (1978) also favored this model.

The Kapuskasing Zone has also been interpreted as the southern extension of the circum Ungava suture (Wilson, 1968). To explain the northeast structural trends in the Kapuskasing Zone, Watson (1980) suggested that the Kapuskasing Zone underwent ductile deformation at depth induced by a sinistral transcurrent motion before being uplifted.

Percival and Card (1983) introduced a new model based on recent rock age determinations, metamorphic pressure and temperature studies and on detailed geological observations. The gradual increase in metamorphic grades and in the proportion of intrusives to supracrustals as one travels from the Wawa subprovince into the Kapuskasing Zone suggest a deepening in the level of exposure from west to east. The presence of a 2 kilometers wide cataclastic zone at the contact between high grade metamorphic rocks of the Kapuskasing Zone and low grade metamorphic rocks of the Abitibi subprovince, as well as the general northeast trend and northwest dip of the rocks of the Kapuskasing Zone, all suggest the presence of a reverse fault along the ILCZ. The gravity high anomaly over the Kapuskasing Zone can also be modelled by a northwest dipping fault with the oldest rocks found in the Kapuskasing Zone. These observations led Percival and Card (1983) to conclude that the Kapuskasing Zone represented an oblique cross-section through some 25 kilometers of Archean crust and that the Kapuskasing Zone was uplifted along a moderately northwest dipping thrust fault. In addition, recent work by Percival and McGrath (1986) demonstrates that the model can be extended to the northern segment of the Kapuskasing Zone.

The thrust fault model developed by Percival and Card (1983) is probably the hypothesis currently accepted by most of the Canadian scientific community. Nevertheless this model was based almost solely on surface geological information. The knowledge of the subsurface structure is necessary in order to either confirm or refute this model. The seismic reflection method is probably one of the best techniques available for imaging subsurface structures. It is the primary goal of the seismic reflection pilot survey to test the feasibility to map reflectors, particularly the ILCZ, in this Archean environment.

CHAPTER 3 THE PILOT SEISMIC REFLECTION SURVEY

The Lithoprobe group designed and performed a short pilot reflection survey over the Kapuskasing Zone in order to evaluate the feasibility of gathering seismic data from this area. The results of this experiment will serve as guidelines for the future major survey (300 to 400 kilometers) which is to be shot over the area during the summer of 1987.

As the energy source, Bolt Technology Corporation provided at cost one of their large (LSS-1T) truck mounted land air guns. This choice was made in an effort to limit field operation expenses. There was, however, some concern about the capability of a single land air gun, even a large one, to generate enough energy for reflections to be recorded, since it was the first time that such an energy source was used to map deep reflections under these geologic conditions (Cook, 1984).

The data were recorded by Can Geo Ltd of Oil Springs, Ontario. They used a set of DFS-V, 96-channel, recording instruments and represented an industry standard. This system did not have the capability of in-field trace summing. At first this incapability appeared as a minor inconvenience; several shots were recorded at each shot station and because they could not be summed, they all had to be stored on magnetic tapes, thus increasing the number of tapes to be manipulated. Fortuitously, it turned out to be an advantage, as after inspection of just a few individual shot records it became evident that the data were afflicted by the serious noise problem (see chapter 1) and that performing a simple sum of the individual records would later prove to be inefficient at eliminating the noise adequately (Figures 3 and 6).

Centered on each receiver station an in-line array of nine 14 Hz geophones was spread over a 33 meters string. This recording geometry was designed to enhance reflected energy emerging near vertical incidence and in an effort to further enhance reflections from the ILCZ, the receiver stations were placed up-dip from the source, assuming the ILCZ was dipping to the northwest. The receiver stations were spaced 67 meters apart, while the air gun was located at 3 station intervals from the first active receiver station. This was done to minimize source generated noise on nearby receivers. The recording filter was set to 0-64 Hz and the sampling interval at 4 milliseconds. The listening time was 15 seconds.

The recording began on July 10, 1984. There was no time for performing extensive noise tests, since the air gun was available for 4 1/2 days only. More noise tests would have been appreciated, particularly to solve ground roll problems which came in very strong on each individual record (Figure 7). Shot stations were located at every other station for a 24 fold common depth point (CDP) coverage. At each shot

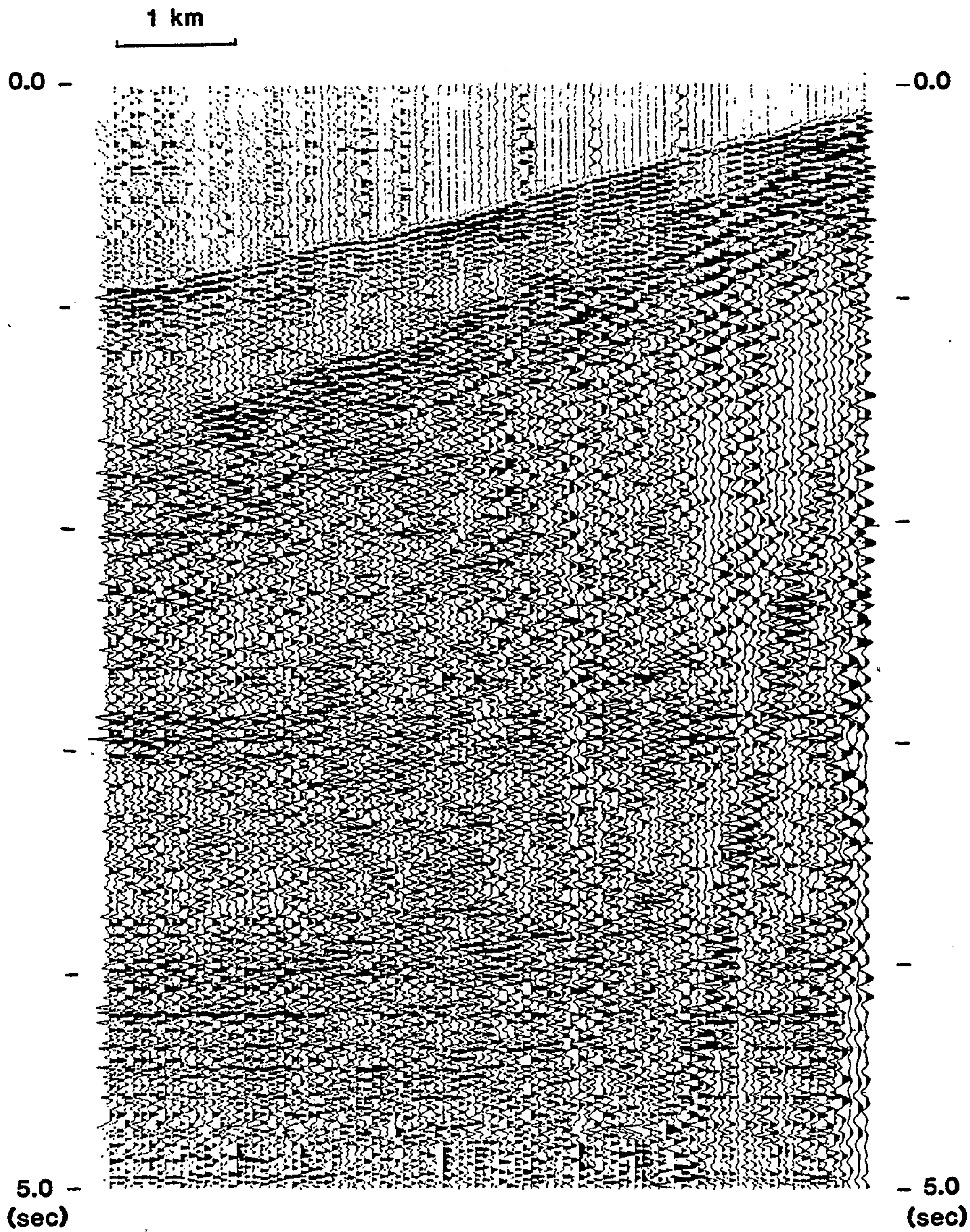


Figure 6, Vertical stack of all 20 records of shot 197.

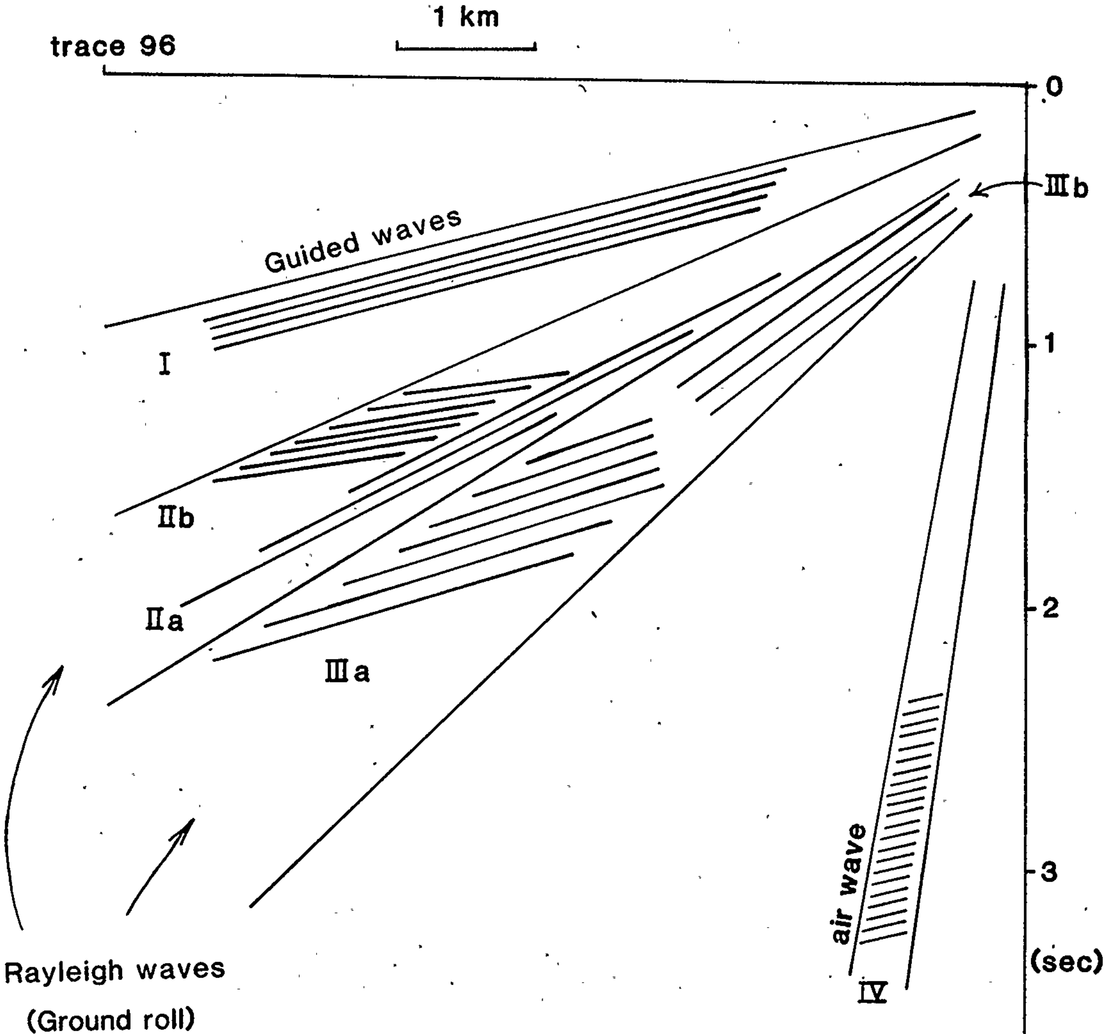


Figure 7, Trends of the apparent (phase) velocity of different coherent noise events as they appear on the shot records.

station the air gun was triggered 20 to 21 times. There was no shot array as it would have been too slow to move the truck. At the end of the survey 65 stations had been recorded for approximately 10 kilometers of data.

The survey was located along a gravel logging road which extends west-northwest from highway 101 at about 20 kilometers to the southwest of Foleyet (Figure 5). The surface geology along the western portion of the line is composed of anorthosite and gabbroic anorthosite members of the Shawmere anorthosite complex and of mafic gneiss, paragneiss and tonalitic gneiss under the eastern segment. Unfortunately, a lack of time did not permit the ILCZ to be crossed. Overburden sediments blanket the bedrock surface with variable and usually unknown thickness. Only between stations 180 and 190 was it possible to assume that the bedrock surface was very shallow as outcrops were seen along the line at that position.

CHAPTER 4 THE DIVERSITY STACK METHOD

The objective of the diversity stack method is the elimination of temporally random high amplitude noise from shot records. To attain this result the diversity stack method requires that at least two shot records be present at each shot location. It is by the application of a particular scaling and stacking process that the high amplitude noise present on individual seismic traces will be scaled down in such a manner as to minimize their influence on the summation of all shot records into a single shot record.

Initial work on the diversity stack method was done by Embree (1968), and a brief description of this technique is provided by Kirk (1981). Kirk's description, although very succinct, contained enough useful information to set up working guidelines for the implementation of the method.

The diversity stack method is designed to stack together shot records that were produced by triggering an energy source several times at the same shot point location while keeping the receivers at their same position. This repeated sampling of the same earth cross-section is a common field procedure which is aimed at improving the signal to noise ratio by summing together all these individual shot records such that coherent energy is enhanced and random noise is attenuated. The stack is usually done by simply summing (vertically stacking) together the shot records. Although this technique can provide a good signal to noise ratio improvement, there are some situations where noise bursts may be so high in amplitude that they will not cancel out. The coherent noise present on the Kapuskasing data is a good example of such high amplitude noise. In this case the diversity stack method provides a more appropriate means of summation as it will perform the stack with the benefit of eliminating the high amplitude noise.

The diversity stack method can be summarized into three distinct steps : scaling, summation and normalization. A diversity stack is performed on sequential groups of traces which display the same offset distance (common offset traces). Thus each common offset group is processed independently of the others. For the process to be effective the high amplitude noise bursts must occur randomly with respect to time within a single common offset group. The following description and examples of each of the three steps involved in the diversity stack process illustrate the point.

The initial step involves the scaling of all seismic traces at one particular offset. Each trace is scaled individually by the use of a moving time window. At each window position, the energy is computed by summing the squares of all sample amplitudes within the window. This energy value is then inverted and becomes the scale factor. The scaling is done by multiplying each sample within the window by this scale factor. The window is then moved down the trace by one full window length and the scaling is repeated. All scaled traces and their associated scale factors, here called gain traces, are kept in the computer's memory. When the scaling window includes some high amplitude noise, the energy values will be very high numbers and consequently the scale factors will be much smaller numbers than when the noise is absent. As a result, the high amplitude noise will be drastically scaled down.

The second step consists in the summation of all scaled traces together and likewise all gain traces together. The contribution of the segments containing high amplitude noise to the scaled trace and gain trace sums is practically insignificant.

The final step normalizes the summed scaled traces by dividing it by the summed gain traces. This operation restores the amplitude variations along the trace as they were present on the original traces with an improvement of the signal to noise ratio comparable to the one obtained from doing a vertical stack and with the additional benefit of having eliminated the high amplitude noise.

This first example will demonstrate numerically the effect of high amplitude noise on the diversity stack process.

Consider the following two digital traces:

trace 1 : $S_1, S_2, S_3, S_4, \ldots$ $\quad$ 1,2,3,4, ... = time samples

trace 2 : $T_1, T_2, T_3, T_4, \ldots$

Using a scaling window of length equal to 2, then for the two window positions the scale factors will be:

trace 1 $\dfrac{1}{S_1^2 + S_2^2}$ and $\dfrac{1}{S_3^2 + S_4^2}$

trace 2 $\dfrac{1}{T_1^2 + T_2^2}$ and $\dfrac{1}{T_3^2 + T_4^2}$

The scaled traces will be:

scaled trace 1 $\dfrac{S_1}{S_1^2 + S_2^2}, \dfrac{S_2}{S_1^2 + S_2^2}, \dfrac{S_3}{S_3^2 + S_4^2}, \dfrac{S_4}{S_3^2 + S_4^2}$

scaled trace 2 $\dfrac{T_1}{T_1^2 + T_2^2}, \dfrac{T_2}{T_1^2 + T_2^2}, \dfrac{T_3}{T_3^2 + T_4^2}, \dfrac{T_4}{T_3^2 + T_4^2}$

The scaled traces are then summed together as are the gain traces (scale factors). Finally, the sum of the scaled traces is divided by the sum of the gain traces to normalize the traces. The entire diversity stack process can then be summarized for the first time samples by the next equation.

$$\left(\frac{S_1}{S_1^2 + S_2^2} + \frac{T_1}{T_1^2 + T_2^2}\right)\left(\frac{1}{S_1^2 + S_2^2} + \frac{1}{T_1^2 + T_2^2}\right)^{-1} \qquad (1)$$

Now, consider the case where S_1 is a high amplitude noise event and is equal to:

$$S_1 = 10T_1 = 10S_2 = 10T_2$$

Then, equation 1 can be expressed in terms of T_1, i.e., the sample amplitude value of trace 2.

$$\left(\frac{10T_1}{100T_1^2 + T_1^2} + \frac{T_1}{T_1^2 + T_1^2}\right)\left(\frac{1}{100T_1^2 + T_1^2} + \frac{1}{T_1^2 + T_1^2}\right)^{-1}$$

and if T_1 is set to one, the signal amplitude, the equation becomes:

$$\left(\frac{10}{101} + \frac{1}{2}\right)\left(\frac{1}{101} + \frac{1}{2}\right)^{-1} = 1.175$$

The first term in the first bracket represents the contribution of the high amplitude noise to the sum of the scaled traces, while the first term in the second bracket represents its contribution to the sum of the scale factors. The contribution to the sums is not very significant, especially for the sum of the scale factors. After normalization a value very close to T_1 , the true signal, will be output (1.175). The effect of the high amplitude noise has been considerably diminished compared to, for example, a vertical stack where the output value would be 5.5, which is still well above the true signal and therefore has not improved the data very much.

If we now consider S_1 and T_1 to be signal, they should then have very similar amplitude and be of the same polarity. The output to the diversity stack would then be very close to the exact average of S_1 and T_1. Furthermore if S_1 and T_1 are now true random noise, they can then be again of about the same amplitude but of opposite polarity. It can be seen from the first bracket of equation (1) that this noise should cancel. This is in fact how the diversity stack methods will increase the signal to noise ratio.

As a last example, two seismic traces, traces 1 and 2 on Figure 8, have been selected from the Kapuskasing data.

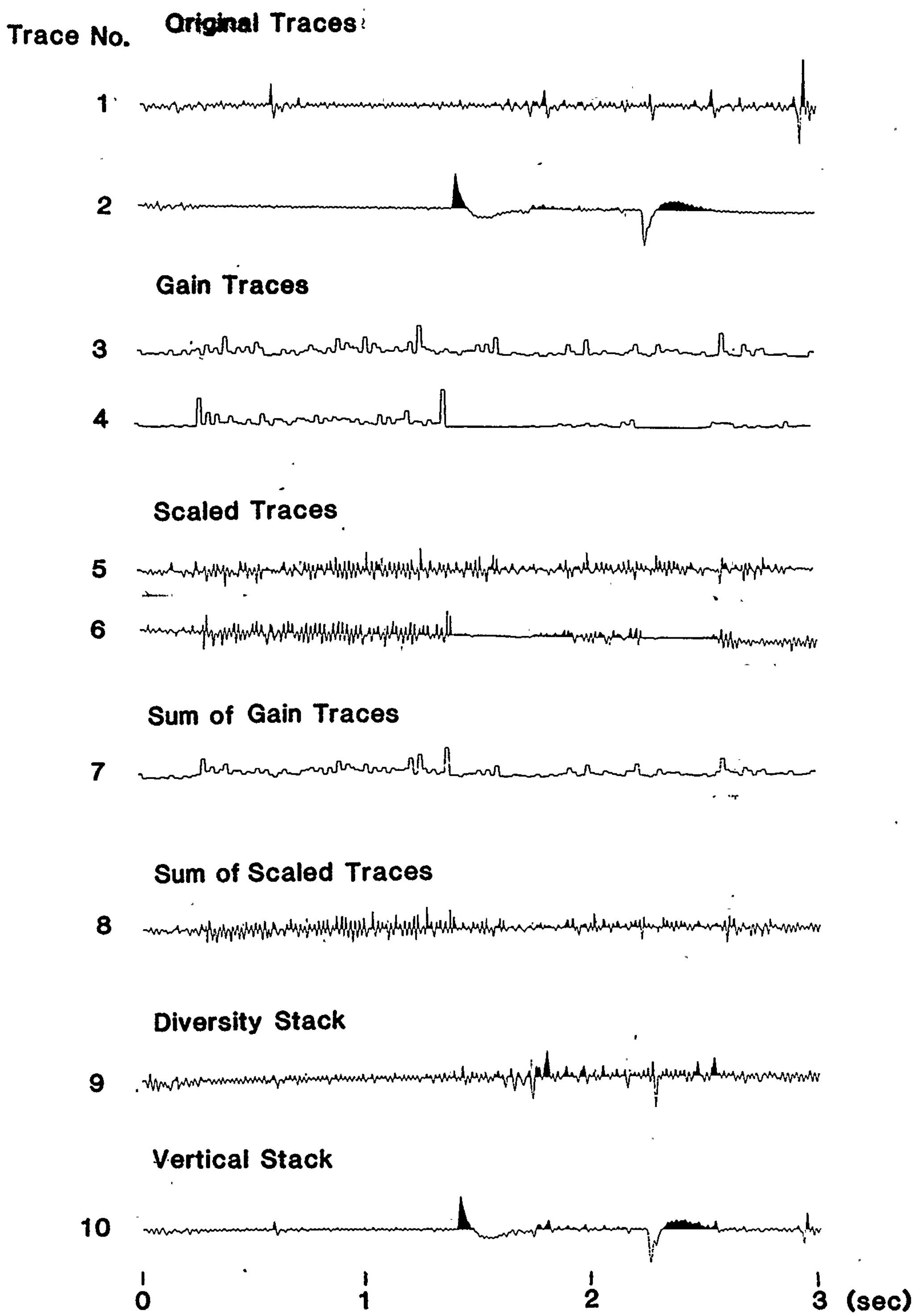


Figure 8, The diversity stack process.

Both traces belonged to the same common offset group. Trace 1 contains only one high amplitude noise event (the peak at 2.94 seconds), whereas trace 2 has very high amplitude maxima at 1.41 and 2.25 seconds respectively. This is more clearly demonstrated when the amplitude values that occur concurrently with the two large peaks on trace 2 are listed (Table 1). In this example, the amplitude of the noise events from trace 2 are over a hundred times higher than the average signal and random noise from trace 1 (Table 1). For this reason, these two traces as well as all the others appearing on Figure 8 are not displayed at a common scale. They have been normalized such that when the noise bursts are absent the trace shape can be seen.

The scaling window was set at 20 milliseconds. The scale factors have been computed for each trace and are displayed as traces 3 and 4 (gain traces). Traces 5 and 6 are the resulting scaled traces. It can be noted that when a high amplitude noise event is present the scale factor becomes a very small number (trace 4, Table 1) and that the amplitude of the corresponding scaled trace (trace 6, Table 1) is also a small number. Then the contribution to the scaled traces and gain traces sums by the high amplitude noise is practically insignificant (traces 7 and 8, Table 1). After normalization (trace 9) the relative amplitudes are restored to what they were on the original traces with an improvement on the signal to noise ratio in addition to the elimination of the high amplitude noise.

Table 1 ; The diversity stack method

Scaling window : 20 msec (5 samples)

Trace	1.408 sec.[1]	2.248 sec.	Comments
1	-2.25×10^{4}	4.52×10^{3}	tr. 96 - rec. 856
2	2.26×10^{6}	-2.27×10^{6}	tr. 96 - rec. 857
3	7.05×10^{-11}	3.36×10^{-10}	gain trace 1
4	5.44×10^{-14}	5.81×10^{-14}	gain trace 2
5	-1.59×10^{-6}	1.52×10^{-6}	scaled trace 1
6	1.23×10^{-7}	-1.32×10^{-7}	scaled trace 2
7	7.06×10^{-11}	3.36×10^{-11}	sum gain traces
8	-1.46×10^{-6}	1.39×10^{-6}	sum scaled traces
9	-2.07×10^{4}	4.13×10^{4}	diversity stack
10	2.24×10^{6}	-2.26×10^{6}	vertical stack

(1) Instrument gain recovery was done on the data during demultiplexing, therefore the listed amplitude values are now unit free.

For comparison, trace 10 was obtained by doing a vertical stack of traces 1 and 2. It is clear that the diversity stack method removes high amplitude random noise bursts far more efficiently than the normal summation.

In addition, one very important aspect of the diversity stack method is that the true amplitude character of the traces is preserved (Kirk, 1981). This was not the case, for example, for the automatic gain control (AGC) scaling done by Cook (1984) in an earlier attempt to attenuate the coherent noise present on the Kapuskasing data.

The key factors that permit the diversity stack method to eliminate noise from shot record data are first that the noise must be of higher amplitude than the normal trace amplitude and second the noise must be temporally random.

CHAPTER 5 PERFORMANCE OF THE DIVERSITY STACK PROGRAM

The ability of the diversity stack method to cancel noise has been compared with the results achieved from doing both a simple vertical stack and an AGC scaling of the shot records prior to vertical stack. These are essentially the only noise attenuation techniques available on the Teknica software other than actual removal of the noisy segments by selective muting of each record.

The first tests were carried out on 2 shot records, records 856 and 857 of shot point 181 (Figures 9 and 10). These records display very good examples of the electrostatic noise. Record 856 contains one large segment of coherent noise at 2.90 seconds and several smaller ones, such as those occurring at 3.25, 3.40 and 4.00 seconds. Record 857 shows two very large coherent noise events, starting at 1.40 and 2.25 seconds respectively. These last for several hundred milliseconds and mask all of the seismic signal. A smaller noise event can be observed at 4.00 seconds.

When several shots are triggered at one shot station, it is normal practice to sum all individual shot records immediately during the field operation. Such a vertical stack is intended to remove the majority of small amplitude noise problems present in most unprocessed seismic data, as well as to significantly improve the signal to noise ratio.

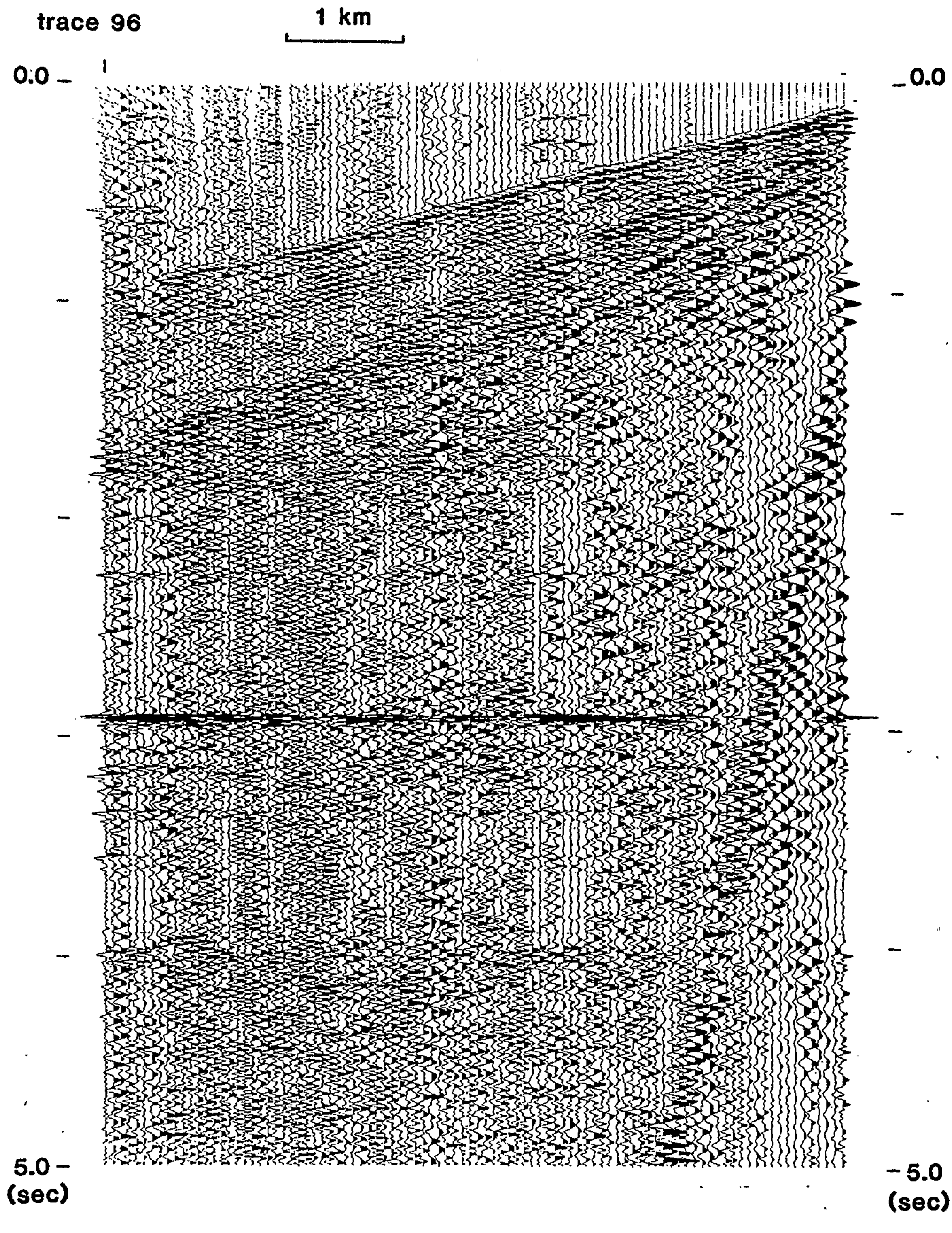


Figure 9, Record 856 of shot 181.

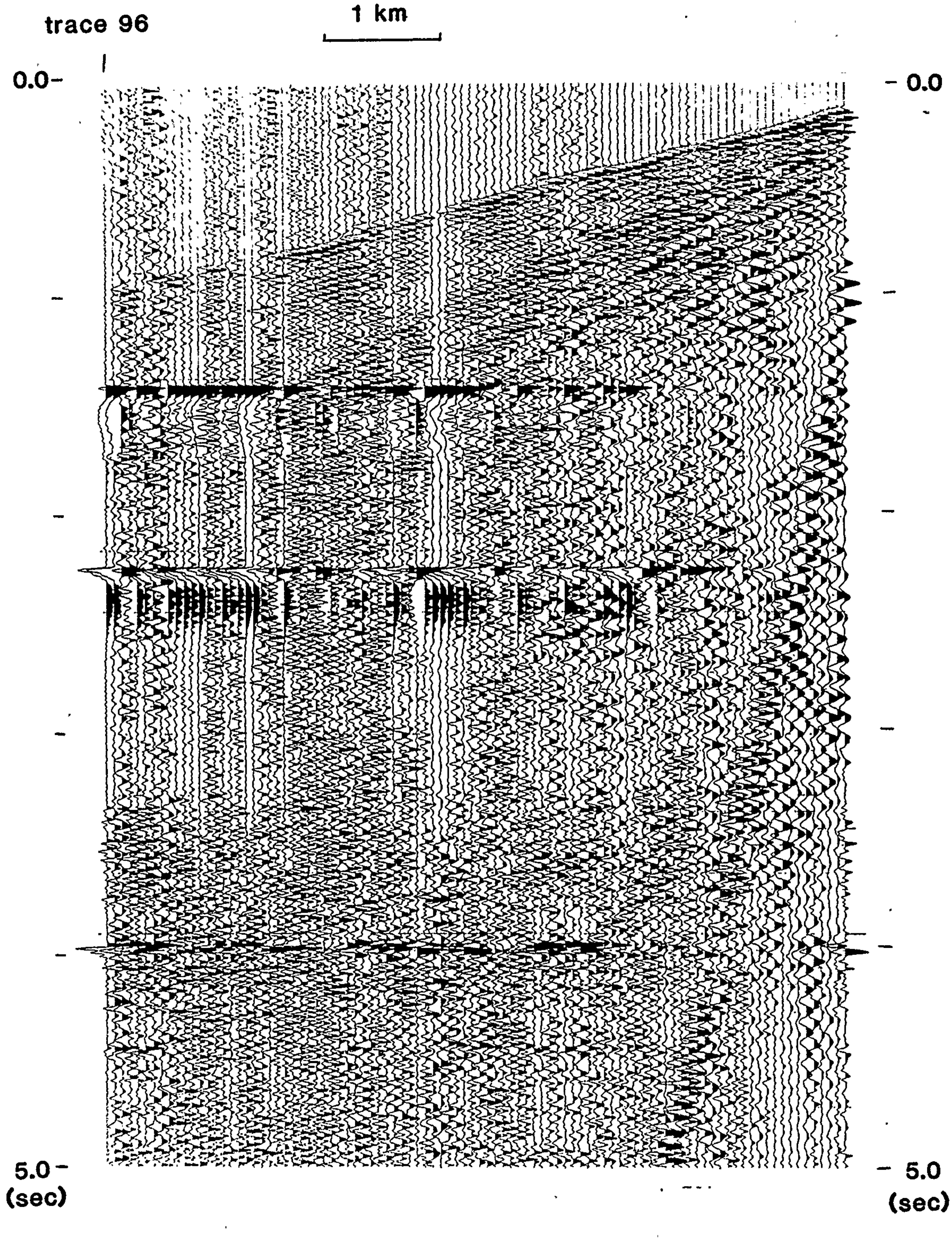


Figure 10, Record 857 of shot 181.

However, if very high amplitude noise, like that encountered on records 856 and 857, is present in the data, a simple vertical stack is not an efficient method of suppression (Figure 11); as the coherent noise is commonly a hundred times higher in amplitude than that of the usual signal and background noise present on a trace. The coherent noise still shows up very clearly after summation and its presence on the shot record can seriously affect the quality of the final stack section. This example clearly demonstrates the importance of keeping all shot records for further treatment at a processing centre, especially if direct suppression of the noise during the field operations proves difficult.

The method that was originally used to remove the coherent noise from the Kapuskasing data consisted of applying an AGC scaling on all shot records with a very short window (50 milliseconds) followed by a summation of all records (Cook, 1984). The purpose of doing an AGC scaling is to equalize the amplitude level along the traces. Its effect is to scale down the high amplitude events in relation to the low ones. One drawback of using an AGC scaling is that the true amplitude character of the traces is lost.

AGC scaling is applied using a scaling window which is moved along the trace. Root mean square (RMS) calculations are performed on the samples contained in the window. These involve the summation of the squares of all the amplitude samples within the window, a division of the sum by the

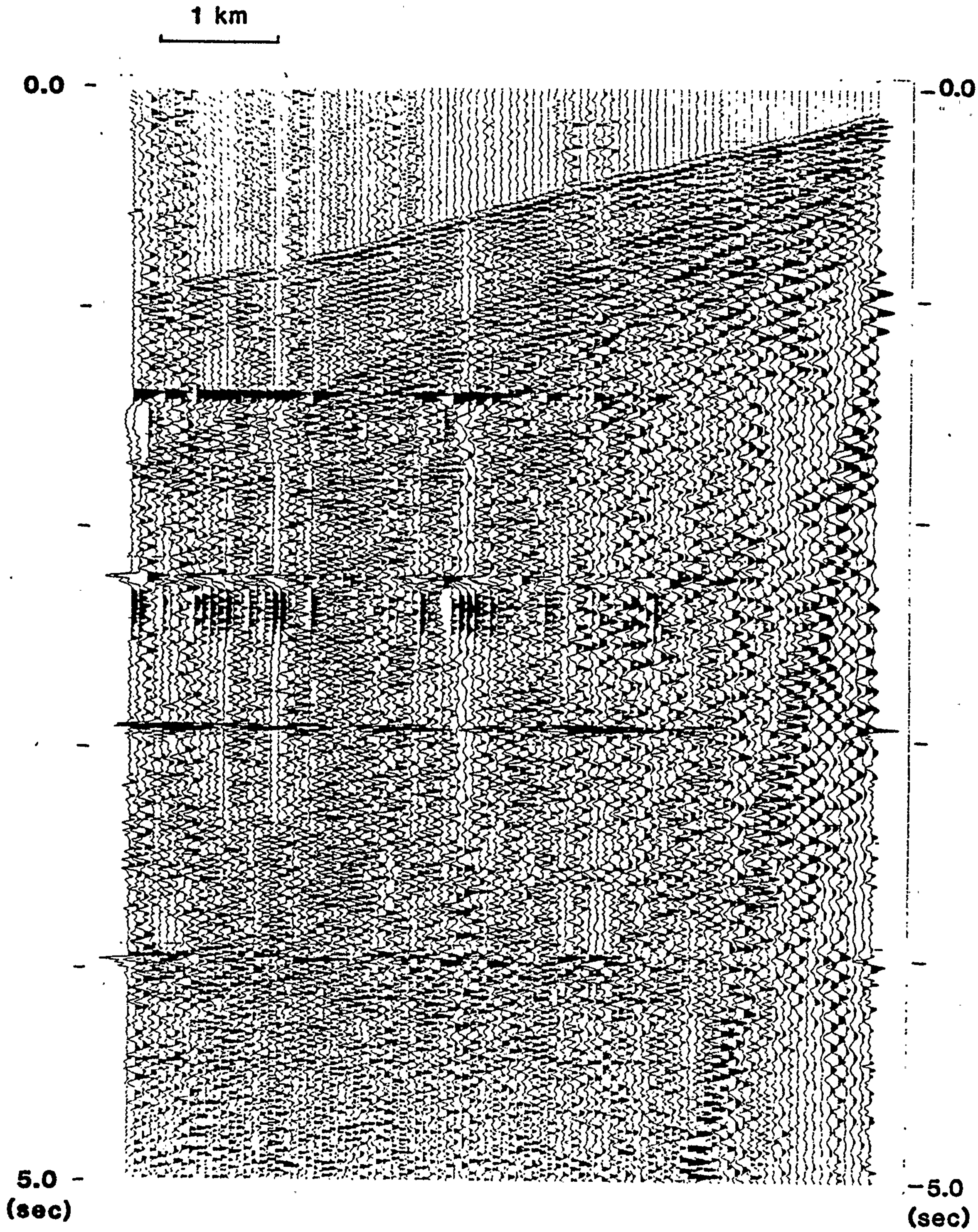


Figure 11, Vertical stack of records 856 and 857 of shot 181.

number of samples used, and finally the extraction of the square root value. This computed number, called the scale factor, is then used to scale the sample in the middle of the window. This is done by dividing the sample by the scale factor. The window is then moved down the trace by one sample and the scaling is repeated.

AGC scaling was done on the two shot records using a 50 milliseconds window. The final record (Figure 12) was obtained by summing the two scaled records together. The attenuation of the coherent noise was satisfactory, even if shadows of the two very large surges at 1.40 and 2.25 seconds were still visible. The general appearance of the record was, indeed, the most striking change. This effect is a direct consequence of using a very short scaling window; the high amplitude segments have been equalized practically to the same level as the low amplitude segments, causing the traces to appear to possess the same amplitude level along their full length. In other words, the true amplitude information of the traces has been lost. Nevertheless, common depth point (CDP) stacking should allow coherent reflections to be visible.

Application of a 50 milliseconds diversity stack window on the two shot records produces the record shown in Figure 13. The superiority of the diversity stack method when compared to a vertical stack or AGC scaling, is obvious. The coherent noise has been efficiently removed and the true amplitude character of the traces is preserved. Despite

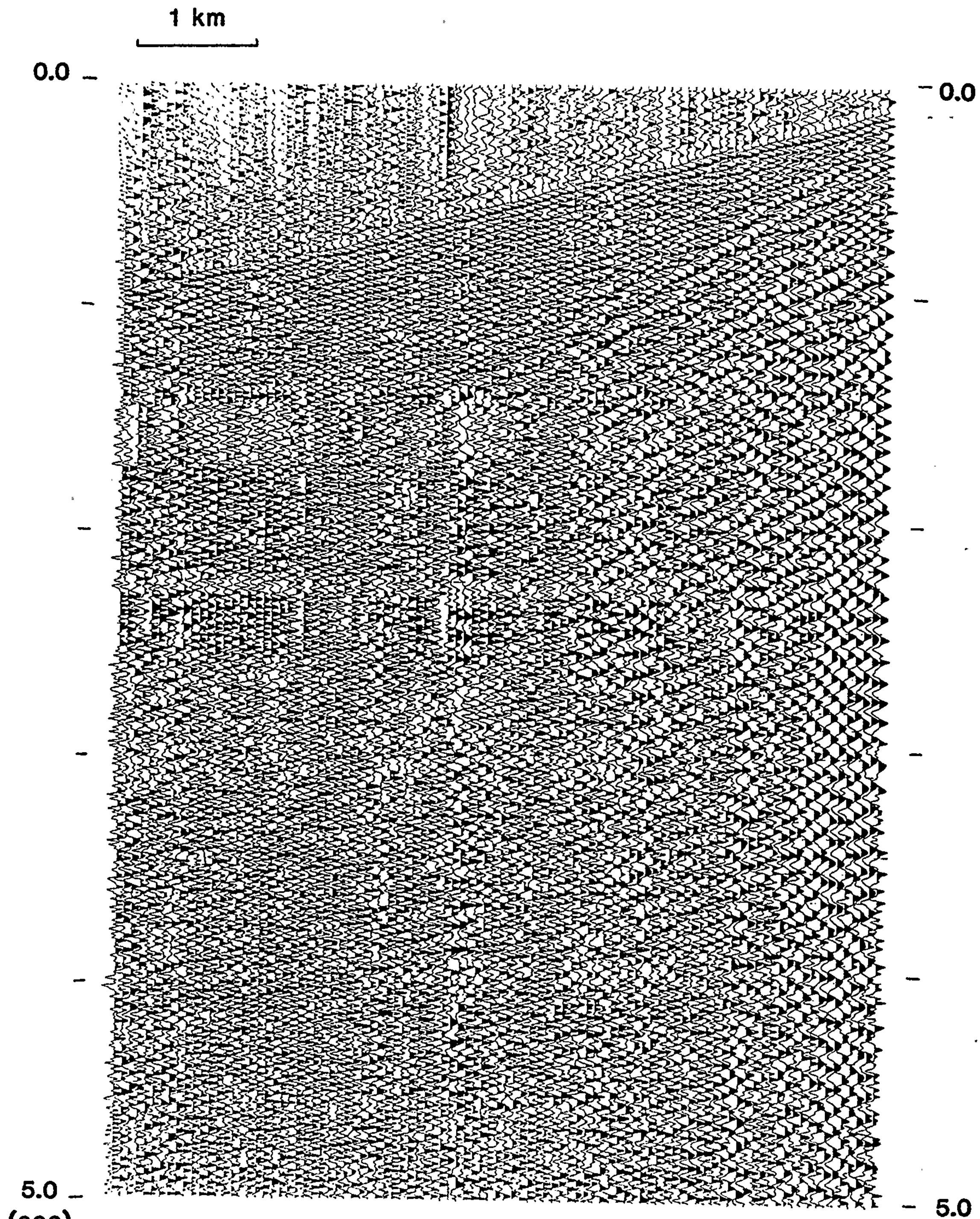


Figure 12, AGC scaling (50 msec window) and vertical stack of records 856 and 857 of shot 181.

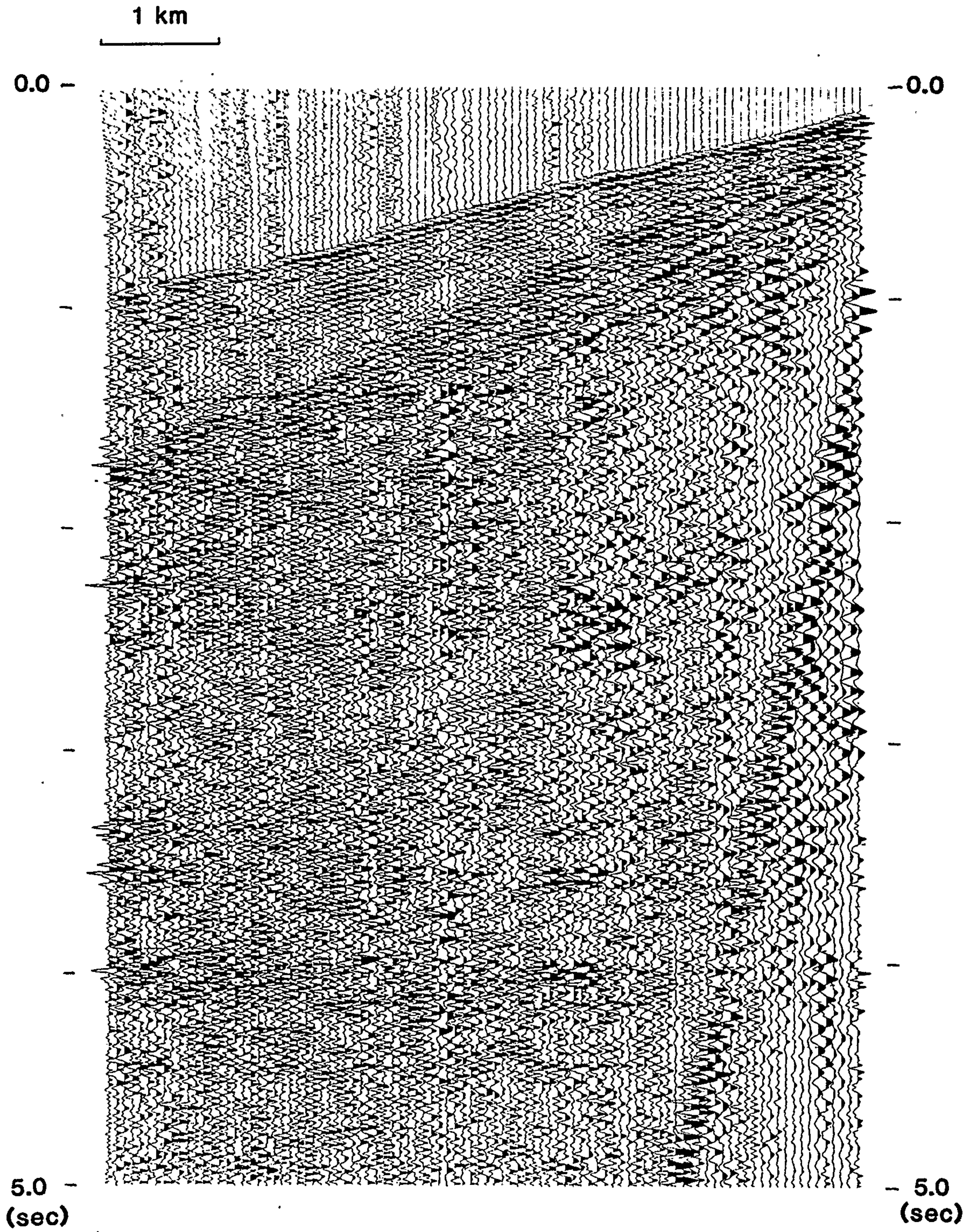


Figure 13, Diversity stack (50 msec window) of records 856 and 857 of shot 181.

these improvements, few remnants of the coherent noise are still faintly visible at 2.25 and 4.00 seconds. These are visible because noise was present at the same times on the two shot records used. The noise with the lowest amplitude passed through. This is in fact the principle behind the diversity stack method. In a common offset group the time segments of the traces which are of higher amplitude than their time equivalent ones on the other traces are considered to be high amplitude noise and are therefore scaled down. Similarly, the low amplitude segments are considered to be signal and are given more weight in the diversity stack. So the lowest of the noise events will show up on the diversity stack record. However, the diversity stack method still produces a much better final record than any of the other techniques used.

A comparison of the vertical stack and the diversity stack within the zones where the coherent noise is absent, above 1.3 seconds for example, shows that the amplitudes and waveforms on each stack compare very well. This means that in absence of high amplitude noise the diversity stack method can achieve a summation that is as good as a vertical stack.

The addition of more shot records to the shot series improved the performance of the vertical stack as well as the AGC scaling. A vertical stack of the 21 shot records from shot point 181 is illustrated in Figure 14. The summation of a large number of shot records effectively

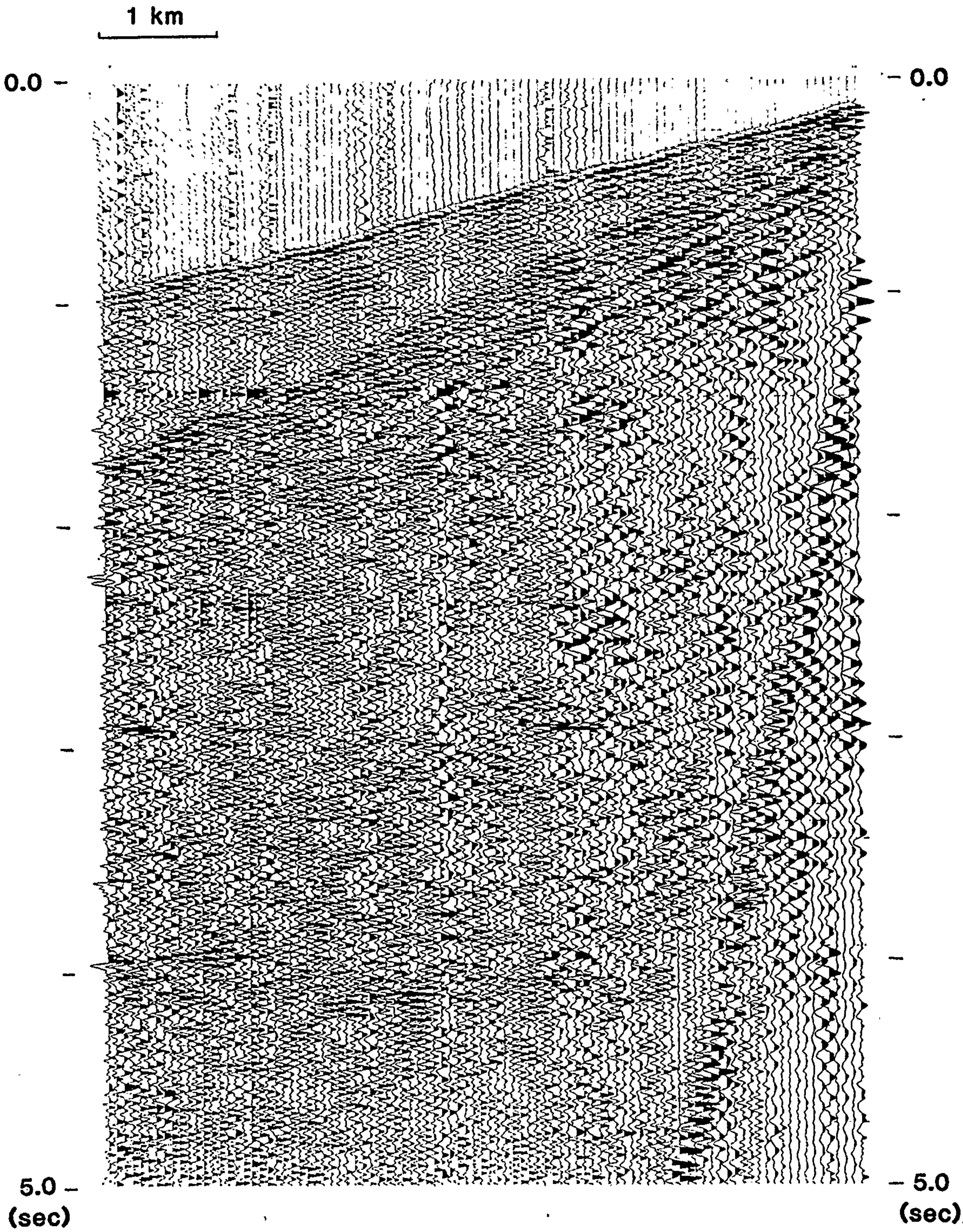


Figure 14, Vertical stack of all 20 records of shot 181.

cancelled the high amplitude coherent noise. The section appears to be reasonably clean with the exception of some remnant noise at 1.40 and 2.40 seconds. The same 21 shot records were passed through the AGC scaling program and vertically stacked (Figure 15). The noise has been eliminated, but again the true amplitude character of the traces has been lost. As predicted, a diversity stack of the 21 shot records resulted in the best record of all (Figure 16). The record is free of coherent noise and the true amplitude information has been preserved.

As a further example, shot 197 was chosen because of its very noisy character. A vertical stack of 21 shot records gave the seismic record in Figure 17. Considerable noise is still present. A diversity stack of the same records (Figure 18) produced a much cleaner result but some low amplitude coherent noise still remained. Coherent noise surges on these shot records were so numerous that many of them occurred at almost the same time on most of the shot records. As a consequence, the coherent noise surges simply added up as true signal. Nevertheless, the diversity stack method still produced the best results.

The choice of the window length is an important parameter. An extreme case is to select a one sample window length. It inevitably produces a spiky record (Figure 19) because the samples near the zero crossings of the trace will be very small numbers and therefore will have a disproportionately heavy weight in the sums. The other

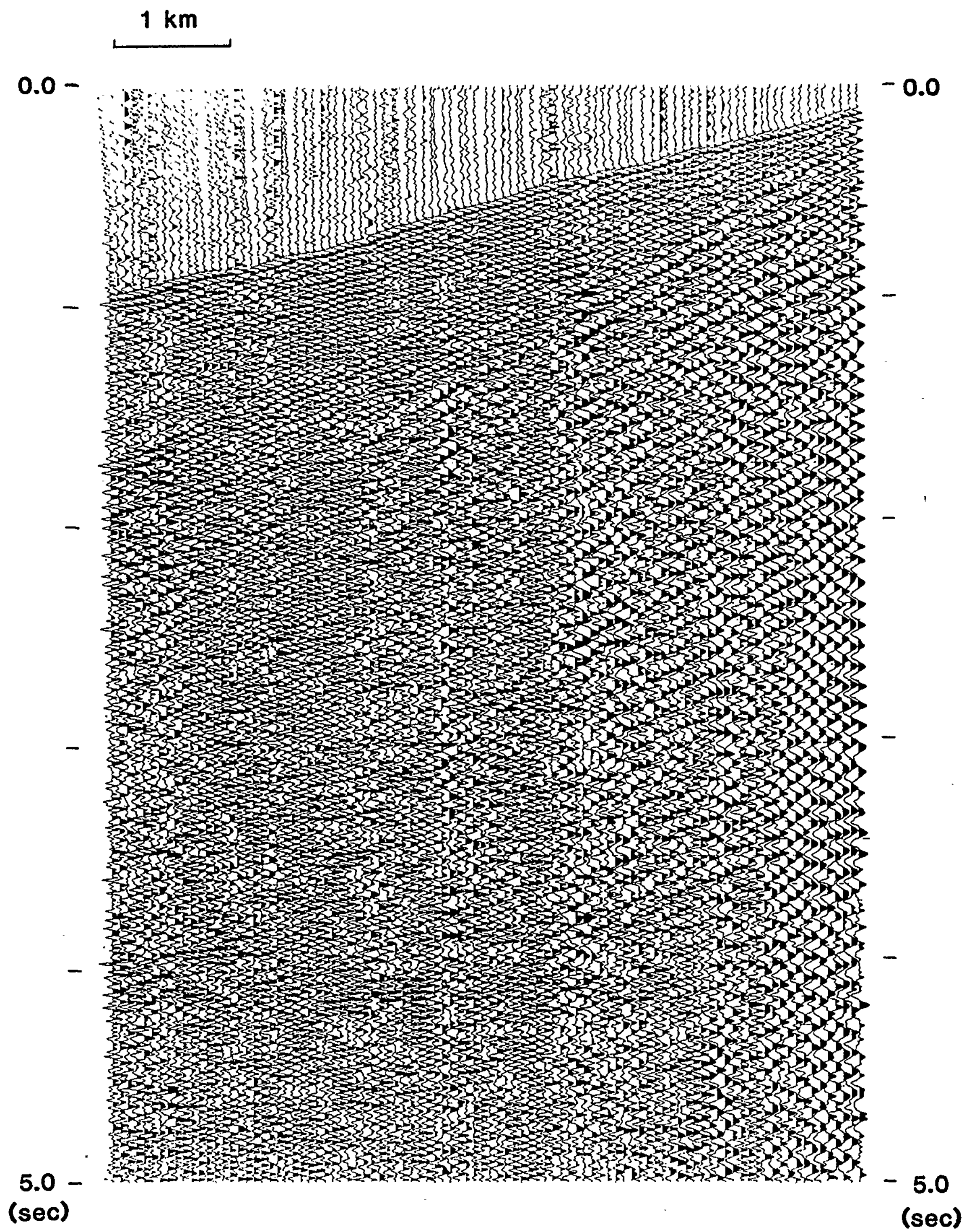


Figure 15, AGC scaling (50 msec window) of all 20 records of shot 181.

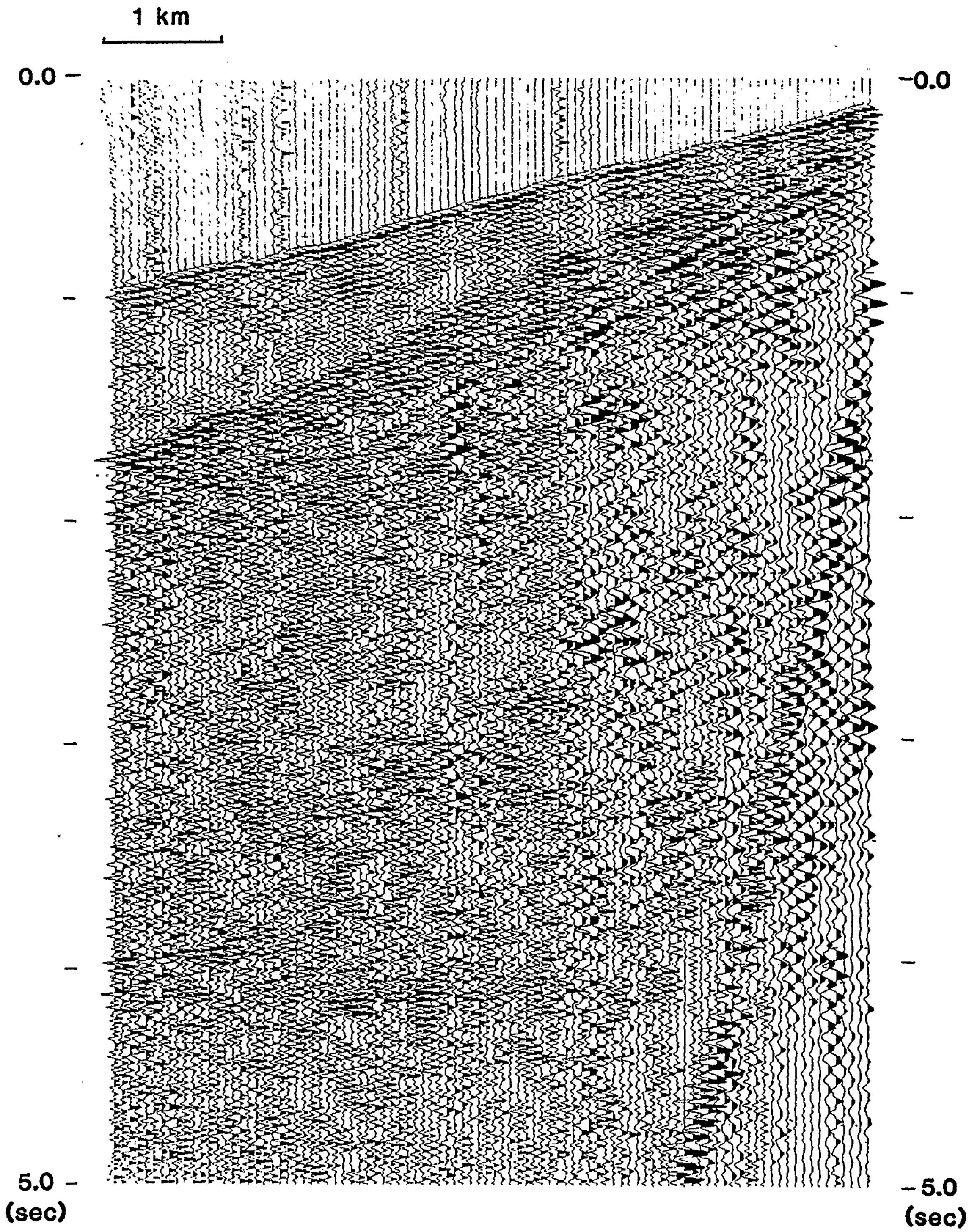


Figure 16, Diversity stack (50 msec window) of all 20 records of shot 181.

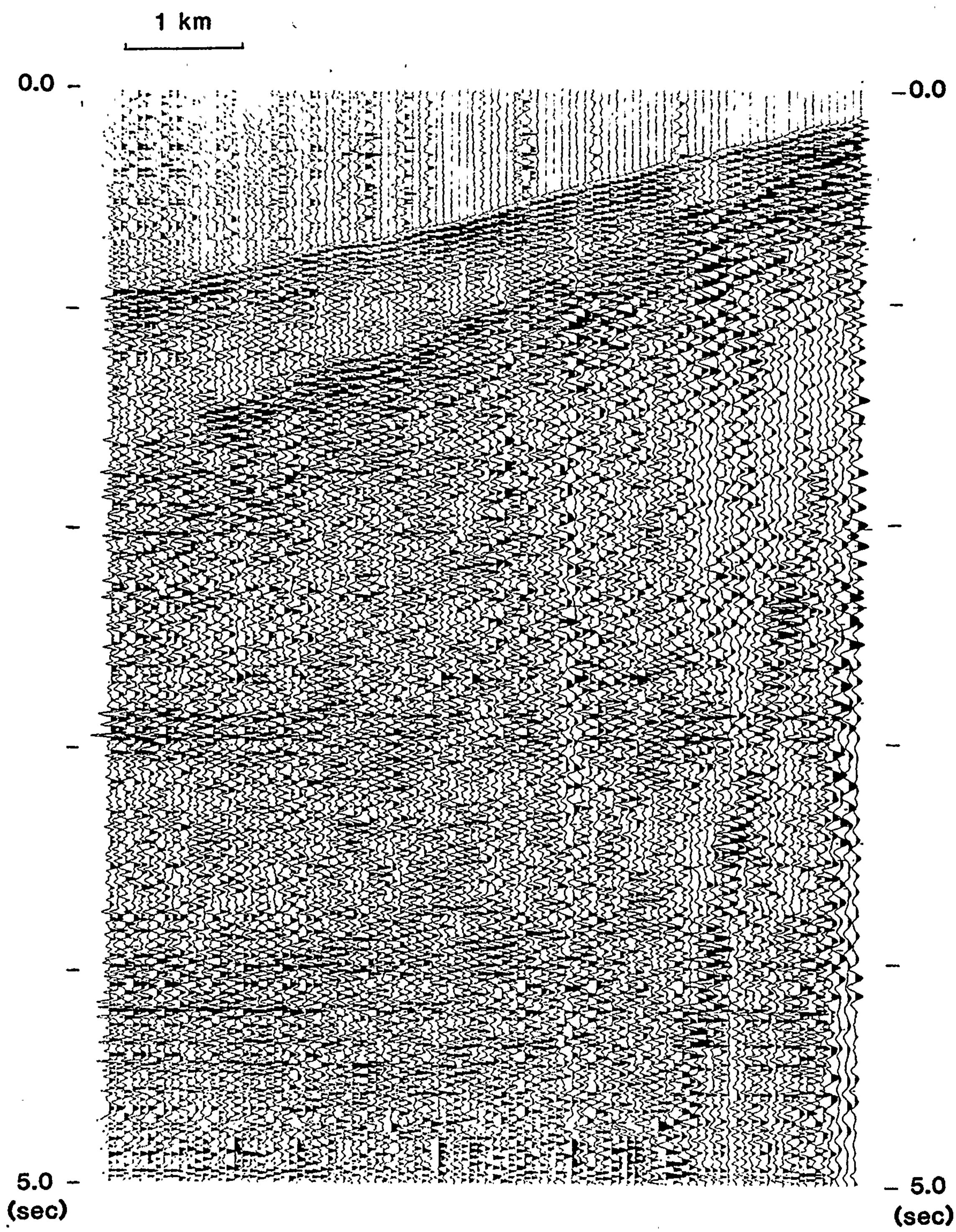


Figure 17, Vertical stack of all 20 records of shot 197.

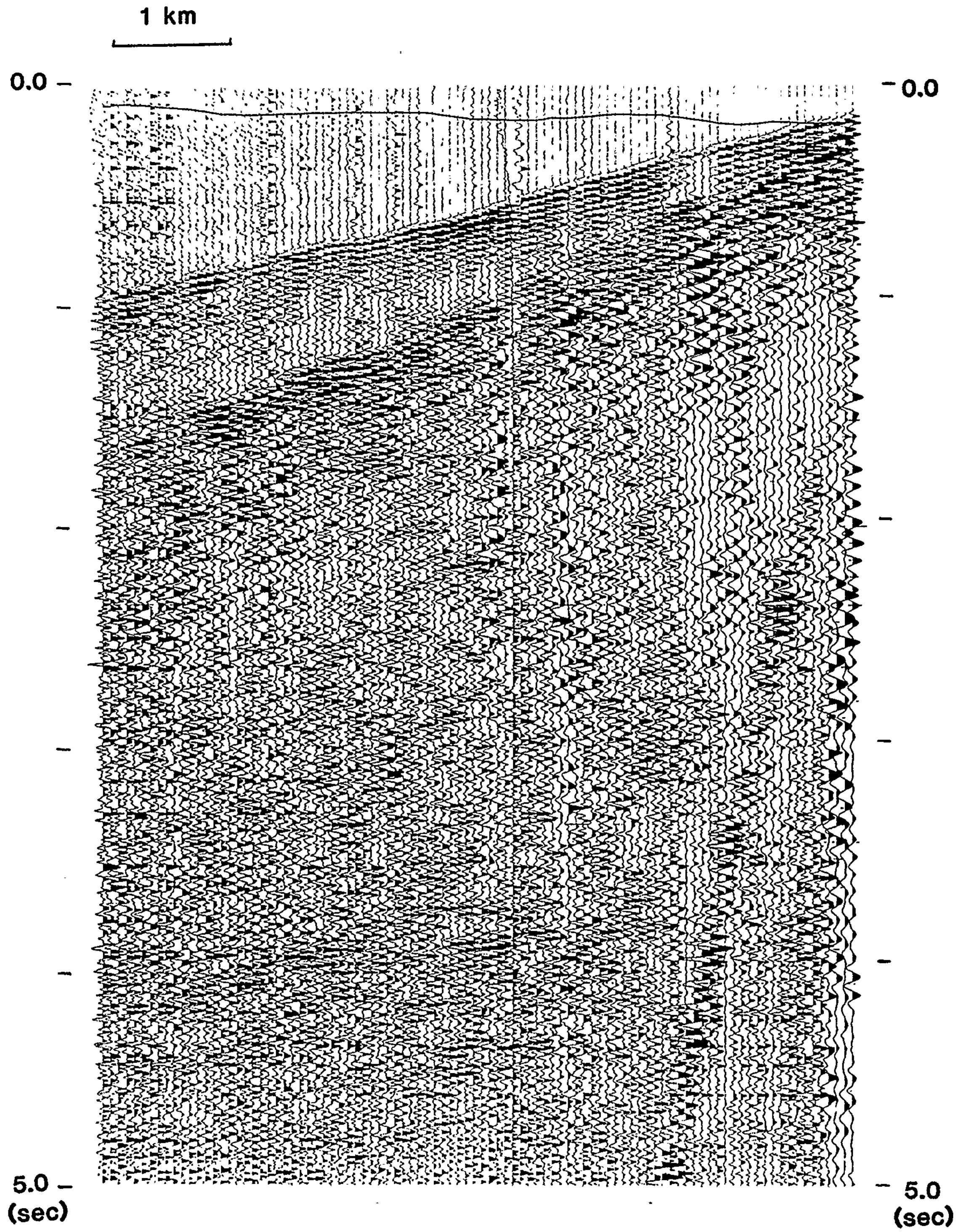


Figure 18, Diversity stack (50 msec window) of all 20 records of shot 197.

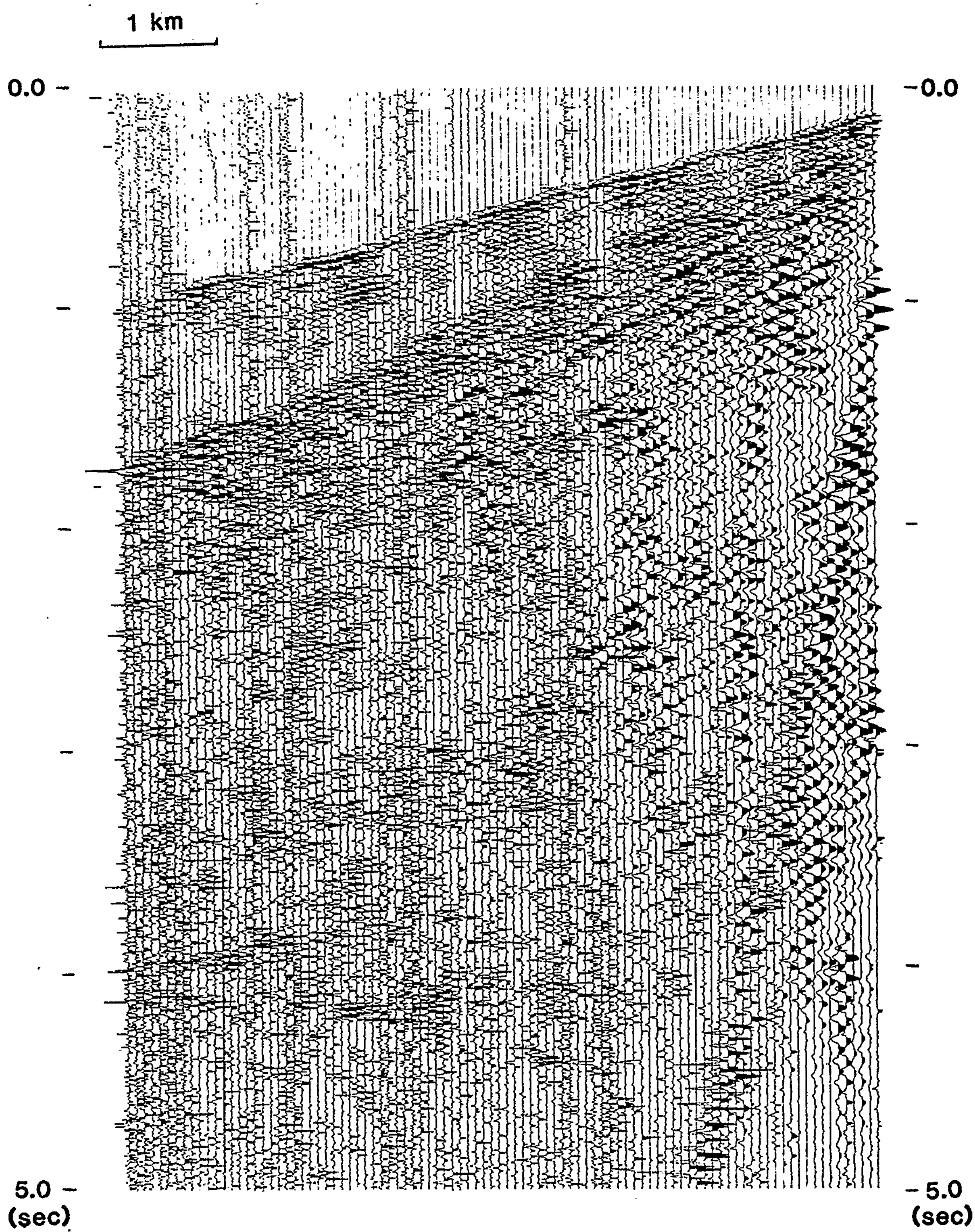


Figure 19, Diversity stack (4 msec window) of all 20 records of shot 181.

extreme is to choose a window of the same length as the traces. In this case, the tendency is to see some noise passing through (Figure 20). With such a window, the whole trace is scaled by the same scale factor. A trace with high amplitude spikes will be drastically scaled down on its full length, thus depriving the stack from the benefits of its normal amplitude trace segments. In fact the traces with the least total energy will have the most weights on the stack. Under such conditions the diversity stack method does not perform very efficiently, as can be seen on Figure 20.

The choice of the window length will also affect the improvement of the signal to noise ratio. Along with the high amplitude noise, a window will likely encompass some samples of normal amplitude. Due to the presence of the high amplitude noise, these samples will be scaled down by a very small scale factor and will not contribute to the improvement of the signal to noise ratio. Furthermore, if these samples were outside the window, they could assist in the elimination of high amplitude noise from other traces, but again, because of their association with a high amplitude spike, such an elimination cannot be effected.

Ideally the window length should be as close as possible to the length of the shortest duration of the noise that is to be removed. This way, signal to noise ratio and high amplitude noise cancellation will be optimized. In order to obtain a smooth record, tests showed that the window must

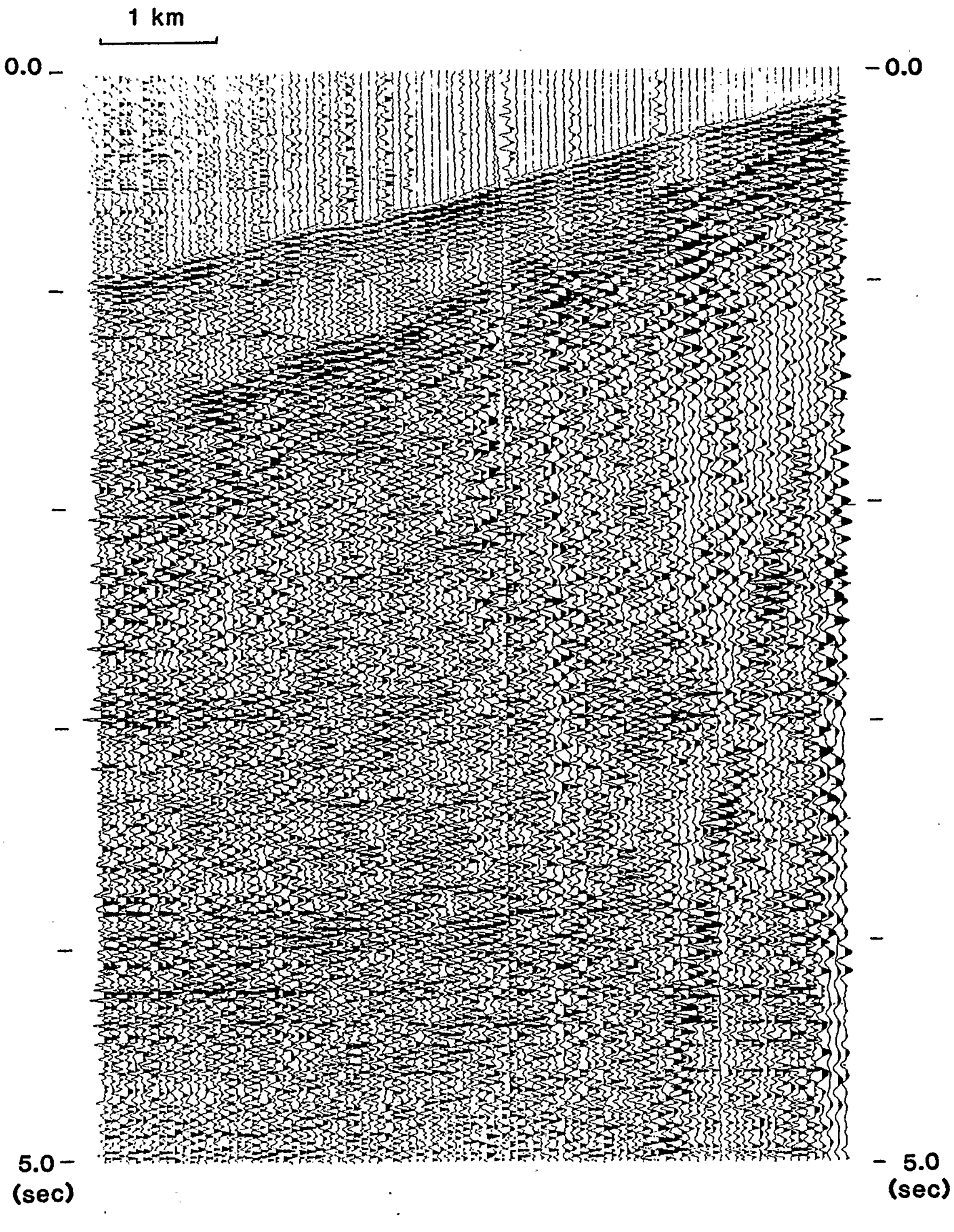


Figure 20, Diversity stack (5000 msec window) of all 20 records of shot 181.

contain at least 5 samples. These tests also demonstrated that very similar results can be achieved using windows 5 to 75 samples in length. Visible degradation of the results started to appear at longer window lengths. Different window lengths also affect computing time; long windows take less time to execute than short ones. Consequently, selecting a window length in the upper portion of the suggested bracket should yield good results under most conditions as well as being less time consuming.

The superiority of the diversity stack method compared to a simple vertical stack or an AGC scaling was well demonstrated by the examples. The coherent noise was efficiently removed and the true amplitude character of the traces was preserved. Regardless of the number of shot records used, the vertical stack method never performed with great success. On the other hand, the coherent noise can be adequately removed by performing an AGC scaling if a sufficient number of shot records are available. Even if true amplitude is lost in the process, it may be better to utilize such scaled records instead of vertically stacked ones, as was demonstrated by Cook (1984).

CHAPTER 6 PROCESSING OF THE PILOT SEISMIC SURVEY AND RESULTS

The processing of the pilot seismic survey was done on the computer system of the Geology and Geophysics department of the University of Calgary. All the computing operations that were executed on the data and the results obtained from these operations meet industry standards. In this section, the principal processing steps performed on the data will be discussed briefly, and the produced stacked section will be interpreted. Table 2 lists the details of each processing step.

Following demultiplexing, the diversity stack program was used to sum together and eliminate the high amplitude noise present on the 20 or 21 shot records that were recorded at each shot point location. A scale window 200 milliseconds long was selected.

Ground roll events are an important source of noise. At the far offsets ground roll noise was recorded at more than 2 seconds (Figure 7). Its high energy can easily mask any shallower primary reflections. A spectral analysis was therefore conducted on the data. By comparing the frequency content of the ground roll with the reflection events it is often possible to design a frequency filter that will efficiently remove some of the ground roll energy without affecting true reflection events.

Table 2 , <u>Processing sequence</u>

1- Demultiplexing

2- Diversity stack on field records

    scaling window = 200 msec

3- Line geometry description and header set up

    strait line geometry

4- First editing

    first break mute

    trace kill

5- Transmission-loss recovery

    scaling window = 300 msec

6- Truncation of data from 15 to 5 seconds

7- Spectral analysis

8- Homomorphic deconvolution and frequency filter

    Bandpass filter = 11-16-35-40 Hz

9- Two-dimensional frequency domain filter

    left dip = all pass

    right dip = 0 to 11730 m/sec reject

    roll-off = 1300 m/sec

10- Second editing

    application of refraction statics corrections

        1st layer velocity = 1000 m/sec

        datum elevation = 250 meters

    trace kill

11- Gathering of CDP traces

    24 fold

(Table 2, continued)

12- Velocity analysis

constant velocity stacks

6500 to 8500 m/sec in 250 m/sec increments

13- Corrections for NMO

CDP no :	206	450	575	
times	velo.	velo.	velo.	times in seconds
0.0	7.85	7.5	7.5	velocities in
2.0	8.0			kilometers/second
3.7	8.25	8.5	8.5	
5.0	8.5	8.5	8.5	

14- Stacking of traces

15- Statics by correlation

trace mix weights = 10-20-40-20-10

correlation window = 500 to 4500 msec

maximum static = 64 msec

16- Stacking of traces

17- Display

RMS scaling window = 2000 msec

The ground roll spectrum typically covers a wide frequency range (Figure 21). Within this range, there is generally a dominant mode between 7 and 16 Hz. Reflections events, on the other hand, have essentially a monomodal amplitude spectrum (Figure 22). This mode is relatively narrow and extends usually from 22 to 33 Hz and has its peak amplitude at 29 Hz. Amplitude spectra of portions of data which do not contain any reflections or ground roll are commonly relatively flat. They have a wide band and no dominant frequency.

From these observations, it is certainly possible to significantly improve the data by first filtering out the dominant frequency (7-16 Hz) of the ground roll and second to select a high cut frequency close to the high frequency end of the reflection event mode. Thus a frequency filter with limits of 11-16-35-40 Hz was applied to the data.

To further attenuate the ground roll energy a two dimensional frequency domain (F-K) filter was applied to the data. On the shot records several ground roll events (modes) can be observed (Figure 7). Each ground roll event can be characterized by an apparent (phase) velocity which will map at a specific position in the frequency-wavenumber (F-K) domain (Figure 23). The apparent velocity of each one of these events is a function of the geophone group spacing (trace spacing), the geophone array and the angle of incidence of the event. It often has a different velocity than the envelope velocity which always travels at the true

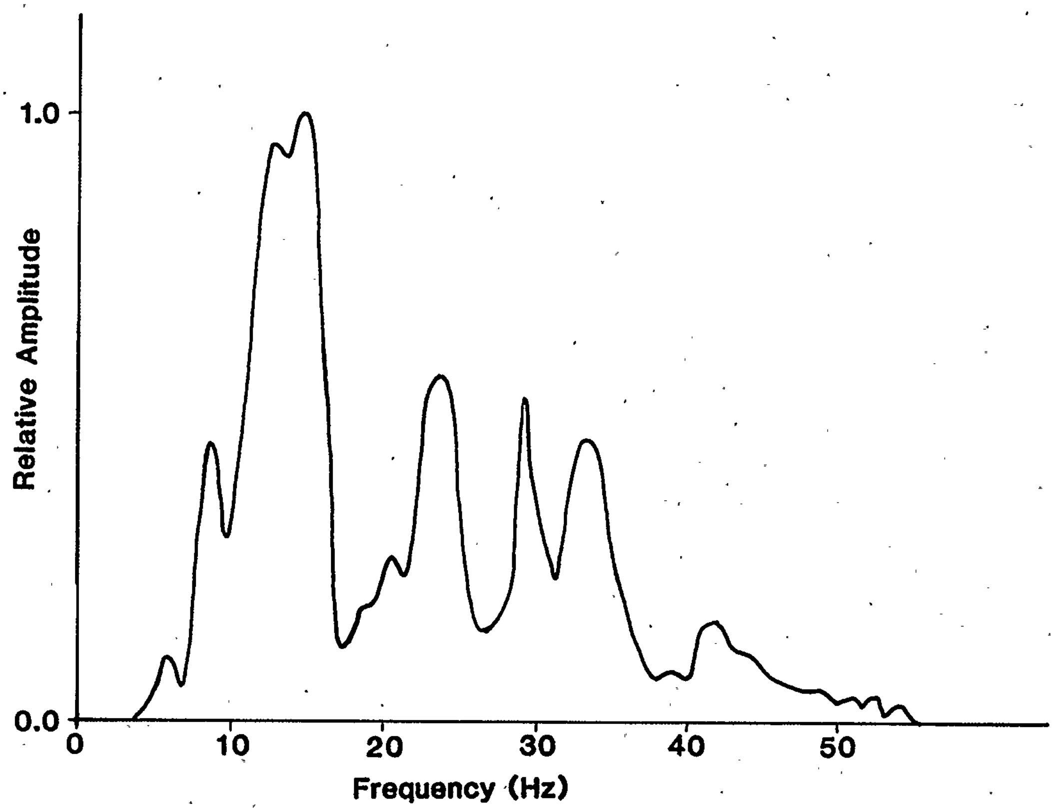


Figure 21, Typical ground roll amplitude spectrum.

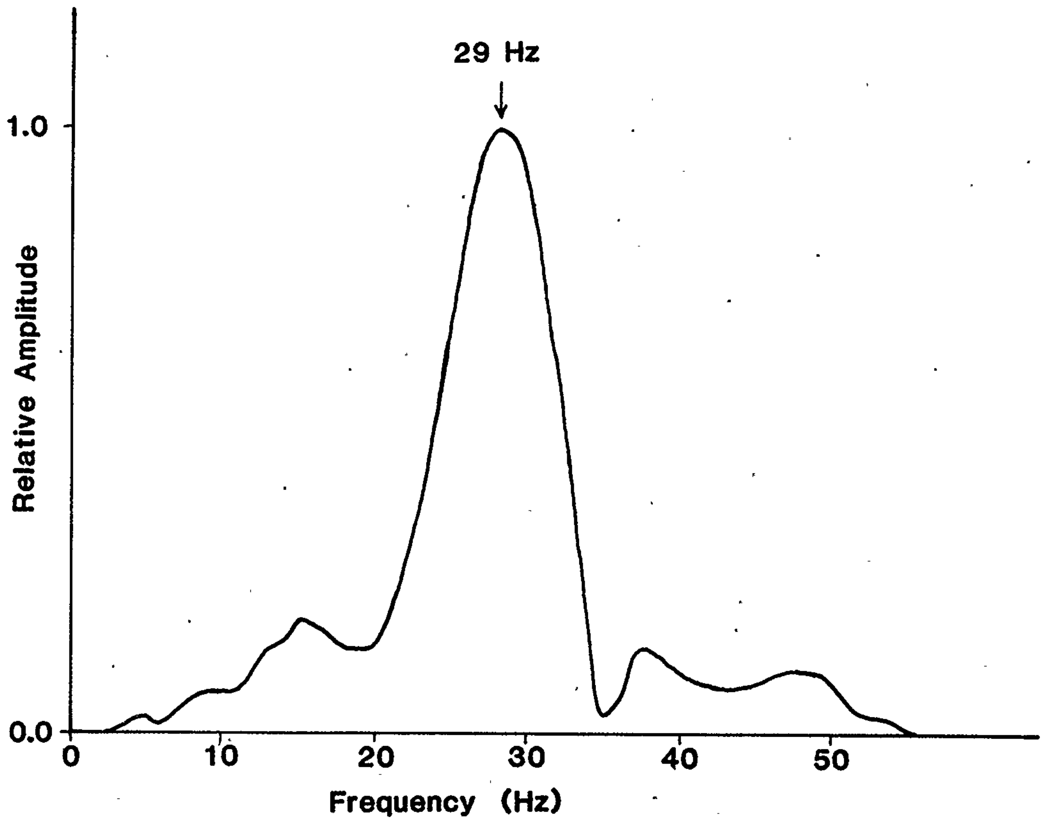


Figure 22, Typical reflection event amplitude spectrum.

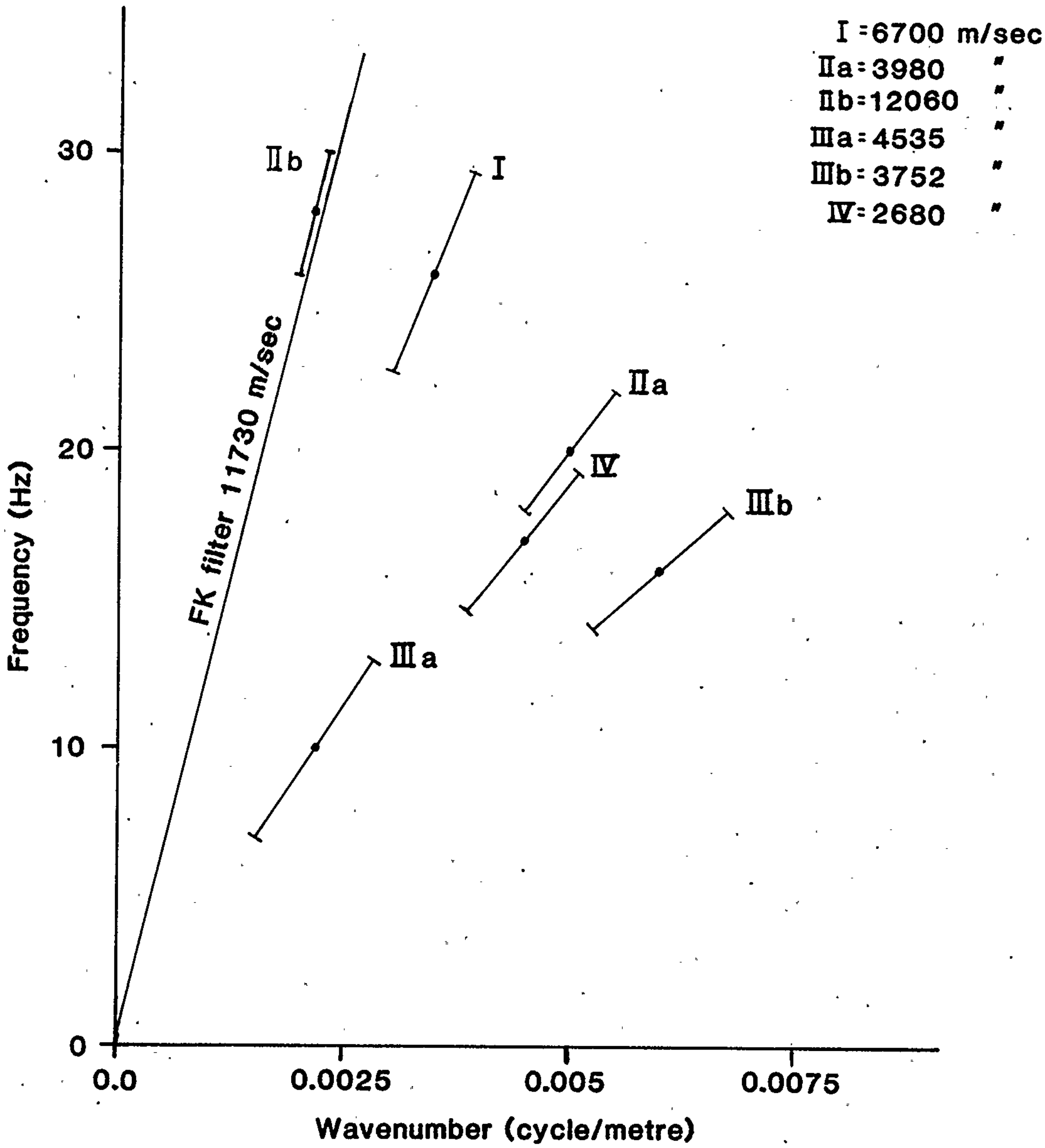


Figure 23, F-K domain representation of the apparent (phase) velocity of the different coherent noise events of figure 7.

velocity of the event. The reason for this difference is spatial aliasing, which simply means that the travelling seismic wave field is undersampled by the recording geometry and cannot be represented adequately. Aliasing is likely what makes ground roll event IIb appear to have an apparent velocity of 12060 meters/second and the air wave an apparent velocity of 2680 meters/second.

In the F-K domain, apparent velocities are used as criteria for filtering out undesirable events. The rejected apparent velocities are simply not used in the reconstruction of the time-space section. An apparent velocity of 11730 meters/second was selected for the filter (Figure 23). It was carefully chosen so as not to affect any possible reflection event, especially at their far offsets.

The next step consisted in the application of the elevation and weathering static corrections at each trace location. To perform accurate corrections, the velocities and thickness of the overburden and weathering layers as well as of the unaltered rock above the datum elevation must be known. Unfortunately, this information was not available, and it was not possible to retrieve it from the recorded data, as the spacing between the shot stations and the first receiver station (201 meters) and the receiver stations spacing (67 meters) were too large. The lack of this information can seriously handicap the quality of the final stack section and it is a problem that will have to be addressed adequately in any future reflection seismic survey over this area.

The static corrections were best calculated using a computer routine which used the refraction theory. The refraction information had to come from the shot records and therefore all of their first breaks had to be digitized. However, all first breaks could be fit relatively well with a straight line. This meant that only one velocity could be calculated from each record. It was then assumed that these velocities represented the velocity variations of the unaltered bedrock along the line.

The computed velocities varied from 7144 +/- 259 meters/seconds to 8740 +/- 820 meters/second, with an average of 7789 +/- 250 meters/seconds. These velocities might seem unusually high, but laboratory measurements on rocks samples collected along the profile produced velocities of 7000 to 7400 meters/second (Fountain D.M., personal communication, 1986), which are in general agreement with the refraction velocities.

Since it was impossible to gather information on the overburden and weathering layers, a simple 2 layer model was implemented. The first layer comprised the overburden and weathering layers together. It was assigned an arbitrary velocity of 1000 meters/second. It was selected from published velocities of comparable materials (Telford *et al* 1976; Dobrin, 1976). The second layer was the unaltered bedrock. The computer program was then able to calculate the thickness of the weathering layer along the line and from these finally compute an individual static correction for each shot and trace.

The velocity analysis was done with constant velocity stacks. With this method a single velocity is used for correcting the CDP gathers for normal move out (NMO). The resulting stack sections will provide evidence for the reflections which can be best stacked with each velocity. This method is very effective on data with a low signal to noise ratio as it allows a visual check of reflection coherence. Constant velocity stack panels were generated in increments of 250 meters/second for velocities between 6500 and 8500 meters/second.

The seismic stack section of Figure 24 is the final product of this processing sequence. Figure 25 is a line drawing diagram of the stack section.

There is a prominent group of reflections between 3.2 and 4.2 seconds. They have a slight dip to the east. In order to calculate a depth to these reflectors, accurate velocity information must be available, however, crustal velocities in this part of the Superior province are not well constrained. The stacking velocities used are not accurate enough to provide good velocity estimates. Seismic refraction studies in the Superior province in southern Ontario and Manitoba by Green *et al* (1980), Halls and Brisbin (1982) and Hall (1982) revealed that the velocity of the upper crust (0 to about 20 kilometers) averaged between

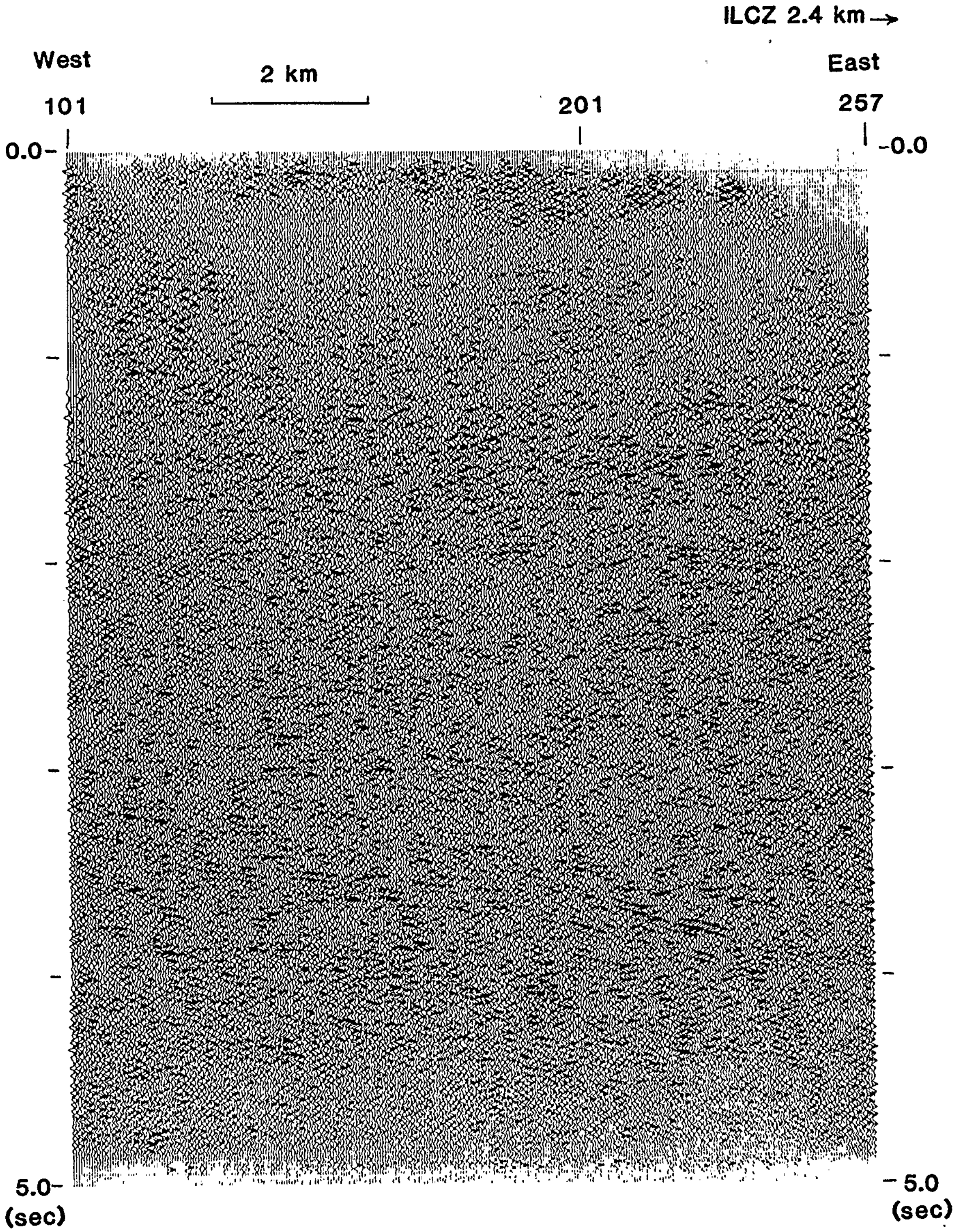


Figure 24, Stack section of the pilot seismic reflection survey. Diversity stack was done using a 200 msec window.

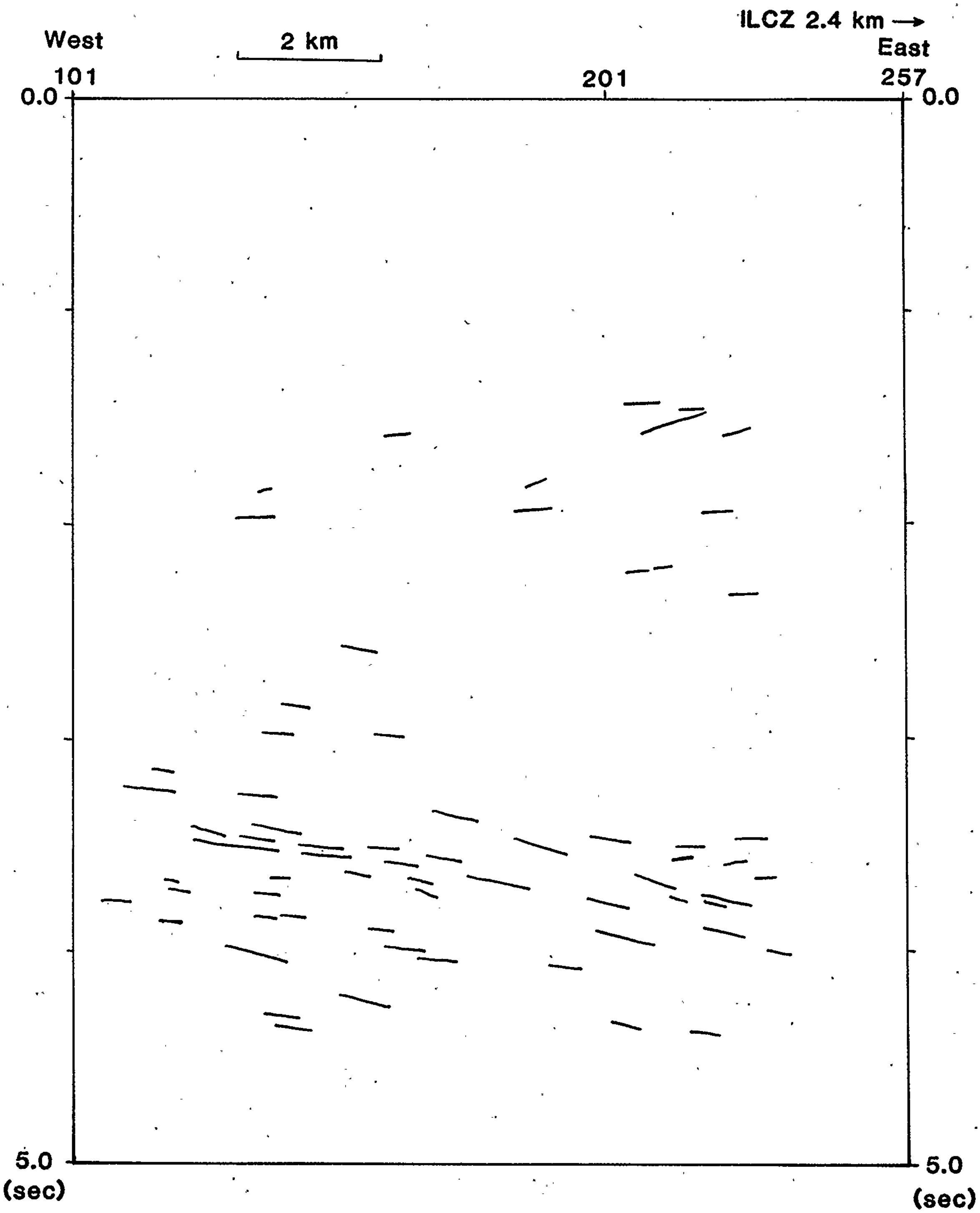


Figure 25, Line drawing diagram of Figure 24.

6.2 and 6.5 kilometers/second. More recently, preliminary work by Northey and West (1985) suggests that slightly higher velocities, around 6.6 kilometers/second, might be present under the Kapuskasing Zone. Furthermore, velocities of the near surface rocks as determined by the shot records' first breaks and by rock samples analysis (Fountain D.M., personal communication, 1986) are approximately 7.5 kilometers/second. However, this velocity may correspond only to the velocity of the Shawmere anorthosite complex, thus it may apply for only to the first 1 to 5 kilometers of crust. The group of reflections that is present between 3.2 and 4.2 seconds on the seismic section then likely correspond to a transition boundary at a depth range of 10 to 15 kilometers.

In a crustal model described by Percival and Card (1983), granitic batholiths, supracrustal belts and gneiss haloes may constitute the geologic environment of the first 5 to 10 kilometers of the crust and would be geologically equivalent to rock assemblages as can be found at the surface in the Abitibi subprovince. Tabular batholiths of gneiss and xenolithic tonalites similar to the rock assemblages found just west of the Kapuskasing Zone in the Wawa subprovince may comprise the next 10 to 15 kilometers of the crust. The reflection events seen between 3.2 and 4.2 seconds might be speculated to correspond to a transition boundary between these two geologic environments.

At shorter times no major reflection can be identified on the seismic stack section. In contrast, Cook (1984) observed a west dipping event starting at 1.8 seconds (Figure 26 and 27) on the east end of the section and extending to about 3.5 seconds on the west side of the section. Cook (1984) interpreted this event as the ILCZ and computed a 35 degree dip to it. The only candidate for a similar reflection is visible at 1.5 seconds near shot point 210 (Figure 25). This is a very important difference, since one of the primary goals of the pilot seismic reflection survey was to determine the feasibility of recording reflections from the ILCZ. This difference brings the following question immediately to mind: Is the ILCZ reflection visible on Cook's section a real event or an artifact of the processing sequence, or did the reprocessing of the data actually erased this reflection? This is a very difficult question to answer, primarily because there is no way to verify if a reflection is really present. That is, no clear reflection event can be seen on the individual shot records or on the common depth point gathers at that travel time.

There were substantial differences between Cook's (1984) processing flow (Table 3) and the one followed during this research project (Table 2). Could, for example, the use of the diversity stack program be responsible for the elimination of this shallow event? This is very unlikely, as demonstrated in previous chapters this technique can not eliminate events which are not temporally random like a

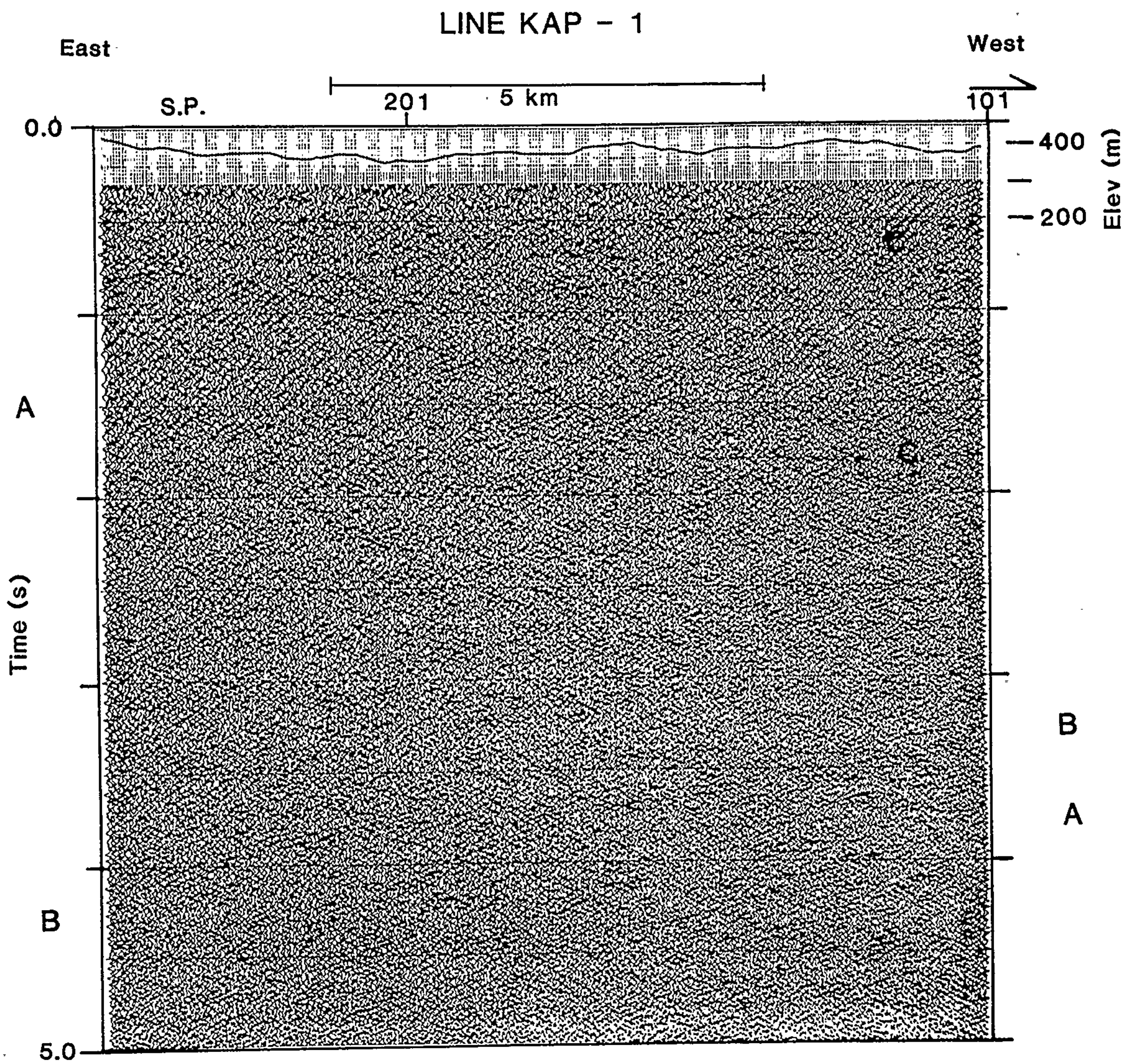


Figure 26, Stack section from Cook (1984).

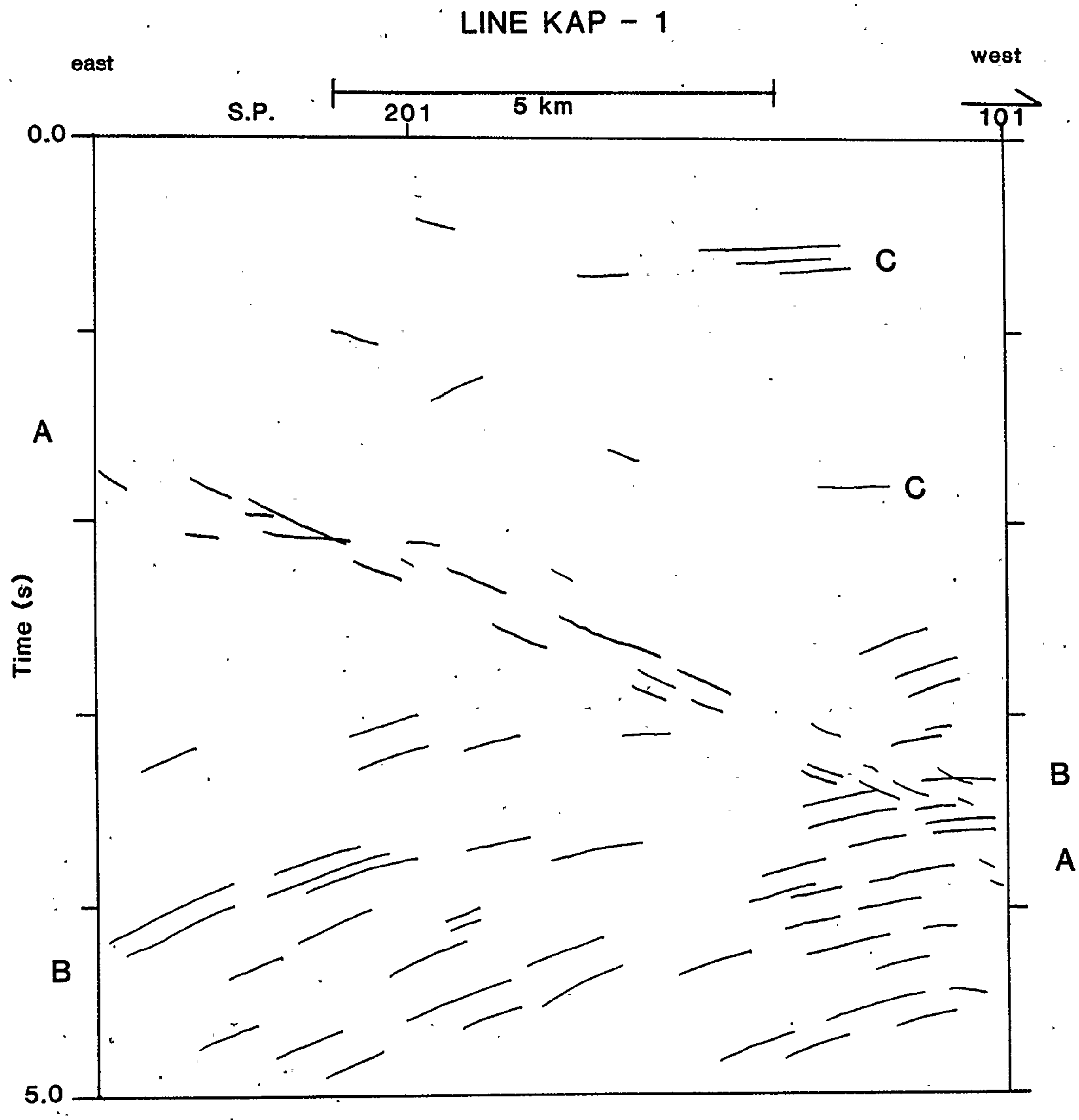


Figure 27, Line drawing diagram of Figure 26 (Cook, 1984).

Table 3 , <u>Cook's (1984) processing sequence</u>

1- Demultiplexing

2- 50 msec AGC scaling

3- Vertical stack

  sum of all records (20-21) at each shot location

4- Edit

  first break mutes

  application of elevation statics

    elevation velocity = 5000 m/sec

6- Gathering of CDP traces

  24 fold

7- Velocity analysis

  constant velocity stacks

8- Brute stack

9- Statics by correlation

10- Stacking of traces

11- Display

reflection event, it should enhance them. In addition, by comparing the overall amplitude character of the two stack sections (Figure 24 and 26), it appears that the signal to noise ratio is significantly better on the one with diversity stack (Figure 24) than the one with AGC scaling (Figure 26). For example, the deep reflections between 3.2 and 4.2 seconds appear to be more visible.

The application of bad statics corrections would cause the misalignment of reflection events on CDP gathers and consequently a poor stack would result. Is it possible that the use of the refraction statics program, instead of the more strait forward one layer model statics program used by Cook (1984), could have resulted in the computation of bad statics corrections? It is a possibility; however, if it was the case the group of reflections between 3.2 and 4.2 seconds should also be considerably attenuated, but they have been enhanced as compared to Cook's (1984) stack section.

The F-K filter used may seem severe (11730 meters/second) and therefore it might have filtered out parts of the reflection branches of the ILCZ fault plane. Yet, consider that the survey was shot updip to the postulated fault plane position and with a dip of about 35 degrees there should be a significant shift of the apex of the fault reflection on the shot records toward the far offsets. In the F-K filter design no filtering was done on coherent events with apparent velocities dipping toward the near offsets. This means that the branches of the fault reflections which are "dipping" toward the near offsets will not be filtered, neither the area near the apex, where the apparent velocities approach infinity. Thus there are only the branches near the far offsets which might have been filtered out. If the far offset branches were the only parts of the reflections that were recorded, then of course the fault would have been erased.

Different stacking velocities were also used, but tests showed (constant velocity stacks) that even another set of velocities could not reproduce this reflection.

In spite of the differences in the processing flows it was not possible to pinpoint the cause or causes for the non-stacking of this event, and the reason for this again is simply the impossibility to distinguish clear reflection events on the shot records or CDP gathers. Nevertheless, the reprocessing of the pilot seismic survey confirmed the presence of reflection surfaces at depth, thus demonstrating the feasibility of recording reflection events from the crystalline crust of the Superior Province.

A second objective of the pilot survey was to identify logistical and processing problems which can be improved upon for the shooting of a major reflection survey which is to be conducted during the summer of 1987. During the course of this research it was possible to identify some of these problems. First, there are the problems caused by the electrostatic discharges. Shooting during a drier season would likely help to minimize their occurrences and the use of a diversity stack would assure their complete elimination prior to processing. It might also be worth considering using a telemetric recording system which would have the advantage of not having any receiver connecting cable, thus completely eliminating the electrostatic noise occurrences.

Noise tests should also be carried out to identify ground roll events and the recording parameters such as source and geophone arrays be designed in consequence. In the light of the noise study done on the Kapuskasing data set it seems that arrays in the order of 130 meters in length would be necessary. This would be clearly very difficult to do, but there are some processing techniques available, such as trace mixing which could artificially construct such an array. The computation of elevation and weathering static corrections also need to be improved. A better knowledge of near surface and weathering velocities is therefore necessary. The recording of several hammer seismic refraction profiles along the survey line might give very useful velocity informations. Access to an efficient refraction static correction program is also strongly recommended. The use of an 800-channels recording system, as described by Zoback and Wentworth (1986), might also be considered. This technique appears to permit good static corrections and, by a better coverage, to increase lateral resolution.

Finally, very few reflection events could be positively identified on the individual shot records and in spite of all the efforts put into processing the data, very few reflection events were visible on the stack section. These observations tend to demonstrate that impedance contrasts between rock types in this crystalline environment or across fault planes are probably very low, therefore stressing the need for a more powerful energy source such as dynamite or Vibroseis.

CONCLUSION

The need for the development of a diversity stack algorithm came from the necessity to adequately remove high amplitude coherent noise from data recorded by the Lithoprobe group over the Kapuskasing Zone, Ontario. A likely cause of this noise was electrostatic discharge into the receivers' connecting cable. The diversity stack method proved to be very efficient in the elimination of the noise.

The usefulness of the diversity stack method to eliminate noise is not limited solely to noise of this type, any noise which fulfills the following conditions will be attenuated as well. First, the noise must be of higher amplitude than the normal signal and background noise amplitudes, and second, the noise must occur randomly with respect to time. In addition, the diversity stack method is to be used on shot records only and in order for the diversity stack method to work, at least two shot records must be present at each shot point location. The reason for this condition is that to eliminate high amplitude noise the diversity stack method does a statistical weighting of all traces of each shot record before summing.

Tests were run to compare the performance of the diversity stack method from doing a vertical stack or doing an AGC scaling before a vertical stack. In the presence of high amplitude noise the diversity stack method performed far better than any of the other techniques tested. On normal signal and amplitude levels the diversity stack method appeared to attain a similar signal to noise ratio improvement as a vertical stack, and as a vertical stack, the diversity stack preserves the trace true amplitude informations. This was not the case however when AGC scaling was done prior to a vertical stack. To adequately remove the noise it was necessary to use a very short AGC scaling window whose effect was to degrade resolution and destroy the true amplitude information.

It is a common field procedure to do the summation of the shot records as the survey is executed. The examples shown clearly demonstrated however the importance of keeping all individual shot records for further processing in a processing center if there are some risks for the data to be contaminated by high amplitude noise. The diversity stack algorithm is relatively short and simple, it is also a program which runs fast and for which parameters are easy to set. For these reasons it could be advantageous to implement a diversity stack version for field instruments. The diversity stack option could then be used instead of the usual vertical stack each time that shot records have to be summed together.

All the examples showed in this report came from the Kapuskasing data set which was shot using a single air gun. It goes without saying that the diversity stack method can also be used on data shot with any other types of explosive or non-explosive sources such as uncorrelated Vibroseis data for example (Kirk, 1980).

The reprocessing of the Kapuskasing data set using the diversity stacked shot records confirmed the presence of an important group of reflection events between 3.2 and 4.2 seconds. Following Percival and Card's (1983) crustal model, these reflections might represent a transition boundary at a depth of 10 to 15 kilometers. There are however no other prominent reflection events on the seismic section in contrast to data processed by Cook (1984), who identified a westerly dipping reflection starting at about 1.8 seconds and which he associated with the ILCZ. Unfortunately, it has not been possible to ascertain if that reflection was real and then removed during reprocessing, or whether it was just an artifact of the earlier processing sequence. Nevertheless, the results of this research project confirmed the feasibility of recording reflection events at depth in this particular geologic environment.

The reprocessing of the pilot seismic reflection survey also helped to identify problems which can be improved upon for a future major seismic survey (300 to 400 kilometers) that is to be shot during the summer of 1987. The use of a stronger energy source, the design of receiver and source arrays for ground roll attenuation, a better knowledge of near surface and weathering velocities as well as access to an efficient refraction static correction program are all examples of areas that can be ameliorated in order to obtain better quality data.

From the results of this research project it is now thought that the seismic reflection method can successfully assist in improving the knowledge about the structure and evolution of this enigmatic segment of the Canadian Shield.

REFERENCES

Bennett G., Brown D.D., George P.T. and Leahy E.J., 1967, Operation Kapuskasing. Ontario Department of Mines, Miscellaneous Paper 10, 98 p.

Brown R.J. *et al*, 1977, Weighted vertical stacking in crustal seismic reflection studies on the Canadian shield. Geophysical Prospecting, v. 25, pp. 251-268.

Buhl P., Stoffa P.L. and Bryan G.M., 1974, The application of homomorphic deconvolution to shallow-water marine seismology, Part 2: Real data. Geophysics, v. 39, pp. 417-426.

Burke K. and Dewey J.F., 1973a, An outline of Precambrian plate development, in Tarling D. and Runcorn S. eds., Implication of Continental Drift to the earth sciences. Academic Press, London, v. 2, pp. 1035-1045.

--------- 1973b, Plume-generated triple junctions: Key indicators in applying plate tectonics to old rocks. Journal of Geology, v. 81, pp. 406-433.

Carmichael R.S., 1982, Handbook of physical properties of rocks. CRC Press Inc., Carmichael ed., v. 2, 345 p.

Ciesielski, A., 1986, L'histoire de la region de la baie d'Hudson. GEOS, v. 15, no. 4, pp. 14-18.

Cook F.A., 1984, Report to the Lithoprobe steering committee on the results of the Kapuskasing seismic reflection pilot study. 37 p., unpublished report.

--------- 1985, Deep basement seismic reflection profiling of the Purcell anticlinorium using a land airgun source. Journal of Geophysical Research, v. 90, pp. 651-662.

Dobrin M.B., 1976, Introduction to geophysical prospecting. McGraw Hill ed., 3rd ed., 630 p.

Embree P., 1968, Diversity seismic record stacking method and system: U.S. patent 3 398 396.

Ernst R.E. and Halls H.C., 1984, Paleomagnetism of the Hearst dike swarm and implication for the tectonic history of the Kapuskasing structural zone, northern Ontario. Canadian Journal of Earth

Sciences, v. 21, pp. 1499-1506.

Fountain D.M. and Salisbury M.H., 1981, Exposed cross-sections through the continental crust: Implications for crustal structure, petrology and evolution. Earth and Planetary Science Letters, v. 56, pp. 263-277.

Garland G.D., 1950, Interpretation of gravimetric and magnetic anomalies on traverses in the Canadian shield in northern Ontario. Publication of the Dominion Observatory, Ottawa, v. 16, no. 1, 58 p.

Gaucher E.G., 1966, Elsas-Kapuskasing-Moosonee magnetic and gravity highs, in Report of activities. Geological Survey of Canada, paper 66-1, pp. 189-191.

--------- 1967, Magnetic properties and gravity of selected anomalies, in A preliminary study of the Moose River belt, northern Ontario. Geological Survey of Canada, paper 67-38, pp. 12-26.

Gibb R.A., 1978, A gravity survey of James Bay and its bearing on the Kapuskasing gneiss belt, Ontario. Tectonophysics, v. 45, pp. T7-T13.

Gibb R.A. and Walcott R.I., 1971, A precambrian suture in the Canadian shield. Earth and Planetary Science Letters, v. 10, pp. 417-422.

Goodwin A.M., 1972, The Superior province, in Variations in tectonic styles in Canada. Geological Association of Canada, Special Paper II, pp. 527-624.

Graul M., 1986, Basic Chevschool, an EXEC short course. Exploration Education Consultants, Houston, Texas, 420 p.

Green A.G. and Clowes R.M., 1983, Deep geology from seismic reflection studies in Canada. First Break, v. 1, pp. 24-33.

Green A.G. *et al*, 1980, Cooperative seismic surveys across the Superior-Churchill boundary zone in southern Canada. Canadian Journal of Earth Sciences, v. 17, pp. 617-632.

Hall D.H. and Brisbin W.C., 1982, Overview of regional geophysical studies in Manitoba and northwestern Ontario. Canadian Journal of Earth Sciences, v. 19, pp. 2049-2059.

Halls H.C., 1982, Crustal thickness in the Lake Superior region, in Geology and tectonics of the Lake Superior basin. Geological Society of America, memoir 156, pp. 239-243.

Innes M., 1960, Gravity and isostasy in northern Ontario and Manitoba. Publication of the Dominion Observatory, Ottawa, v. 21, no. 6, pp. 261-338.

Innes M., Goodacre A., Weber J. and McConnell R., 1967, Structural implications of the gravity field in Hudson Bay and vicinity. Canadian Journal of Earth Sciences, v. 4, pp. 977-993.

Iyers H.M. *et al*, 1969, Project early rise: seismic probing of the upper mantle. Journal of Geophysical Research, v. 74, no. 17, pp. 4409-4441.

Jolly W.T., 1978, Metamorphic history of the Archean Abitibi belt, in Metamorphism in the Canadian shield. Geological Survey of Canada, paper 78-10, pp. 63-78.

Kirk P., 1981, Vibroseis processing, in Developments in geophysical exploration methods. Fitch, A.A. ed., Applied Science Publishers Ltd, London, v. 2, pp. 37-52.

Klasner J.S. *et al*, 1982, The Pre-Keweenawan tectonic history of southern Canadian shield and its influence on the formation of the Midcontinent rift, in Geology and tectonics of the Lake Superior basin. Geological Society of America, memoir 156, pp. 27-46.

MacLaren A.S., 1967, Aeromagnetic interpretation, in A preliminary study of the Moose river belt, northern Ontario. Geological Survey of Canada, paper 67-38, pp. 7-11.

Northey D.J. and West G.F., 1985, Acquisition and interpretation of the crustal seismic refraction profiles across the Kapuskasing structural zone, north-west Ontario. 91 p., unpublished report.

Otis R.M. and Smith R.B., 1977, Homomorphic deconvolution by log spectral averaging. Geophysics, v. 42, pp. 1146-1157.

Percival J.A., 1983, High grade metamorphism in the Chapleau-Foleyet area, Ontario. American Mineralogist, v. 68, pp. 667-686.

--------- 1985, The Kapuskasing structure in the Kapuskasing-Fraserdale area, Ontario, in Current research, part A. Geological Survey of Canada, paper 85-1A, pp. 1-5.

Percival J.A. and Card K.D., 1983, Archean crust as revealed in the Kapuskasing uplift, Superior province, Canada. Geology, v. 11, pp. 323-326.

--------- 1985, Structure and evolution of Archean crust in central Superior province, Canada, in Evolution of Archean supracrustal sequences. Geological association of Canada, special paper 28, pp. 179-192.

Percival J.A. and Coe K., 1980, Geology of the Kapuskasing structural zone in the Chapleau-Foleyet area, Ontario, in Current research, part A. Geological Survey of Canada, paper 80-1A, pp. 61-68.

Percival J.A. and Krogh T.E., 1983, U-Pb zircon geochronology of the Kapuskasing structural zone and vicinity in the Chapleau-Foleyet area, Ontario. Canadian Journal of Earth Sciences, v. 20, pp. 830-843.

Percival J.A. and McGrath P.H., 1986, Crustal structure and dynamics in the Kapuskasing-Fraserdale area of Ontario: An integrated petrological, geophysical study. In press.

Schilt F.S., Kaufman S. and Long G.H., 1981, A 3 dimensional study of seismic diffraction patterns from deep basement sources. Geophysics, v. 46, pp. 1673-1683.

Smithson S.B. *et al*, 1979, Structure of the Laramide Wind River uplift, Wyoming, from COCORP deep reflection data and from gravity data. Journal of Geophysical Research, v. 84, pp. 5955-5972.

Stockwell C.H. *et al*, 1970, Geology of the Canadian shield, in Geology and economic minerals of Canada. Geological Survey of Canada, Economic geology report no. 1, pp. 43-150.

Stoffa P.L., Buhl, P. and Bryan G.M., 1974, The application of homomorphic deconvolution to shallow-water marine seismology, Part 1: Models. Geophysics, v. 39, pp. 401-416.

Telford W.M., Geldart L.P., Sheriff R.E. and Keys D.A., 1976, Applied geophysics. Cambridge university press, Cambridge, 860 p.

Thurston P.C. *et al*, 1974, Geology of the Chapleau area, Districts of Algoma, Sudbury and Cochrane, Ontario. Ministry of Natural Resources of Ontario, Open file report 5079(2).

--------- 1977, Geology of the Chapleau area, Districts of Algoma, Sudbury and Cochrane, Ontario. Ontario Division of Mines, Geoscience report 157.

Ulryth T.S., 1971, Application of homomorphic deconvolution to seismology. Geophysics, v. 36, pp. 650-660.

Wallace M., 1980, Deep basement reflections in the Wind River line 1. Geophysical Research Letters, v. 7, no. 10, pp. 729-732.

Watson J., 1980, The origin and history of the Kapuskasing structural zone, Ontario, Canada. Canadian Journal of Earth Sciences, v. 17, pp. 866-875.

Wilson J.T., 1968, Comparison of the Hudson Bay arc with some other features, <u>in</u> Sciences, history and Hudson Bay. Department of Energy, Mines and Resources, Ottawa, pp. 1015-1033.

Wilson J.T. and Brisbin W.C., 1965, Mid-north America ridge structure, <u>in</u> Abstracts for 1965. Geological Society of America, Special paper 87, pp. 186-187.

Zamislak R.L. and Smithson S.B., 1981, Problems and interpretation of COCORP deep seismic reflection data, Wind River range, Wyoming. Geophysics, v. 46, pp. 1684-1701.

Zoback M.D. and Wentworth C.M., 1986, Crustal studies in central California using a 800-channel reflection recording system, in Reflection seismology: A global perspective. Geodynamics series, American Geophysical Union, v. 13, pp. 183-196.