A CONTINUOUS DEEP-CRUSTAL SEISMIC REFRACTION AND NEAR-VERTICAL REFLECTION PROFILE IN THE CANADIAN SHIELD INTERPRETED BY DIGITAL PROCESSING TECHNIQUES

A Thesis

Present to

the Faculty of Graduate Studies and Research

University of Manitoba

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

---

by

Zoltan Hajnal

February 1970

ABSTRACT

A section of a regional crustal deep seismic sounding, between latitude 49°30' N and 52°N and longitude 93°W to longitude 98°W, was examined in detail by a 52 mile continuous combined refraction and wide-angle reflection survey. This survey confirms the existence of the Intermediate and Mohorovicic discontinuities as was determined by the regional study. It also reveals a major crustal fracture zone in the Intermediate discontinuity with maximum movement of 3.5 km.

The present study was the first attempt on this continent to apply continuous profiling techniques in deep crustal seismic investigations. It proves that the ordinary survey methods can lead to an oversimplified interpretation of the earth's crust.

The observed data was processed with the latest digital filtering techniques. Description is given of the developed computer programs and the analog to digital conversion system.

An eleven mile experimental nearly-vertical reflection survey exhibits arrivals from the Intermediate discontinuity. It was found that this method is applicable on the Precambrian Shield, but the results indicate that

for successful studies of this nature further modifications are required on field survey procedures.

ACKNOWLEDGEMENTS

The writer wishes to express his many thanks to Dr. D. H. Hall of the Department of Earth Sciences, University of Manitoba for his supervision, for his many suggestions, and for his many efforts to create favorable conditions under which this study could be carried out.

Thanks are due to Dr. K. B. Burke of the Department of Geology, University of Fredericton for his unlimited help during the one year period which he spent at the University of Manitoba.

The author wishes to acknowledge the collaboration of Dr. C. D. Anderson of the Department of Earth Sciences, University of Manitoba for his many genuine attempts to make the digital processing less troublesome.

The author is grateful to Drs. H. D. B. Wilson, D. T. Anderson and W. C. Brisbin for providing many valuable explanations and suggestions concerning the geology of the surveyed area.

This study would never have been possible without the devoted attention of observers R. J. Brown, P. W. Wagner, A. Wiegert, J. R. Stilborn and all the other fellow crew members who were willing to take the discomforts of four summers field operations.

Mr. M. A. Knudsen of Keewatin, Ontario handled the explosives with extreme care and caution.

Over all the scientific aspects this work would never have been achieved without the extreme patience and moral support of my wife.

The regional survey, referred to as the background of the present thesis, was conducted with support from the National Research Council of Canada. The field work for the thesis was made possible by the generous support of the Department of Mines and Natural Resources of the Province of Manitoba as part of Project Pioneer.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES

CHAPTER I

INTRODUCTION

Explosion studies of the crust of the earth were started in Manitoba and Northwestern Ontario at the beginning of the 1960's. Results of these investigations have been published in several papers; Hall and Brisbin (1961), Hall (1964), Hall and Brisbin (1965). These represent studies in Central Western Manitoba. Hobson (1967a), Hobson et al (1967), Hunter and Mereu (1967), Barr (1967), Ruffman and Keen (1967), Mereu and Hunter (1969), Hall (1969), Hajnal (1969) deal with information from the Hudson Bay area. Hall and Hajnal (1969) describe surveys in Northwestern Ontario and Southeastern Manitoba. With the exception of the last paper, all the papers describe reconnaissance refraction profile surveys with recording locations some considerable distance apart. Hall and Hajnal (1969) report a regional deep seismic sounding of the earth's crust in considerably more detail over an area between latitude 49°30' N and 51°30' N and from longitude 93°W to longitude 96°W. This was the first report on a continuing program of crustal surveys in this area. The present thesis includes maps of the portion of this larger survey to the west of the area reported on by Hall and

Hajnal to latitude 52°N and longitude 98°W. This area covers the southeast region of Manitoba, including the southern section of Lake Winnipeg. The surface geology in this region indicates several major faults, extension of the English River gneissic belt, as well as large granite plutons.

The field surveys were carried out in three separate steps. First, the regional studies were continued and contour maps of depths to Intermediate and the Mohorovicic discontinuities prepared. The results of this investigation show a major crustal structure in the surveyed region. This is an extension of structures evident on the maps of Hall and Hajnal (1969). Second, a continuous refraction profile was run over this feature to obtain further detail on it. This profile, together with the third step, namely, an eleven mile vertical reflection profile that was run partly across the gneissic belt and partly in the bordering granitic zone south of the belt, are the principal subjects of investigation of the present thesis.

The crustal surveys applied both the refraction as well as the variable angle (or wide-angle) reflection methods. The vertical reflection survey used the same instrumentation but because of frequency considerations, the type of geophones were changed. Energy was initiated by under-water explosions, which varied in weight from a few pounds in the case of the reflection survey to a thousand pounds for the longest shot-recorder distances in the refraction work.

The field data underwent extensive laboratory processing before interpretation. First, analog playback techniques were applied and then interpretation using these results was carried out using the standard refraction as well as the modified time term or station-pair method, described by Hall and Hajnal (1969).

One main objective of this study was to develop a digital processing technique for crustal seismic data. A new analog to digital convertor was incorporated in the already existing instrumentation. A method was developed for the continuous digitization of a large volume of analog seismic data. Programs were written to check the new digital data as well as to convert them to a form compatible to the University's I.B.M. 360/65 computer. Programs were created to design band-pass filters to given specifications. Digital velocity filtering and multiple correlation and integral processing were also carried out where the data required it.

As a result of the digital processing, the seismic sections are presented with the best possible detail. The digitally processed data shows significant improvement over the direct analog data mainly due to the elimination of low frequency noise. The investigation indicates the extreme versatility of the digital processing technique. The many possibilities of variations in the display of data become apparent when the description of the developed plotting programs are examined in detail.

The velocity determination followed the techniques of Hall and Hajnal (1969). A new iteration process was developed to find unique velocity values for the incorporation of the wide-angle reflection data. The values of velocity obtained from the application of different methods, reveal a layered crust with uniform velocities between interfaces.

The interpretation of the continuous refraction survey data reveal a major fracture zone in the upper part of the crust. Criteria for the recognition of deep crustal fracture zones were described and tested. Significant correlations were observed between the crustal feature and the available surface geological information. A description is given for the application of combined refraction and wide-angle reflection data in the process of interpretation.

The nearly-vertical reflection profile discloses near-surface geological features. It shows possible arrivals from the intermediate discontinuity. The results indicate that with some modifications this technique is applicable on the Precambrian Shield. It can provide details of close-surface and deep-crustal structures, which would be difficult or impossible to detect with other methods.

The crustal interfaces exhibit just as detailed and sudden structural changes as are observable in near-surface investigations. The present study proves that complete understanding of the deep structural conditions in the crust requires detailed seismic investigations. It is also evident that large separation between recording sites will lead to results which in many cases will over-simplify the crustal geological picture.

CHAPTER II

FIELD PROCEDURES

There are three distinct sets of observed data. These sets of data come from regional refraction surveys, continuous profiling refraction surveys and near-vertical reflection surveys. The field survey techniques are somewhat modified from one survey to another and these differences and possible further modifications require description and thus are presented here.

Regional Refraction Surveys

The recording was carried out with truck mounted Texas Instrument VLF-2 equipment. The technical description of the complete system is given in the section on instrumentation. Recording with the equipment is possible even at very remote or nearly inaccessable areas if aircraft or track mounted transporting equipment is available. The present study was limited to those recording sites which were accessible by a three-quarter ton truck. The recording crew personnel comprised one observer and two field assistants. The production is usually one observation per day. Two observations per day are possible provided the recording sites are less than sixty miles apart.

The present system is equipped with two half-mile long seismic cables. These cables have twelve take-outs four hundred and forty feet apart. The seismometers connected to the take-outs were Geo-Space HS-10-1 types. Four horizontal and eight vertical seismometers were used. These are velocity-sensitive, high-output detectors. When possible, the seismometers were buried, approximately one to two feet in the ground. The "number one" take-out was located at the end of the array closest to the shotpoint. The horizontal detectors were located in pairs at array locations two, three, and array locations ten and eleven. An attempt was made to locate one horizontal detector of each pair in the direction of the energy propogation and the other at a right angle to it. Because the point of interest for depth determination was in the range of 10 km. or deeper, the recording site was mainly located at distances of 40 km. or more from the shotpoint.

The approximate position of the recording sites were determined on topographic maps prior to the survey. An attempt was made to find a mile section of the road which was relatively straight and level, with a direction having a minimum deviation from the direction of energy propogations. If the planned location did not fit into the above specifications when it was visited, the site was relocated if a better place was found in approximately a 4-5 mile radius. The new location was marked on the topographic map. Figure 1 shows the recording sites used in the present survey.

Regional surveys were started in this area around 1963. Only one segment of the long term project is a part of this study. The results of the investigations between 1963 and 1967 were published by Hall and Hajnal (1969). The data which extends the investigations to latitude 52°N and longitude 98°W are presented here. This entire project is supported by the National Research Council and field investigations are already extended beyond the above limits.

Limiting the survey to travelable roads makes it impossible in many instances that the detector array is in line with the shortest straight line direction towards the shotpoint. Deviation from this ideal situation can vary from zero to ninety degrees. If the deviation is more than five degrees, the observed arrival times from one detector site to the other, do not show any useful or even observable time differences. This in some cases complicates the recognition of the types of arrivals. During previous phases in the University of Manitoba's crustal studies several observations were made by moving the array off the road in the required direction. This in most cases meant cutting narrow lines in the bush and laying the cables there. The observed background noise in these cases was so high that this practice was abandoned. These experiments were carried out at the times when magnetic tape

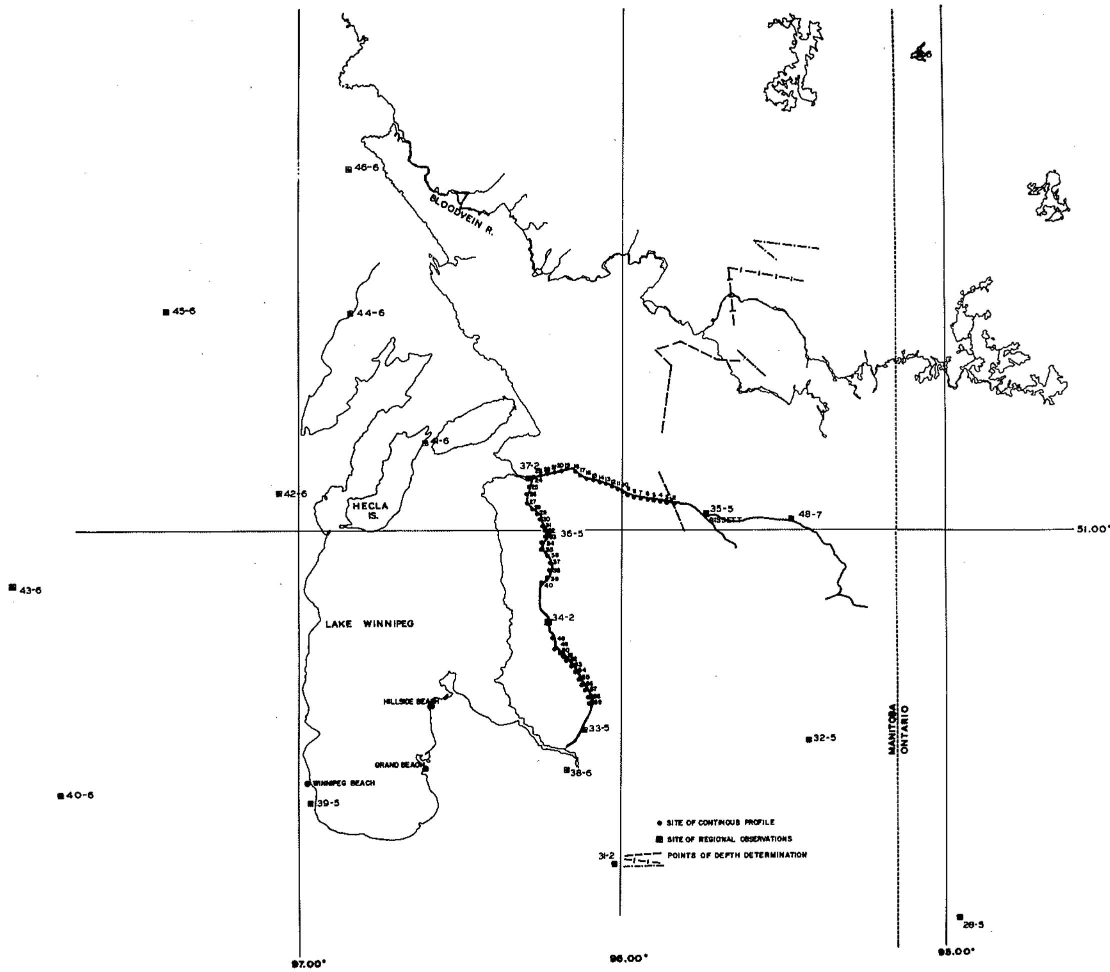


FIGURE 1. Location map of the regional and detailed refraction survey sites.

recording was not available. It could be useful to try the same experiment recording the data on magnetic tape and applying digital filtering techniques to the observed data. In these cases multi-detectors per channel might eliminate some of the noise. A better control of the noise would be possible if the seismic amplifiers are equipped not just with high cut filters as in the present case, but also with filters for the lower side of the frequency spectrum.

Continuous Refraction Profile

The instrumentation of this survey was exactly the same as in the previous case. The crew personnel was also unaltered. This technique requires a continuous seismic survey along a given distance. The observations were taken along the Provincial Highway Number 304 starting from the town of Bissett. The recording points are indicated on Figure 1. The first fourty sites are along the road from Bissett to south of Sandy River. The second set of twelve sites start at the intersection of O'Hanley River and the highway and continues south along the road. Every recording covers 1 mile. After each observation both cables were rolled up and when the new set up was laid out the previous number twelve detector location became the number one detector position for the new site. Under favorable weather conditions the three men could cover five miles a day. This production could be improved quite extensively with a larger crew and a second set of cables and detectors.

Vertical Reflection Profile

This short study was only experimental in nature. This method has gained only occasional application in crustal seismic studies; therefore, a standardized surveying technique does not exist. Recently Kanasewich and Cumming (1965), Clowes et al (1968) reported good results with near-vertical reflection arrivals from deep crustal layers using the same VLF-2 recording system as used in the present study. Both Clowes and Dix (1965) indicate that the arrival frequencies were somewhat higher than in cases of equivalent refractions. Dix (1965, p. 1069) in theoretical calculations shows that the principal frequency can vary from 12 to 25 cps. Clowes et al (1968) contribute the good quality of the field data they obtained to the specially designed arrays of sources and detectors. Their arrival frequencies were dominantly between 10-15 cps..

Using these references, the one cps. detectors were replaced with EVS-4, 7.5 cps. detectors. The study of near surface refraction records in this area showed that the ground roll has a frequency range of 2.85 to 3.7 cps. with average velocity of propogation of 3.1 km./sec.. The design of a detector array which would eliminate this noise would require a complex cabling arrangement which we do not have.

Because of its unusual nature no standard system could be used. The making of the cable and the extra crew it would require to move it created such a financial burden on the budget of the experiment that the use of the special detector array could not be used. Thus the VLF-2 recording system with the standard cables and one 7 1/2 cps. detector per take out were implemented for the project. It was found that by burying the detectors the noise level was markedly decreased. The location of the nearly vertical reflection survey, including the recording sites and shotpoint are indicated on Figure 2.

Shotpoint

The success of the deep seismic sounding depends in a major proportion on the effectiveness of the applied energy source. If the energy source is too small or the energy is not efficiently propogated in the direction of interest, only small and unreliable arrivals will be observed. Large distances between shotpoint and recording sites in crustal refraction surveys require usually large energy sources. The most accepted energy source at the present time is the detonation of explosives. The physical conditions under which the shot is fired have a large influence on the amount of energy and the character of the seismic waves. A good shotpoint location must be large enough for a load of over a thousand pounds of explosives. It must provide sufficient tamping to ensure that the gases do not blow out in a time comparable with the longest

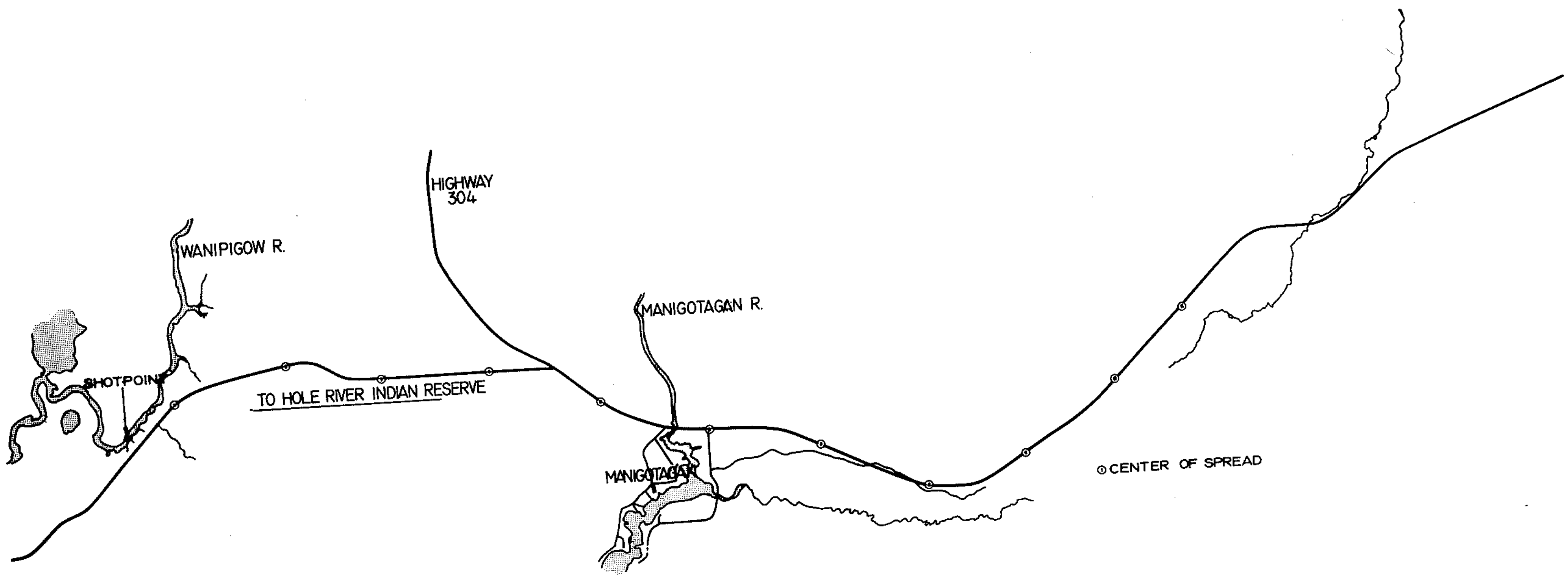


FIGURE 2. Location map of the vertical reflection survey sites.

period of interest in the refracted arrival.

In previous studies (Hall and Hajnal, 1969, p. 82) experiments were carried out using abandoned mine shafts and ventilation raises for shotpoint locations. Although deep and waterfilled mine shafts are good shotpoints there are only a very few in existence in the surveyed region; therefore the use of this type of shotpoint had to be discarded.

Because the Precambrian section of the surveyed area is extensively covered with lakes, detailed procedures were developed to use underwater explosions as the source of seismic energy. Cole (1948), O'Brien (1959, 1967), Weston (1960), Steinhart and Meyer (1961), Barnhard (1967) give general descriptions of experimental shooting in water. The conditions existing in the present case required some special considerations. Most of the charge sizes applied here were in the range between 400-1500 pounds, but only 60-70 feet of water depth was available in the lakes where the location of shotpoint became necessary.

When a charge of explosives is detonated underwater the immediate result is a very large amplitude pressure pulse roughly in the form of an exponential spike. The duration of the spike increases as the cube root of the weight of the charge (Cole 1948). At regular intervals thereafter a series of pulses of much smaller amplitude is radiated. These are associated with the pulsating bubble of hot gases and consequently are referred to as bubble pulses. These pulses carry only a small fraction of the energy in comparison to the primary pulse, but in certain cases can lead to later arrivals, which can cause problems in interpretation.

Cole (1948, p. 401) concludes that the first bubble pulse will be radiated at a time T_1 after the primary shock wave where

$$T_1 = 4.4\ W^{1/3}\ (d + 33)^{-5/6}\ \text{sec.}$$

W = charge size in pounds

d = depth in feet

There is no reference concerning the bubble pulse when several smaller charges, separated 150 feet were detonated at the same time. It was considered here that they behave as separate units. During the refraction profile survey fifty-two shots were fired from the same shotpoint. The charges varied from three one-hundred pound units to five one-hundred pount units. The water depth was 70 feet. The bubble pulse time for one-hundred pounds of explosives for the above water depth is 0.43 sec.. No consistant arrival delayed with such a time factor from the first break was observed on the fifty-two records.

O'Brien (1960, p. 32) states that according to the scaling law for the shock waves the seismic amplitude is

$$A = X\ W^n$$

where X = constant scale factor and n = 2/3 for marine work, but can change slightly from one explosive to another. According to this last equation the maximum seismic amplitude will only be obtained by splitting the charge into a number of smaller units. Using several smaller charges at the same time makes it possible that less water depth will still provide enough tamping for the total charge package.

The usual unit charges were two 50 pound cans of ammonia nitrate (Nitrone SM-Super X) blasting agent. These charges had their own cap and booster. They were lowered to the bottom of the lake from a small boat. The units were located 150 feet apart. For safety precautions every package was submerged in the water by rope and all the package locations were marked with a buoy. The same procedure was followed during the entire field survey.

For the vertical reflection program the shotpoint had to be located in the Wanipagow River approximately one mile from the Hole River Indian Reserve. Here the water depth was only 15 feet. The applied explosive charges were two and a half pounds, twenty-five pounds and fifty pounds. The computed bubble pulse times are 0.277 sec., 0.5099 sec., 0.6424 sec. respectively. Because of the shallow water conditions even in the case of small charges, very poor tamping was created. Radial plume was formed right after the first shock wave and the expanding gases broke the water surface.

No comparison could be made between the efficiency of underwater explosion energy source and shots fired in drilled holes. O'Brien (1967, p. 163) shows a table which indicates that the underwater explosions are far more efficient at producing low-frequency energy than the underground explosions. He also indicates that the water bottom conditions could effect the transmission of the incident energy, which can make the underwater explosion less efficient than the standard underground charges.

CHAPTER III

INSTRUMENTATION

Recording System

The complete seismic instrumentation of the University of Manitoba Department of Earth Sciences is shown in outline form in Figure 3. The basic unit is the Texas Instruments Incorporated VLF 2 refraction system. This includes the power supply and the RS-12 recording oscillographs.

This unit has a flat frequency response between 1 to 40 cycles per second. Gain adjustments are made in 6 decible steps between 0 and 66 decibles. The high cut frequency switch adjusts the cut-off frequency of the high cut filter at 8, 12, 16, 24, 32, and 48 cycles per second. The recording units have twenty-five galvanometers, twelve for high level gain and twelve for low level gain. There is a four to one (twelve decible) amplitude ratio between the two sets of galvanometer outputs. The twenty-fifth galvonometer is used for time information data. A basic time signal was received through a Specification Products Model WWVT receiver. The original unit had operating frequencies of 2.5, 5, 10, 20, and 25 megacycles. This was later modified, a 2.5 megacycle crystal was replaced with a 3.3 megacycle one. This made it possible to receive the

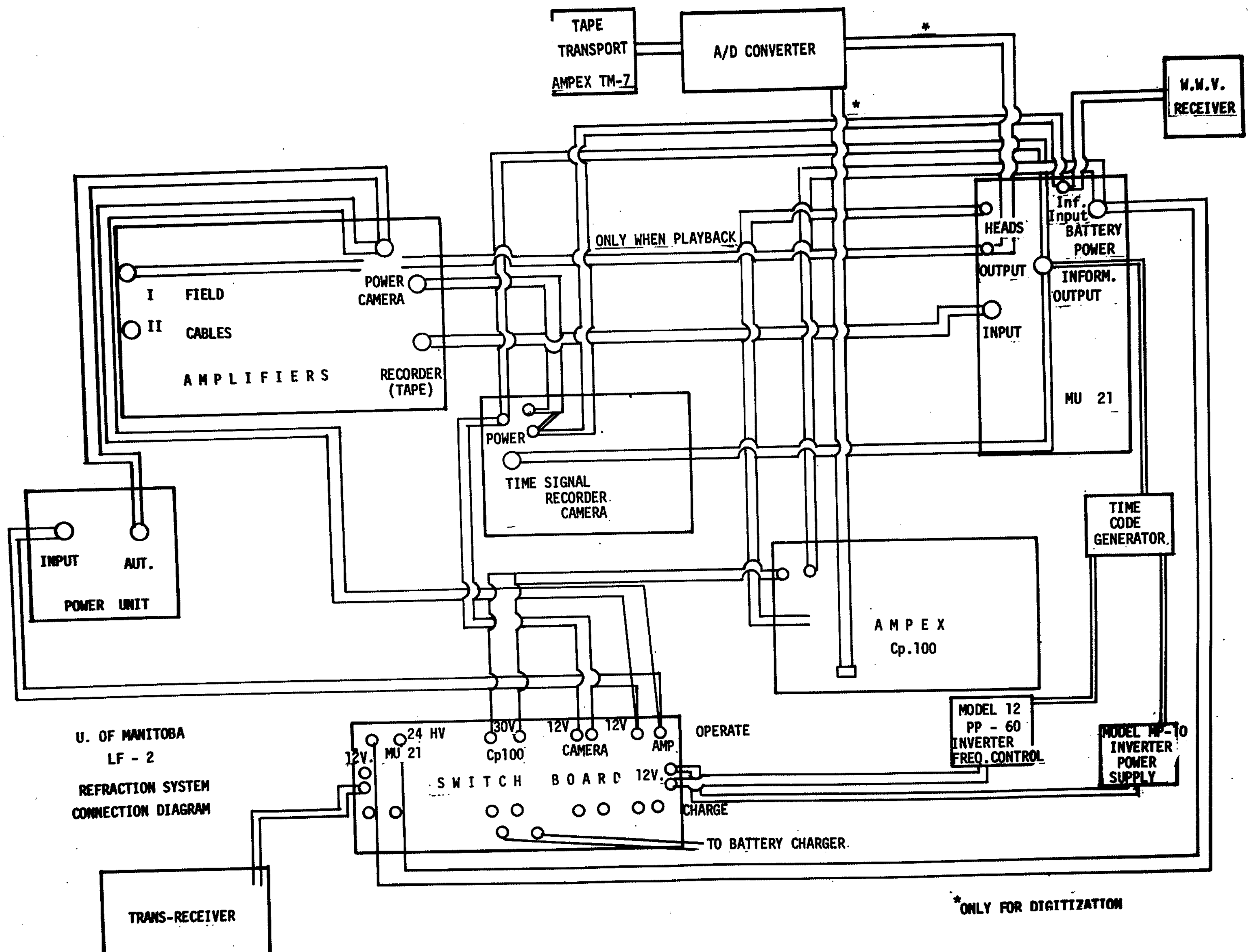


Figure 3.
Recording instrument lay out.

Canadian standard time signal. The audio output of this receiver can be set at 440, 600, and 1000 cycles per second.

The system was significantly modified in 1966 when an Ampex Model CP-100 fourteen channel tape recorder and a Southwestern Industrial Electronics Model MU-21 modulator-demodulator unit was added. The tape transport takes one inch magnetic tape. One reel contains 3600 feet of tape. Tape speed can be varied in the following manner 1 7/8, 3 3/4, 7 1/2, 15, 30, and 60 inches per second. For the seismic operation it was set at 3 3/4 inches per second. At this speed the signal to noise ratio is 42 decibles between 0-125 cycles per second. The total harmonic distortion is not more than 2%.

The model MU-21 is a fourteen channel, transistorized, frequency-modulated, record reproducing electronic unit. It contains seven transistorized dual channel modulators and seven transistorized dual channel demodulator units. Maximum input voltage level is ±0.375 volts. The maximum output voltage level is at ±2.2 volts. The center frequency is set at 3375 cycles per second. The total carrier swing is between 1750-6250 cycles per second. Its frequency response is within 3 decibles between 1 to 300 cycles per second.

The original unit was set to record at -30 decibles through channels 1 to 6 and at 0 decibles through channel 7 to 12. Channels 13 and 14 were used for timing signals.

With the present system channels 1 to 6 were modified to record at 0 decibles. With this it becomes possible to record on magnetic tape the outputs of 12 high-level Texas Instruments amplifiers. The acquisition of a Model 3000 oscillographic time-code generator made it possible to eliminate recording delays which were caused by poor reception of the WWV signals. This unit is a product of the Chrono-Log Corporation. This time-code generator produces an 8-4-2-1 binary coded digital representation of time. Once every minute a complete time code pattern is generated. The power requirement is 115 volts, 60 cycles per second. The unit uses the 60 cycle per second frequency as the time base. The modification this unit required are the following; the WWV signal was moved to channel 13 on the magnetic tape and to galvanometer number 24 on the camera and the cronolog signal goes to the twenty-fifth. In order to have recordable binary pulses the 100 cycle per second standard signal was connected from the camers to the MU-21 modulator through the power supply plug. The contact closures on the time generator are now used to open or suppress this continuous pulse during recording. With this method the binary pulses, which are 3 seconds, 1 second, 0.4 second in duration can be analysed as close as 0.01 seconds.

As it was pointed out previously, the accuracy of the time code generator depends upon the 60 cycle per second frequency. The unit requires 300 watts of power at peak period and 15 watts in average performance. Because the seismic system is operated in remote areas the main power supply available is a 12 volt battery. An invertor was therefore required to supply 60 cycles per second A.C. voltage with the above power requirement. It became infeasible to obtain a single unit which has the necessary specification. Modifications were made in which a Heathkit model MP-10 invertor supplies the driving power and a model PP-60 invertor supplies the standard frequency. This second unit has accuracy of ±5 ppm. With this arrangement the time code generator is accurate to ±6.8 milli-seconds in an hour. One good automotive 12 volt battery can supply enough power for an eighteen hour operation.

All twelve of the detectors used for the observations were Hall-Sears, Model H.S.-10-1 with natural frequency of one c.p.s.. These seismometers have 4000 ohms standard impedance. Eight of the detectors were vertical seismometers and four were horizontal seismometers.

Analog to Digital Conversion

The Data Acquisition System described here is a product of Radiation Incorporated. The major components of the system are indicated on Figure 4. The operations and specifications of the significant components are described in the following;

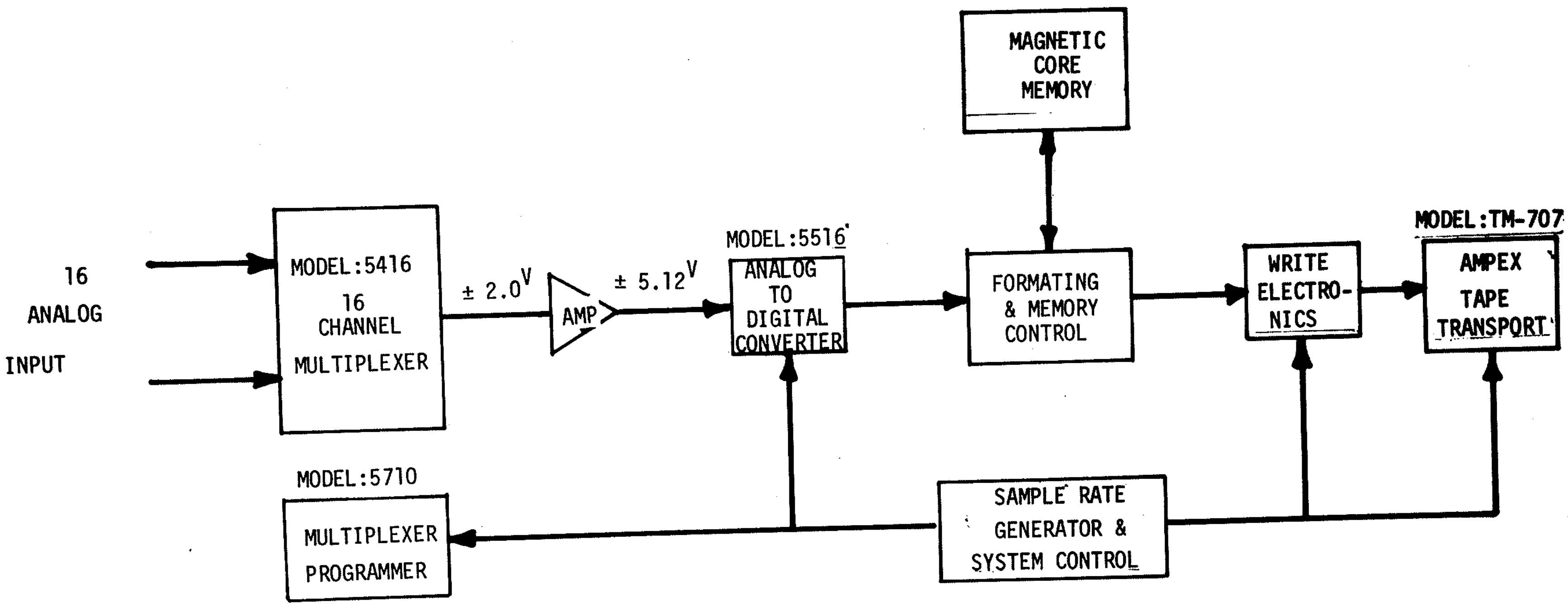


Figure 4.

Block diagram of analog to digital conversion system.

The Model 5416 multiplexer contains 16 input gates with associated address buffers. The packaging concept employed in the design of the system makes it possible to combine any number of units without modification of the basic package. With this combination, the number of digitized channels can be expanded in sets of sixteen. Every package must operate a minimum of two channels. Input signal is from 5 microvolts to 10 volts full scale. The input signal is fed through two sets of 16 phone plugs. The two input jacks, 51A and 51B provide two functions: (1) analog input connectors (2) switching between differential and single ended signals, placing the output signals on the proper buses. 51A is the 3 wire differential input jack whose bushing is 0.2 inches which will not accept the standard 0.25 plug used for the single-ended signal.

The Model 5710 Multiplexer Programmer provides the necessary gating information to open and close the gates of companion multiplexer units during data acquisition. The unit is able to control 64 channels that is 4 multiplexer units in one cycle. A front panel control provides the possibility to monitor any one of the 64 channels. This gives a chance to check any one of the channels for input signal. The Programmer contains a six stage binary counter which counts the number of channels examined. The counter may be patched to recycle to zero at any predetermined count, so that it is adaptable to any number of multiplexer channels (2 through 64). Patching is accomplished by the use of actual patch-modules in the Programmer. Patch-modules, designated in octal code (0 through 8) are provided with the system. The calculation for the required modules is shown on an example for a 12 channels operation

$$\frac{12}{8} = 1 + R\ 4 = \text{octal } 14$$

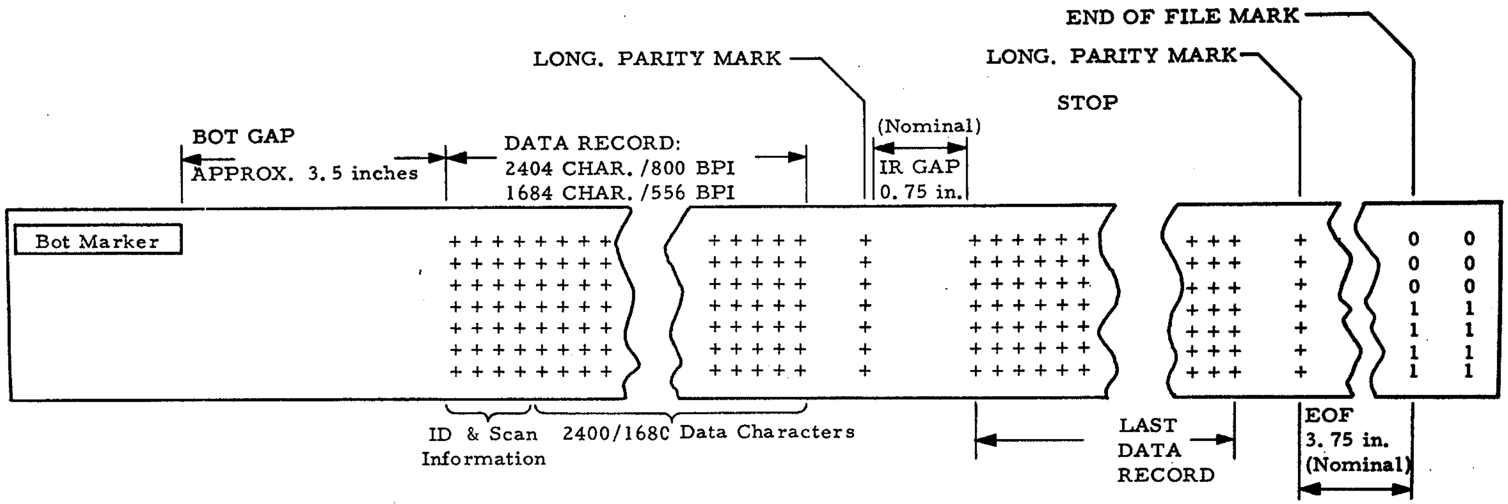
Thus to run the system with 12 channels an octal 1 module and an octal 4 module are required at plug A5B and A7B on the Programmer board. This procedure is described in more detail in the instruction manual of the Multiplexer Programmer.

The actual conversion of an analog data sample to digital form is carried out by the Model 5516 analog to digital converter. The input voltage range of this unit is 5.120 volts full scale. The normal digital output of the converter is an eleven bit (plus sign-bit) binary format in either serial or parallel form. The conversion of the analog input voltages into binary number is accomplished by a feedback method known as the half-split sampling technique. With this method a current is generated which is proportional to the input voltage and which is compared sequentially with a series of internally generated currents which have a binary relationship to each other. The display unit on the front of the panel consists of thirteen lights which indicate the sign (+ or -) and the presence or absence of bits of the binary word.

The unit between the analog to digital converter and the tape recorder provides the control for the entire system. The system produces IBM compatible seven track magnetic tapes at a packing density of 800 bits per inch or 556 bits per inch. Figure 5 exhibits the seven track magnetic tape format.

The set of 2404 or 1684 characters represent a digital record. The analog record may require many digital records. For the proper identification of the digital records the control unit has the following logic developed. Each digital record is identified with two numbers. The first one is generated by the header identifier. This is a digitran thumbwheel switch, set up in binary coded octal characters. This number stays constant unless the operator makes changes on the thumbwheel. This character therefore is used for the identification of the analog record.

The second number is generated by an 8 stage (2^7) binary counter. The binary counter counts the number of digital records written on tape and the present record number is inserted into the header information. The counter does not reset to zero when recording is stopped. If it is required that this counter starts at zero at the beginning of the digital record the Scan Identification Reset switch must be pushed before the recording is started.



TAPE DATA FORMAT

TRACK	DATA WORD	
C	P	P
B	+1	2^5
A	2^{10}	2^4
8	2^9	2^3
4	2^8	2^2
2	2^7	2^1
1	2^6	2^0

TAPE DIRECTION
(OXIDE SIDE)

FIGURE 5. 7 track magnetic tape format

Figure **Tape Format**

2—3

The Ampex tape transport uses an IBM compatible one half-inch magnetic tape. The tape speed is 22.5 inches per second during the digitization period.

Shotpoint Equipment

The shotpoint instrumentation is designed for the accurate observation of the time of detonation of the energy source. The schematic instrumentation is shown in Figure 6.

A paper recording at the shot instant and absolute time were made by the Century Model 444E 31-3 recorder. This is a four channel dry photographic type instrument. It has four electrically controlled externally selectable speeds, 1, 5, 10, or 50 inches per second. The unit uses Model 210 galvanometers available with 10 different natural frequencies and the 30 cps frequency was used. The galvanometers sensitivity is also variable between 0.015 to 140 MA per inch. The sensitivity decreases with the increase of the natural frequency. In the present operation, channel one records the WWV standard signal and channel four indicates the moment of explosion.

The detonation of the explosive materials was achieved by a Hall Sears Model HS-200 blaster units. This instrument is able to provide from 0 to 150 volts D.C. for the firing line. It is equipped with a line testing component as well as a remote firing system.

The timing signal receiver is equivalent to the

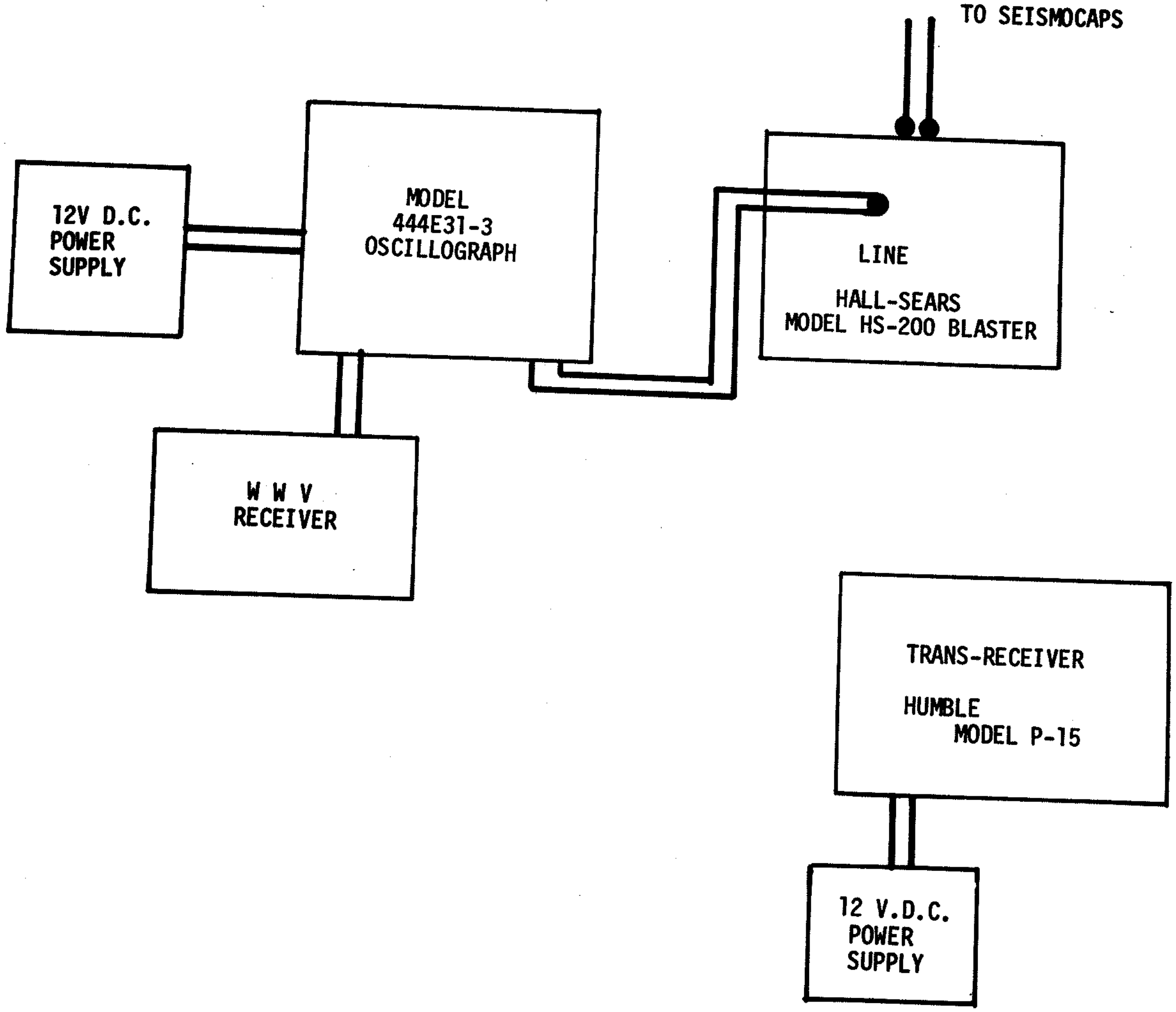


Figure 6.

Shotpoint equipment lay out.

instrument described for the recording site facilities.

Communication between the shotpoint and recording site was achieved using two Humble Model P-15 radio-telephones. Both these units have four crystal tuned channels and both are able to transmit 20 watts energy. With proper off center antennae they provide excellent communication to a distance as far as 300 miles.

CHAPTER IV

GENERAL COMMENTS

As the previous descriptions indicate the original low frequency crustal refraction unit underwent several modifications to improve its performance and reliability. In its present form it has provided excellent records, even under severe field conditions.

Suggested New Instrumentation:

(i) At Recording Site

The combination of the Ampex tape recorder and the VLF-2 system however has some drawbacks which should be examined when considering new instrumentation. The tape recorder and modulator have only twelve seismic channels while the VLF-2 system has twenty four. In the present system the twelve high level outputs of the VLF-2 amplifiers are connected to the magnetic tape system. This arrangement creates some problems in the case of extremely strong signals. Extremely high amplitude signals are distorted by the amplifiers and are recorded in a clipped form by the magnetic tape. The tape system itself has a very large dynamic range and could probably record the original signal without any distortion. It is possible to modify this problem by taking six high level output and six low level outputs from the amplifiers and record these signals on the magnetic tape. However, this step reduces the number of useful channels as much as fifty percent in extreme cases. A better modification appears to be a switch of six channels of the high level output to automatic voltage control.

(ii) At Shotpoint

Amplitude studies of crustal seismic data requires the knowledge of the pulse shape created by the explosion. The connection of a low sensitive seismometer to one of the channels of the shotpoint recorder could give some indications about the original wavelet.

CHAPTER V

DIGITIZATION

The block diagram of the digitizing process is shown on Figure 7. To obtain the proper analog signal for digitization the following modifications were carried out. All demodulators have one high level and one low level output. The high level outputs are not used for the seismic recording and playback operations; therefore, these were available output sources for the digital process. Pins one to twenty four on the geophysical output plug are wired for the standard seismic operation. By connecting the high level outputs of the demodulators to pins 25 to 36, of the same plug seismic playback and digitization, can be carried out by having one mating connector of the above plug wired for output signal from pins 1-24 and the other for signal 25 to 36. This second output is connected to the 12 input channel of the 5416 Multiplexer through 12 telephone plugs.

It was indicated in the description of the instrumentation that the analog to digital converter system requires ± 2 volts for full scale digitization. If the analog signal level is higher than the above limit the digital data will be highly distorted. It is possible to change the output level of the demodulators and with the

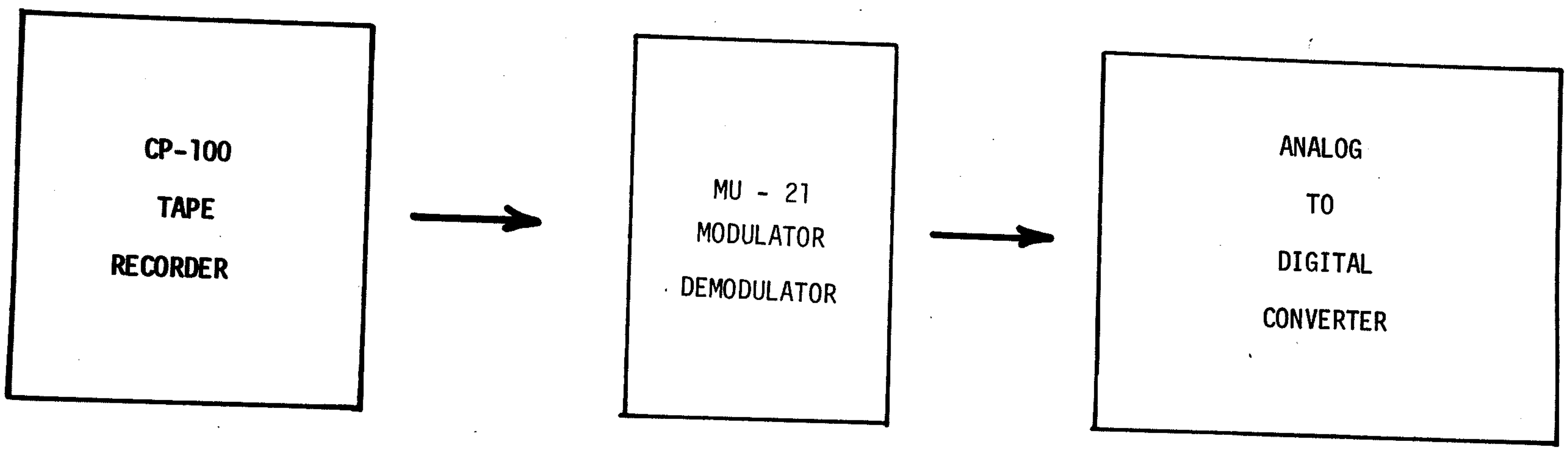


Figure 7.

Block diagram of the digitizing process.

proper setting the previous problem can be eliminated. Several strong seismic records were played back and the output voltage levels were observed on calibrated oscillc-scope. It was found that by setting the carrier voltage level to 0.7 volts ninety eight per cent of the present seismic data could be digitized without any distortion.

The analog to digital converter system is equiped with an external start/stop switch. When the system is in the external operation stage it requires a 0 volt level pulse, applied by another system, to start the digitizing process. This starting pulse was taken from the drive switch of the CP-100 tape recorder. When the drive switch starts the tape recorder, a KRP-50, 24V DC relay closes the converter unit external start circuitry this at the same time starts the converter. The above relay is located in the tape recorder, right of the recorder's switch housing. A two prong plug from the converter must be connected to the relay to make the remote system operational. The operational theory of the analog to digital conversion is described in detail by the Radiation Incorporated Manual titled "Data Acquisition Systems".

The analog to digital converter system has a sampling rate of 7000 Hz. This is divided between the number of channels digitized at the same time. In the present case 12 channels were used; therefore the number of samples per channels per second is equal to $\frac{7000}{12} \approx 583$ s/c/s.

This represents $\frac{1}{583} \approx 0.00171$ sec. digital sampling interval of the seismic traces.

The final product of the digitization process is loaded on a 7 track magnetic tape. The magnetic tape format is shown on Figure 5. As this diagram indicates, every digital block consists of 2404 digital characters, 2404 representing the actual data, the remaining four characters are created by setting a number at the Header Identifier. The second two characters are the result of the counting of the number of digital block put on the tape. This number changes from 0 to 255. If the scan of the counting clock was not reset at the beginning of the digitization then the above number will start where the clock stopped in the case of previous operation.

Although the above data is compatible with the IBM 360 computer system, it is cumbersome to handle it in this form. To make the programming less difficult, the 12 bit binary numbers on the seven track magnetic tapes were converted to 16 bit binary numbers on nine track tape. This second format is a basic unit for the 360 system.

The conversion of the digitized data was carried out on the IBM 360 computer using a program called BINBIN. The detailed documentation of this program as well as the actual program written in COBOL language, are enclosed in the Appendix.

After the conversion of the digital data to the 9 track tape the length of the output, the location of the first break time with respect to the digital blocks, as well as the absolute time of the beginning of digitization with respect to the shot instant, all have to be determined before processing of the data can be started.

As the documentation of the BINBIN program shows, it is possible to print out the entire data using this program. Unfortunately this procedure was found unsatisfactory for the solution of the above problems. This is a service program provided by the university's computer center. Any modification would make it too specialized; therefore, it would become useless for the other users of the analog to digital conversion systems.

A simple program, BLOCK 50, was consequently written to provide all the necessary information for the previous problems. This is a FORTRAN IV program. It's description and the program itself are listed in the Appendix.

Knowing the total number of blocks in one digital record, the determination of the length of the seismic record is the following:

NN x 0.171 = length in seconds of the digital seismic record

where NN = total number of blocks

The location of the first breaks requires the examination of the printed digital blocks. The analog to digital conversion was usually started six to seven seconds before the first arrival time; therefore the printing of the first fifty blocks of every digital record was found satisfactory to locate the first breaks. The recognition of the first arrivals is a simple matter. They are represented by a sudden increase of the digital number, almost a hundred times above the background noise. This is illustrated in the following example.

577	42				
56	52	-14	-19	-63	46
21	24	-36	-77	-91	40
48	45	-43	-42	-67	89
40	42	-39	57	-20	88
35	30	-21	46	23	56
20	20	-14	51	-10	0
8	16	-5	67	-35	-10
-161	15	-6	76	-19	-13
-1935	10	22	-2	-21	23
-1735	650	43	-14	-33	9
-1747	2001	3	-7	-51	-26
-1738	1998	-170	15	-31	-16
-1742	1985	-1989	8	41	-59
-1783	263	-1855	-14	47	-67
1496	-115	-1842	-720	2	-80
1398	-110	-1843	-1731	-65	-21
1542	-145	-1837	-1760	-732	25
1545	-153	-868	-1741	-1054	-406
1375	-155	1305	-1736	-1086	-1893
1364	-156	1546	-1740	-1085	-1750
1544	-738	1456	-1718	-1086	-1733

Now the absolute time of start of digitization is

$$T = A - [(B \times .171) + (\Delta B \times 0.00171)]$$

A = first arrival time, determined on analog record

B = number of the block where the first arrival is located. This is 42 in the present example.

ΔB = number of samples in the above block before the first break. This is 7 in the present case.

If A = 8.50 sec. then the digitization of record 577 was started at 8.50 - [(42 x .171) + (7 x 0.00171)] = 1.306 seconds.

This simple procedure shows many rewards at the time of processing of the digital data. If the time of the start of the digitization is known for every record, the programmer can develop his programs using the real times, which are usually determined when the data is examined in analog form.

To eliminate unnecessary repetition of calculations and observations a Digital Tape File book was started. This book contains the following information.

1. Digital number of seismic record.
2. Original number of seismic record.
3. Number of 7 track tape on which the analog digital conversion was made.
4. Number of blocks in the digital record.
5. Footage counter reading on CP-100 tape recorder when digitization of the record was started.
6. Number of the block where the first breaks are located.
7. Absolute time of start of digitization.

CHAPTER VI

GEOLOGY

The area of investigation extends to latitude 50°50' at the south and latitude 52° in the north, as well as longitude 95° east and 98° west. The surface or near surface rocks for large percentage of this area are Precambrian in age. In the western portion of this area, the near surface rocks are Paleozoic in age. The detailed surface geological studies are spotty and mainly restricted to the south-eastern corner of the area.

Precambrian Shield

The Precambrian Shield east of Lake Winnipeg is relatively flat. Its elevation is less than 1000 feet above sea-level and its maximum relief seldom exceeds 100 feet. The depressions in the surface are occupied by numerous lakes and swamps. More recent geological studies in the area are: Davies (1950), Davies (1951), Davies (1953), Davies et al (1962), Ermanovics (1968). The glacial drift, which is thin in this area, consists mainly of clayey boulder-till occupying the hollows between rock ridges.

This part of the shield is a portion of the Superior geological province. The Superior province is characterized by east-trending volcanic sedimentary-belts in which volcanic rocks are as abundant or more abundant than sedimentary rocks. The rocks show low to moderate metamorphism.

The lithology of the shield area is very complex in detail. One short description is given by Davies et al (1962, p. 16).

> The volcanic rocks consist of light to dark colored andesites and basalts (commonly ellipsoidal), volcanic breccia (andesitic, dacitic, and rhyolitic), and tuffs. Intervanded with these in places may be coarse grained massive hornblende-plagioclase rocks that have often been regarded as coarse centers of flows but more probably are sill-like intrusions related in origin to the volcanic rocks. The sedimentary rocks are mainly impure quartzites and greywackes, although conglomerate, slate, and arkosic rocks are also common. Stock-like masses and small batholitic bodies of massive granitic rocks (actually most are tonalites) invade the volcanic sedimentary series and in most areas are elongated parallel to the trend of these rocks. Outside the volcanic-sedimentary belts and forming the bedrock over most of the Precambrian Shield, are complexes of granite and granite gneisses (here, also, many or most of the rocks are not true granites but closer to granodiorites and tonalites). Sedimentary and volcanic rocks associated with these granitic rocks may be extensively granitized.

On the general structural trends of the shield the above authors give the following description:

> Structurally the Precambrian is exceedingly complex. In many areas the sedimentary and volcanic rocks have been isoclinally folded and extensively faulted. Dips are normally steep. Major unconformities are recognizable in places, but in many areas, even though the sedimentary rocks may be separated from the underlying volcanic rocks by an unconformity, no angular discordance between the two series is evident.

A large proportion of the seismic survey was carried out in the Rice Lake-Beresford Lake District. The rocks of this area are formed by the Rice Lake group of volcanic, sedimentary, and derived metamorphic rocks which lie in a continuous belt from Lake Winnipeg to the Manitoba-Ontario boundary, and potassic intrusions and granitic gneisses which border the Rice Lake group on the south and north.

The Rice Lake group shows folding at the Beresford Lake and Rice Lake Area. The limbs of these folds are steeply dipping, although Davies (1951) does not find evidence of anticlinal or synclinal structure along the Manigotogan River in the Manigotogan area.

A number of east trending longitudinal faults can be recognized in the Rice Lake volcanic and sedimentary rocks.

North of the Rice Lake district no detailed geological information is available. Early geological maps from this area, Johnston (1938), indicate mainly granitic rocks, with belts of volcanic and sedimentary rocks.

Sedimentary Rocks

The sedimentary sequence in the area of interest start at the eastern shore of Lake Winnipeg. The thickness gradually increases towards the west, but does not reach significant proportions in the surveyed area.

The Precambrian surface is covered with an Ordovician sandstone. This is followed by a series of dolomite formations. The upper most of these dolomite formations at the boundary of the survey is the Interlake Group. This is Silurian in age.

The total thickness of the consolidated sedimentary rocks reach only 0.28 km. at the western margin of the surveyed area. Davies et al (1962, Figure 36) estimates that the glacial drift varies between 0 to 15 meters in this part of the province.

CHAPTER VII

DIGITAL PROCESSING

The major difficulty in the interpretation of seismic data is the occurence of noise. The noise is everything in the observed signal that is not related to the subsurface structure. The recorded data contain the desired signals and the noise, which is in most cases superimposed on the signals. The problem is to identify the signal in the presence of the noise. The processing of the data must maximize the signal to noise ratio.

Over the years much has been done to improve the signal to noise ratio in seismic operations. One of the most important steps in the data improvement was the introduction of magnetic recording. With this advance it became possible to reproduce the recorded seismic signals and a much greater flexibility in processing was achieved. Different type of frequency filtering, mixing of traces, as well as multiple visual displays all entered in the processing of the data.

In recent years other fundamental progress was achieved by the introduction of digital processing of the seismic signal. The continuous analog seismic trace is converted into a sequence of numbers. Each number represents the reading of amplitude of the trace at a specific time instant. Accompanying these changes in recording procedure was the application of the general communication theory to the field of digital seismic data processing. The theory was developed on a statistical basis. It is considered that the received digital seismic trace is one sample from a collection of possible signals that might have occurred.

In the view of the present study digital processing is considered to be the application of certain mathematical operations to seismic data. These operations or filtering processes are more effective in enhancing signal to noise ratio than the conventional seismic analog filters. Figure 8 is a simple block diagram of the different analog and digital filters. A linear can be described with its amplitude and phase characteristics. The conventional analog filter is constructed of inductances and capacitances. The ordinary digital frequency-filter is represented by a set of weighing coefficients. Both of these filters are designed on the principles that they pass a selected band of frequencies and reject all others. As the diagram indicates, the application of the digital filtering techniques resulted in the development of the optimum filters. Frequency filters are designed on an arbitrary basis without reference to the signal or the noise, and without reference to the effectiveness of the filter. The

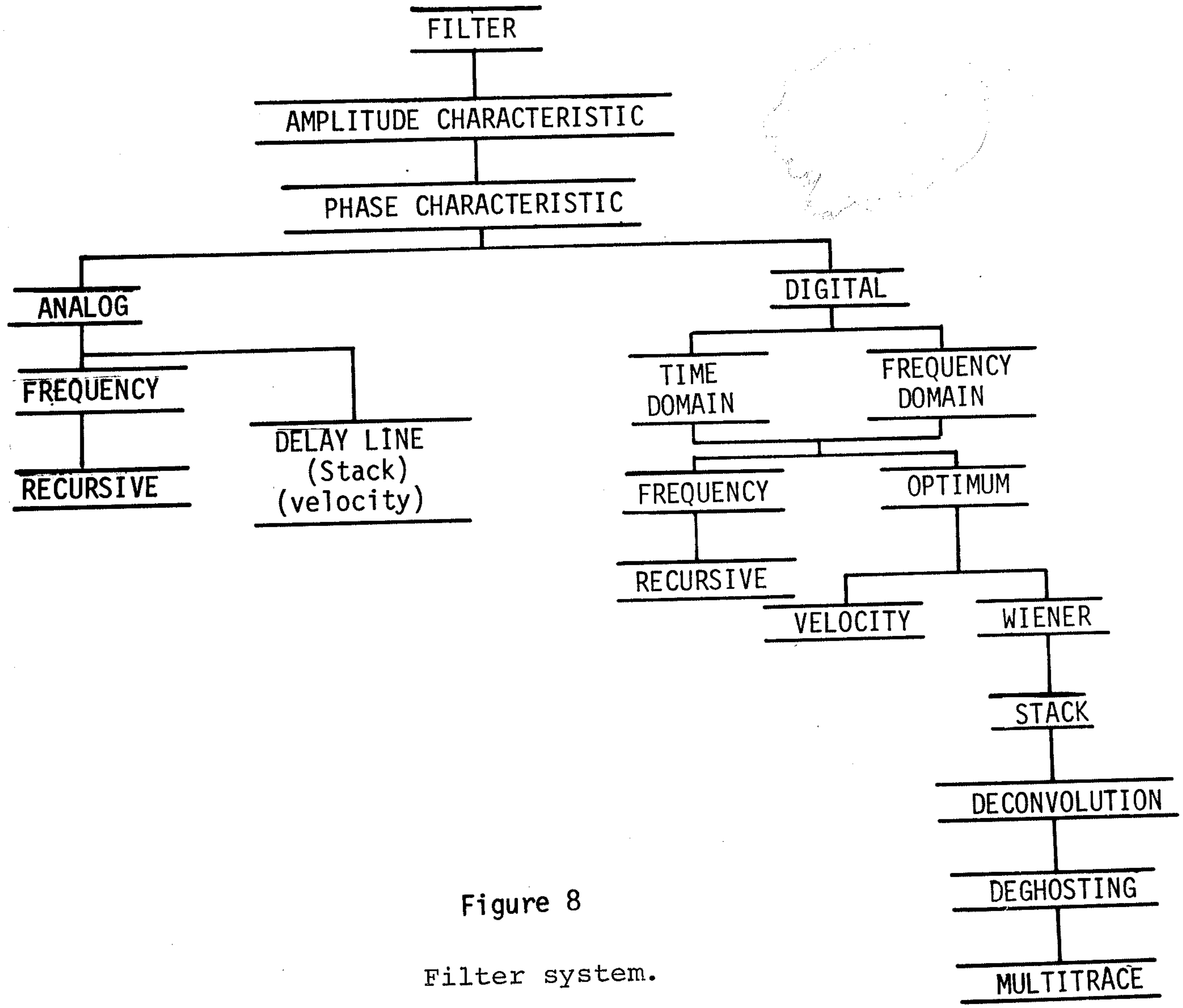


Figure 8

Filter system.

optimum filter is designed on the basis of a specific character of signal and noise. For example, the Wiener filter is designed on the basis of the actual input signal and the desired output to have an optimum fit, and this fit is defined by the least square error criterion.

Only some of the available filtering techniques were applied in the present case and only these will be dealt with in more detail.

Band-pass Filter

The band-pass filter is built on the principle that there is some spectral separation between the signal and the unwanted noise. The frequency response of the filter will indicate the band of frequency which is passed by the system. In the case of the digital filter design this means the application to the sampled data of a set of linear operators. Several papers give a summary of the digital filters design, Ormsby (1961), Papoulis (1962), Robinson (1967a), Wood (1968). The development of suitable linear operations in terms of linear weights and the time-sampled version of the filter weighting function, is based on the fitting of the associated filter frequency response function to a proposed shape.

The communication theory starts out with the computation of a low-pass filter and this is modified for the band-pass filter case.

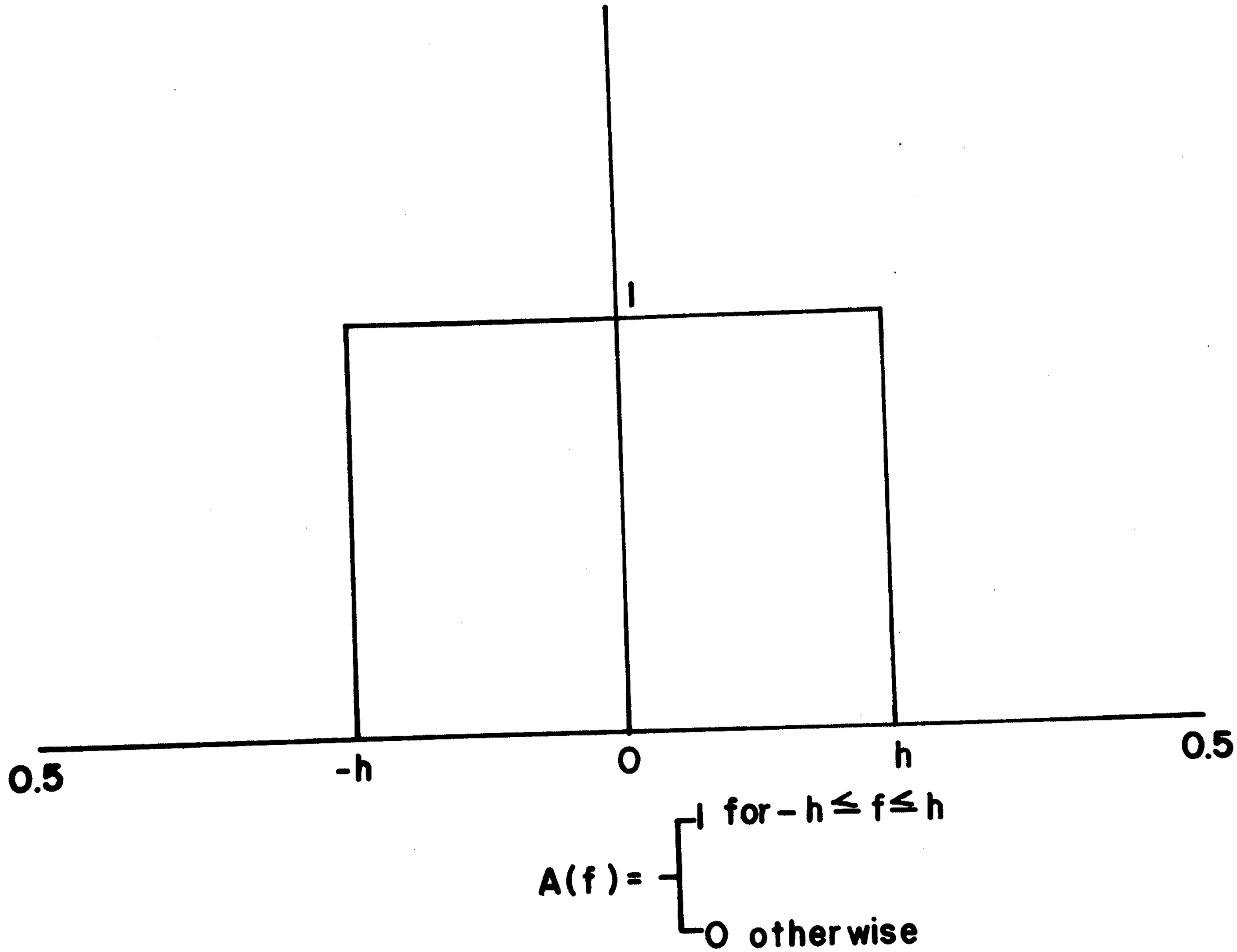


FIGURE 9. Frequency response of the ideal low-pass filter.

Figure 9 shows the frequency response of an ideal low pass filter. The weighting coefficients "a_t" of the filter are the Fourier coefficients of this frequency function, that is

$$a_t = \int_{-\infty}^{\infty} A(f) \exp (2\pi i\ ft)\ df = \int_{-h}^{h} \cos (2\pi\ ft)\ df$$

$$= \frac{1}{2\pi t} \sin 2\pi\ ft \Big]_{-h}^{h} = \frac{\sin 2\pi ht}{\pi t}$$

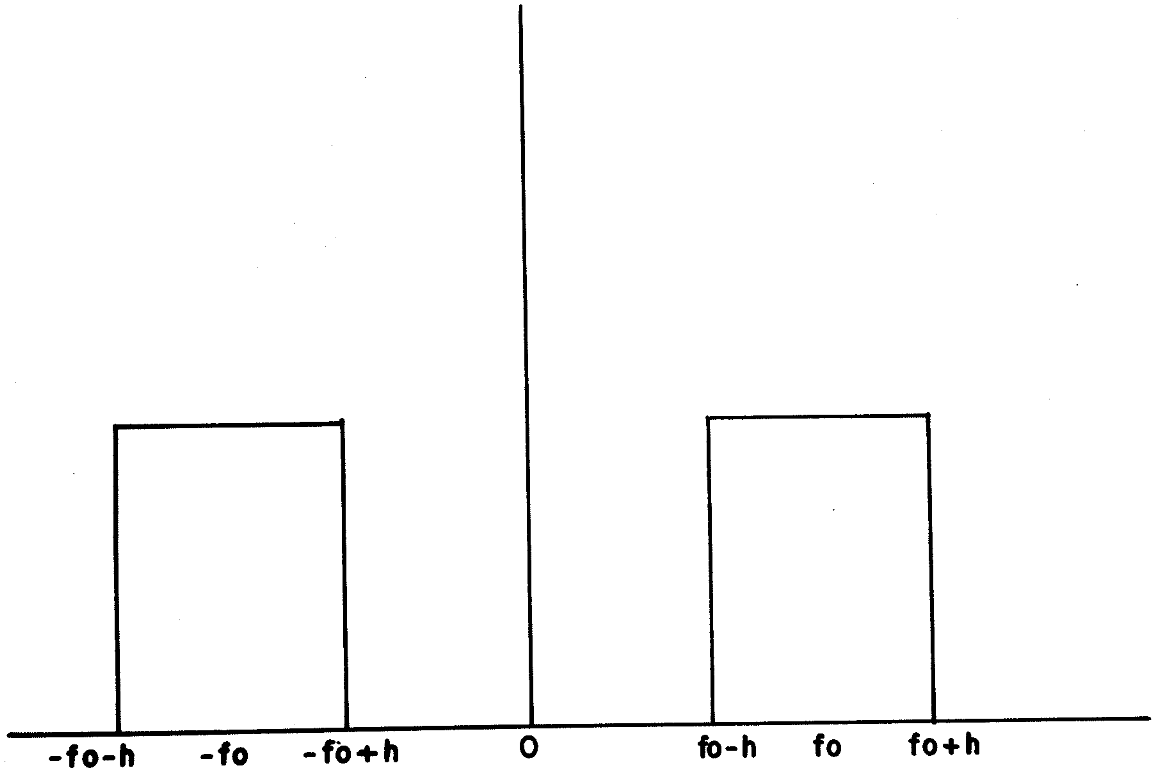
where t ranges over all integers from - to + . The detailed theoretical aspects of this derivation is described by Papoulis (1962, Chapter 6).

The theory of the ideal low-pass filter can be used for the design and a set of low-pass filters can be used for the application of band-pass filtering. One simple scheme is expressed by the equation

$$S_n = S_{n_1} - S_{n_2}$$

where S_{n_1} and S_{n_2} are the outputs from two low-pass filters with different cutoff frequencies. The mathematical derivation of the two low-pass filters is identical. The use of band-pass filters in this manner can result in about twice the maximum error of the component low-pass filters due to the addition of errors.

The design which was used is obtained by frequency shifting as follows: Given a low-pass filter with response



A_b {
1 for fo-h ≤ + ≤ fo+h
1 for -fo-h ≤ ≤ -fo+h
0 in all ather cases

FIGURE 10. Frequency response of an ideal band-pass filter.

$A(f)$, define $A_b(f) = A\ (f - f_o) + A\ (f + f_o)$ where f_o is the centre frequency of the designed band-pass. If inphase band-pass filter is considered, then the negative and positive frequency spectra functions are the same. This means that $A_b(f) = A^*\ (-f)$ for real weights. The graphic presentation of this filter is indicated on Figure 10.

The coefficients for the right hand side are

$$\int_{-\infty}^{\infty} A\ (f - f_o)\ \exp\ (2\pi i\ ft)\ df$$

$$= \int_{-\infty}^{\infty} A(f_1)\ \exp\ [2\pi i\ (f_1 + f_o)t]\ df_1$$

$$= a_t\ \exp\ (2\pi\ f_o t)$$

where $f_1 = f - f_o$

The equation for the left side is $= a_t\ \exp\ (-2\pi i\ f_o t)$. The ideal band-pass filter is the sum of these last two equations; therefore the weighting coefficients of an ideal band-pass filter are

$$b_t = a_t\ [\exp\ (2\pi\ f_o it) + \exp\ (-2\pi\ f_o it)]$$

$$= 2\ a_t\ \cos\ 2\pi\ f_o t = \frac{2\ \sin\ 2\pi ht}{t}\ \cos\ 2\pi\ f_o t$$

This of course requires that t takes values from $-\infty$ to ∞. This last equation also indicates that the ideal band-pass filter has coefficients which are equal to the product of a carrier $\cos 2\ f_o t$ and the coefficients a_t of the equivalent low-pass filter. A more general derivation of this formula is presented by Papoulis (1962, p. 123).

The frequency band of the filters and the data is limited because of the digitization process. The highest frequency limit is determined according to the following criteria. In order for the sampling process not to lose information about the original trace, it is required that the sampling frequency is at least twice the highest frequency contained in the signal. If t_s = sampling interval, then $f_n = 1/2\ t_s$ is called the Nyquist frequency of the sampling. If a higher frequency than f_n is present in the original signal then it appears as a lower frequency after the digitization process. For computational convenience t_s is chosen as the unit of time. In this case the Nyquist frequency becomes 1/2 cycle per time unit.

This limit of frequencies does not affect the application of the theories applied here and in the following sections. The mathematical proof is given by the sampling theorem which is described in great detail by Goldman (1955, p. 67).

In practice the band-pass filter is limited to a finite number of coefficients. The length of the weighting function is controlled by the angularity of the response curve at the cut-off frequency, the attenuation rate, and the amount of rejection. The longer operator may remove more of the noise but it may remove some of the higher frequency signal also. The shorter operator may give a good performance but it lowers the Nyquist frequency of the filter which can be a problem if the signal has high frequency noise in it.

The spacing of the weighting coefficients should be at least twice the highest signal frequency. The truncation of b_t between $t = \pm n$ leads to errors at the cut-off frequencies or at the points of discontinuity. Lanczos (1956) describes the so called Fejer's method which introduces a set of new weighting factors. Fejer's arithmetic-means method completely eliminates the Gibbs oscillations. This means that the ideal filter design data must be corrected with these coefficients.

The Fejer weighting factors are $k_t = 1 - |\frac{t}{n}|$ for $-n<t<n$. Then the filter weighting coefficients are

$$c_t = b_t k_t = \frac{2}{\pi} \sin \frac{2\pi h t}{t} \cos 2\pi\ f_o t\ (1 - |\frac{t}{n}|)$$

For computer applications this formula is revised using the following trignometric relationships,

$$\sin x \cos y = 1/2\ [\sin (x-y) \pm \sin (x+y)]$$

From this the final formula for the band-pass filter is

$$b_t = \frac{1}{t} [\sin 2\pi(h+f_o)t - \sin 2\pi(h-f_o)t]\ (1 - |\frac{t}{n}|)$$

for $-n<t<n$. This is a modified formula of Robinson (1966).

It is possible to compare the designed filter to the ideal case by computing the Fourier transform of the impulse response of the filter. Considering a symmetric filter the computation is carried out by the following formula

$$B(t) = b_o + 2 \sum_{t=o}^{n} b_t \cos (2\pi ft)$$

Using formula b_t and B_t a computer program was written for the design of the band-pass filter. The description and complete listing of this program is found in the Appendix.

Figure 11 exhibits the frequency response of three 5-25 cps. band-pass filters. The plotted data is listed in Table 1. These were computed using the previously described computer program. All were corrected with Fejer's weighting factors but the number of filter coefficients were changed from 50 to 200. The increase of the number of coefficients from 50 to 100 improves the over all frequency response 8%. But the change of the number of operators from 100 to 200 resulted in only a 3 to 4% better frequency response curve. At the same time the 200 linear operators increase the computer processing times approximately three fold with respect to the operation carried out applying only 50 coefficients. As a compromise the 100 linear operator function was used for the filtering of the observed data. The applied data is listed in Table 2.

Convolution

When the set of filter operators are determined,

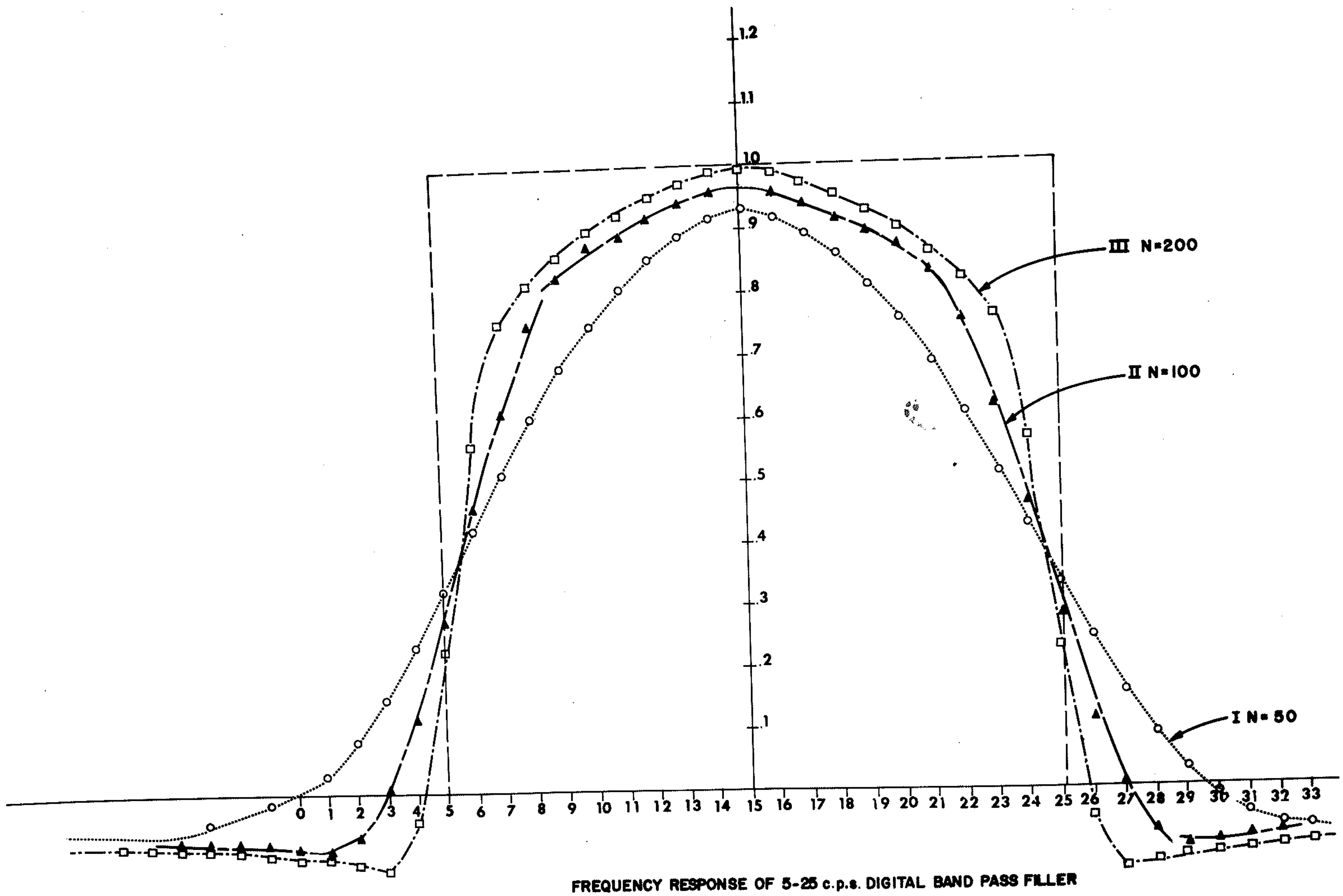


FIGURE 11. Frequency response of the 5-25 cps. digital band-pass filter set.

TABLE I

COMPUTED FREQUENCY RESPONSE OF 5-25 CPS.
BAND-PASS FILTER

Frequency	50 samples frequency response	100 samples frequency response	200 samples frequency response
15	.940	.975	.994
16	.915	.956	.982
17	.890	.933	.965
18	.855	.911	.944
19	.810	.894	.925
20	.754	.872	.899
21	.685	.830	.859
22	.604	.750	.822
23	.515	.623	.758
24	.420	.460	.561
25	.323	.279	.226
26	.238	.115	-.050
27	.154	-.006	-.135
28	.085	-.075	-.119
29	.025	-.098	-.112

TABLE II

WEIGHTING COEFFICIENTS OF THE 5-25 FEJER'S FILTER

Impulse Response Fejer Filter 100 coefficients			
0.06801	-0.00563	0.00081	0.00179
0.06634	-0.00335	0.00142	0.00180
0.06277	-0.00165	0.00180	0.00173
0.05749	-0.00055	0.00196	0.00159
0.05075	-0.00004	0.00191	0.00140
0.04285	-0.00009	0.00169	0.00119
0.03414	-0.00060	0.00133	0.00095
0.02497	-0.00149	0.00089	0.00073
0.01574	-0.00263	0.00040	0.00051
0.00678	-0.00390	-0.00009	0.00033
-0.00158	-0.00519	-0.00052	0.00019
-0.00908	-0.00638	-0.00088	0.00009
-0.01543	-0.00737	-0.00114	0.00002
-0.02053	-0.00809	-0.00127	0.00000
-0.02429	-0.00850	-0.00127	0.00001
-0.02667	-0.00857	-0.00115	0.00004
-0.02773	-0.00837	-0.00093	0.00008
-0.02756	-0.00773	-0.00062	0.00012
-0.02633	-0.00688	-0.00025	0.00016
-0.02422	-0.00583	0.00015	0.00019
-0.02146	-0.00465	0.00055	0.00020
-0.01827	-0.00340	0.00093	0.00019
-0.01489	-0.00217	0.00126	0.00016
-0.01154	-0.00102	0.00152	0.00011
-0.00839	-0.00002	0.00169	0.00006

the actual digital filtering can be carried out either in the time domain or in the frequency domain. The operation in the frequency domain requires the determination of the amplitude and phase spectra of both the filter and the data. The multiplication of the amplitudes and summation of the phases achieves the filtering process. The application of the Fourier transform to the filtered signal converts it back to time domain again. This type of filtering becomes economical only if the data and the filter operators are very long.

The filtering in the time domain is carried out through the process of convolution. Theory of convolution is described in details by Lee (1966), Goldman (1955), Robinson (1967a). In general the convolution of one function with the other means the folding of one function, then the multiplication of the folded and unchanged functions and finally the product is integrated over a complete period. In mathematical form this is expressed as

$$\rho_{12}(\tau)=\frac{1}{T}\int_{-T\frac{1}{2}}^{T\frac{1}{2}} f_1(t)\ f_2(\tau-t)\,dt = \sum_{n=-\infty}^{\infty} F_1(n)\ F_2(n)\ e^{jn\omega\tau}$$

The second subscript always refers to the function which is placed and folded back. It is important to know that

$$\rho_{12}\ (\tau) = \rho_{21}\ (\tau)$$

therefore it does not matter which function is folded to carry out the convolution.

With signals of finite time length (A_0, A_1, A_2, ... A_m) and B_0, B_1, B_2, ...B_n) the above formula is reduced to

$$C_k = \sum A_i B_{k-i}$$

where the summation is over all i such that $o \leq i \leq m$ and $o \leq k-i \leq n$.

The output function (F(c) has n±m-1 terms. This means that the output signal is always longer than the input signal. The computer application of the above described theory is presented by the CONVOLV program in the Appendix.

Correlation

The development of the optimum filters were built on the theory of correlation. If one time dependent function is correlated with itself, the autocorrelation theory is applied, if two different functions are correlated this involves the crosscorrelation theory. The general theory of correlation is described in considerable detail by Lee (1966), Goldman (1955). A short summary is

$$\gamma_{12}(\tau) = \frac{1}{T} \int_{-T^{1/2}}^{T^{1/2}} f_1(t)\ f_2(t+\tau)\ dt = \sum_{n=-\infty}^{\infty} [\bar{F}_1(n)\ F_2(n)]e^{jn\omega\tau}$$

where $f_1(t)$, $f_2(t)$ are the two functions. $F_1(n)$, $F_2(n)$ are the amplitude spectra of the two functions. $\bar{F}_1(n)$ is the complex conjugate of $F_1(n)$. τ is a continuous time of displacement in the range $(-\infty, \infty)$ independent of t. This equation can be found in Lee (1966, p. 10).

The equation indicates three operations:

1. The second function is displaced by τ.

2. The displaced function is multiplied by the other function.

3. The product is averaged by integration over a complete period.

If τ is replaced by $-\tau$ it can be proven that

$$\gamma_{12}(-\tau) = \gamma_{21}(\tau)$$

which means that the outputs are mirror images of each other.

The other fundamental properties of the cross-correlation function are

(a) If one harmonic is absent in either one of the correlated functions this harmonic will be absent in the crosscorrelation function.

(b) The corsscorrelation function retains the phase differences of the harmonics which are present in both periodic functions.

(c) The correlation of two functions, one of which has been folded back, is in fact convolution of two functions, one of which takes the folded form prior to convolution, is actually a correlation.

If $f_1(t) = f_2(t)$ then

$$\frac{1}{T} \int_{-T^{1/2}}^{T^{1/2}} f_1(t)\, f_1(t+\tau)\, dt = \sum_{n=-\infty}^{\infty} [F_1(n)]^2 e^{j\omega n\tau}$$

if $\tau = 0$

$$\frac{1}{T}\int_{-T\frac{1}{2}}^{T\frac{1}{2}} f_1^{\,2}(t)\,dt = \sum_{n=-\infty}^{\infty} |F_1(n)|^2$$

which states that the mean square value of the function $f_1(t)$ is equal to the sum, over the entire range of harmonics of the square of the absolute value of its amplitude spectrum. This in electronics represents the output power; therefore the results of this equation are called the power spectrum of function $f_1(t)$. The square root of the power spectrum gives the amplitude function.

The equation of the autocorrelation function indicates that it is related to the square of the complex spectrum. This means that although the autocorrelation function contains all harmonics of the original function, it discards all the phase angles. Therefore, functions with the same harmonic amplitudes but different phase angles have the same autocorrelation function.

Fundamentally, correlation theory tries to answer the following questions.

1. Is there any correlation between two seismic traces?

2. What is the degree of correlation?

3. What is the maximum time shift T required for one trace so that the correlation between the two will be maximum?

In other words, correlation theory tries to establish the similarity of two seismic traces, or to the extent to which one trace may be considered to be a linear function of the other.

Before two seismic traces can be correlated some important conditions which are present in seismic recording must be investigated. The factors which have a disturbing effect on the determination of the correlation coefficients are the modulation level of the amplifiers, poor inter-channel balance, D.C. shift, length of the sampling interval. To make the correlation more meaningful these conditions must be eliminated by the normalization of the studied data.

The modulation level or difference in gain level as well as the effect of inter-channel balance is eliminated by the division of the data with the standard deviation of the individual traces. The D.C. shift is eliminated by the subtraction of the average value from the individual samples of the trace. The difference in length of the sampling interval is normalized by the division of the number of the total samples. Thus the equation for a correlation coefficient when a finite number of samples are used is

$$\gamma_{xy} = \frac{1}{n\ S_x S_y} \sum_{i=1}^{n} (x_i - \bar{x})\ (y_i - \bar{y})$$

where n = number of samples per trace

S_x = standard deviation of trace x

S_y = standard deviation of trace y

x_i = digital samples of a trace

y_i = digital samples of the second trace

$\bar{x}$ = average value of trace x_i

$\bar{y}$ = average value of trace y_i

The correlation function from this is

$$\gamma_{xy}(\tau) = \frac{1}{n\, S_x S_y} \sum_{i=1}^{n} (x_i - \bar{x})\ (y_{i+\tau} - \bar{y})$$

where $t = 0, 1, 2, 3, \ldots k$. For stable estimates k should not be more than $k = \frac{n}{10}$.

A general purpose program AUTCRO comprises all the presented theories of correlation. The description of the program and its listing can be found in the Appendix.

Optimum Filters

After initial filtering the records can be further improved in many instances by the application of one or more of a number of linear and/or non linear processes. The nature of the signal and of the noise will determine which of the many optimum filtering processes is the most successful in the improvement of the signal to noise ratio. In the present study two of these processes were applied mainly in connection with the vertical reflection data.

(i) Velocity Filters

Velocity filtering requires multichannel systems whose response to travelling waves is dependent on the apparent velocity of the waves. A variety of these filters has been discussed in the literature: Fail and Grau (1963), Embree et al (1963), Ryall (1964), Foster et al (1964), Galbraith and Wiggins (1968), Laster and Linville (1968).

The present filtering method is built on the assumption that the coherent signal can be correlated from trace to trace. The best correlation is found either by the previously described correlation techniques or the time shift for correlation of the specific arrivals from trace to trace can be computed if the velocity of propogation is known. The time delay $\Delta T = \frac{\Delta X}{V}$ where ΔX is the distance between geophones and V is the phase velocity. If trace number one is delayed by ΔT and summed to trace number two the signal which has phase velocity V will be enhanced. The incoherent noise and coherent noise with different phase velocity will be out of phase; therefore the summation will decrease their amplitude. In practice more than two traces are required to obtain significant improvement in the signal to noise ratio. If the frequency content of the signal is approximately known, the application of band-pass filter before velocity filtering on the data can give some initial improvement.

Consider a linear array of N evenly spaced seismometers. The array makes an angle of α with the direction toward the energy source. The spacing is ΔX, the apparent velocity is V. If the time of the arrival to the first geophone is T_0 the arrival time to the ith detector is $T = T_0 + (i-1)d \cos \frac{\alpha}{v}$. Then the summation of the traces can be expressed by

$$S_v(t) = \sum_{i=1}^{n} f_i(t + \Delta T_i)$$

where f_i represents the band-pass filtered traces.

$$d = \Delta X$$

$$\Delta T_i = (i - 1)d \cos \frac{\alpha}{v}$$

where $1 \le i \le n$.

(ii) Multiple Correlation

The velocity filtering can be further expanded if an even number of traces are available for analysis and if the data have mean values of zero and contain no long period trends.

Multiple correlation here means the following processes. First the traces are shifted and multiplied together and the resulting time series is smoothed by integration. Mathematically

$$I_v(t) = \prod_{i=1}^{n} f_i\ (t + \Delta T_i)$$

represents the multiplication and the integration is expressed by

$$F_v(t) = \sum_{j=o}^{m} I_v\ (t + j\Delta t)$$

Δt = digitization interval

m = the length of the integration

The integration process should sharply cancel the noise and enhance the signal if m is taken large enough. When the signal portion of the trace is multiplied together, assuming the traces were properly lined up, the results are all positive numbers. Therefore at this part of the trace the integrations will give a large positive number also. As the noise is out of phase the summation of positive and negative numbers will lead to a very small number.

If there are a large number of traces for analysis the summation and integration techniques can be combined. First the traces are summed up to two resultant traces. Then these two traces are multiplied together and smoothed by integration.

$$SS_v(t) = S_{1v}(t)\ S_{2v}(t)$$

$$FF_v(t) = \sum_{j=1}^{m} SS_v(t + j\Delta t)$$

The velocity filtering was applied by computer program STACK. The name of the multiple correlation program is HZINTEG. Both these programs are listed and described in the Appendix.

A general purpose plotting program called PLOTMOD is also attached to the Appendix. The program reads the seismic data from magnetic tape and prepares it for any given format of plotting.

CHAPTER VIII

VELOCITY DETERMINATION

The method of determination of the velocity of propogation of the elastic seismic waves is a major factor in the interpretation of crustal seismic data. The interpreter is faced with two choices. One, the observed data is fitted to straight line segments, therefore the seismologists accepts that the crust is divided into discrete constant velocity layers. Two, the seismologist does not accept the layered earth model, and considering other physical parameters, pressure, temperature, chemical composition, the data is fitted to a higher order velocity function curve. Jeffreys (1926) and James and Steinhart (1966) emphasized the problem by pointing out that nearly all phases on traveltime plots are as satisfactorly fitted by straightline segments as by curves. Although the present study relies on a layered model an attempt was made to modify the traditional first order velocity determination technique. Velocities were determined using the reversed profile, station pair, converted wave angle reflection and vertical reflection data. Because not all the methods use the same data, and not all the data were taken at the same area, it was considered that if there is lateral or vertical change in velocity the nature of the data and the application of the different velocity determination techniques will indicate this and the final crustal model in the surveyed area will be modified accordingly. Velocity determinations by the reversed-profile, station-pair and converted-wave methods have been already published, Hall and Hajnal (1969); therefore only a short summary of them will be given here. The use of wide angle reflection data was not applied before. Thus, it will be described in detail.

Reversed Profile

This part of the survey was run along the Red Lake road in Northwestern Ontario. The surveyed segment of the road extends between longitude 93°10' and longitude 93°55' as well as between latitude 50°10' on the south and latitude 51° on the north. The northern shot point was located at latitude 51°41.30' and longitude 94°40.63'. The southern shot point location is latitude 49°40.50' and longitude 93°27.50'. The apparent velocity for the southern shots was 6.81 km/sec. for the intermediate discontinuity and 7.96 km/sec. for the upper mantle. The values for the shots from the north are 6.85 km/sec. for the lower crustal layer and 7.99 km/sec. for the upper mantle. The data indicate a slight dip to the north on both interfaces and the true velocities of 6.83 km/sec. and 7.97 km/sec. respectively for the lower crustal layer and the upper mantle.

Station Pair

This technique is a modified version of the original time-term method. The original method was described by Scheidegger and Willmore (1957), Willmore and Bancroft (1960). The present technique was developed as part of the crustal refraction project and it was presented in detail by Hall and Hajnal (1969). The time term method requires that the shotpoints and the stations are laid out without any particular pattern. The station pair method modifies this and it is required that the survey is done according to a predesigned network of recording sites and shop points. This is indicated in Figure 2 of Hall and Hajnal (1969). For a unique solution one shot to recorder distance must equal twice the critical distance. Because the velocity determination requires subtraction of distances, for good accuracy, some of the stations should be a substantial distance apart. Table II of Hall and Hajnal (1969) shows the computed station pairs. The velocity from this data in the second crustal layer is 6.87 ± 0.05 km/sec. and 7.91 ± 0.07 km/sec. for the upper mantle. For velocity determination this method has the tremendous advantage that the network segments provide velocity for a certain section of the surveyed area and consequently lateral velocity gradients should be observable.

Converted Waves

The use of converted waves for velocity determination was described by Hall (1964, 1966). The velocities obtained from this technique are 6.85 ± 0.05 km/sec. for the intermediate layer and 7.88 ± 0.05 km/sec. for the upper mantle.

Wide Angle Reflection

The use of wide angle reflection data for the determination if interval velocity has been described in the literature by Dix (1955), Clay and Rona (1965). The most general theory is given by Durbaum (1954). The present application requires some modification; therefore some of the equations are described in detail.

(i) One-Layer Case

The reduction of data in the single layer case does not cause major complications. The equation for the travel time is

$$T^2 = 4\frac{H_1^2}{V_1^2} + \frac{X^2}{V_1^2} + \frac{4XH_1}{V_1}\sin\omega_1$$

where

T is the arrival time

H_1 is the perpendicular distance from the interface to the shotpoint

X is the distance between shotpoint and recording sites

V_1 is the velocity of propogation of longitudinal waves in the layer

ω_1 is the slope of the interface.

The derivation of this formula can be found in Jakosky (1957, p. 672) or any other geophysical exploration text book. The first term on the right hand side is the vertical reflection and is usually noted as T_0^2. If the slope of the interface is less than ten degrees the last term of the right hand side is negligible. Then the simplest equation of travel time for a single layer case is

$$T^2 = T_0^2 + \frac{X^2}{V_1^2}$$

The equation is a straight line in X^2 and T^2, where the velocity is determined by the inverse of the slope. The best estimate of velocity is obtained by linear least square fit of the observed data to this straight line. The accuracy of results is influenced of course by the deviation of the interface from the plane, the local irregularities and the effect of neglecting the slope of the reflecting horizon.

In the computational procedure the data is least-square fitted to

$$T_1^2 = T_{01} + D_1 X^2$$

Then the velocity is

$$V_1 = \sqrt{\frac{1}{D_1}}$$

Using T_{01} the value of H_1 is determined.

(ii) Two-layer Case

Reflection theory provides somewhat more complicated equations for the two-layer case. The parametric equations of the two horizontal layers for the time distance curve of these reflections is given by Slotnick (1959, p. 125) as the following:

$$X^2 = 4 \quad \frac{H_1PV_1}{(1-P^2V_1^2)} + \frac{H_2PV_2}{(1-P^2V_2^2)^{1/2}}$$

$$T^2 = 4 \quad \frac{H_1}{V_1(1-P^2V_1^2)^{1/2}} + \frac{H_2}{V_2(1-P^2V_2^2)^{1/2}}$$

where

X = distance

T = arrival time

V_1 = velocity of propogation in the first layer

V_2 = velocity of propogation in the second layer

H_1 = vertical distance from the first interface to the shotpoint

H_2 = vertical distance from the second reflecting horizon to the first

P = the ray parameter

The value of P is equal to the slope of the time distance curve at the point of emergence.

$$P = \frac{dt}{dx}$$

P lies between $0 \leq P \leq \frac{1}{V_2}$

The equation is not a hyperbola as in the one-layer case, but it represents a curve of higher order. Durbaum (1954) proved that the travel time T_j for the reflection from the jth interface can be expanded in a fourth order polynomial. As a result of this the reflection times T as a function of horizontal separation X are fitted by least squares to a fourth order polynomial:

$$T^2 = T_o^2 + \frac{1}{V_{an}^2} X^2 + K X^4$$

The odd terms are introduced in the case of sloping layers

V_{an} = the inverse of the slope of the $\frac{T^2}{X^2}$ line at the origin

K = a constant

The interval velocity V_n is obtained using Dix's (1955) formula.

$$V_n^2 = \frac{V_{an}^2 \cdot T_o - V_{a(n-1)}^2 \cdot T_{o(n-1)}}{T_{on} - T_{o(n-1)}}$$

Le Pichon et al (1968) found experimentally that this method often leads to erroneous velocity values especially where no data is available close to the shotpoint. They overcame the problem by fitting the T^2/X^2 data to a first order line and then applying an iterative procedure which took into account the small systematic error introduced by the curvature of the data. This last technique was applied here with some modifications. The notations are used as indicated in Figure 12.

Procedure: From the one-layer case W_1, V_1, H_1 are computed. A value for V_{a2}, an approximate velocity for the second layer, is assumed. If this is done an W_{a2} approximation for the slope of the second interface can be calculated.

If data is available from X = 0 to larger distances then the arrival times, according to Durbaum (1954) are fitted to

$$T_2 = T_{o2} + D_1X + D_2X^2 + D_3X^3 + D_4X^4$$

The differential of this polynomial then provides the angle of emergence,

$$\sin \psi_1 = V_1 \frac{dT_2}{dX}$$

If this angle is known Snell's law provides the rest of the angles for the complete ray. Knowing these angles, the data can be reduced to a single layer case and from these the interval velocity can be computed.

Because of the lack of data close to shot distances, this procedure cannot be followed here. As a first approximation the data is fitted to a linear least-square line. This provides intercept time T_{o2}. From this

$$T_{om} = T_{o2} - (2\ H_1/V_1)$$

Then,

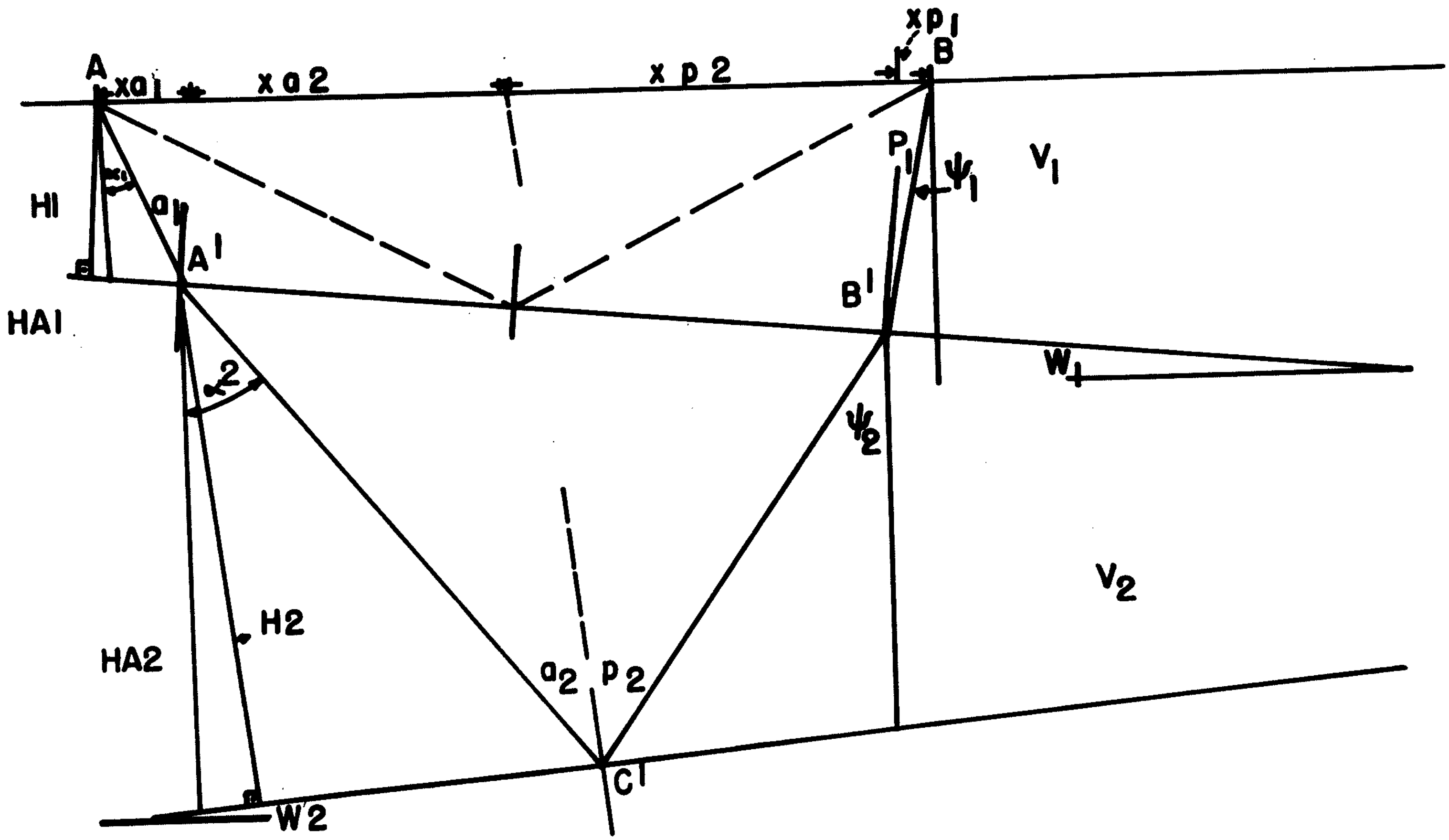


FIGURE 12. Two-layer reflection ray.

$$H_2 = \frac{1}{2} (T_{om} V_{a2})$$

From Snell's law

$$\frac{\sin P_1}{\sin P_2} = \frac{V_1}{V_2}$$

Estimate P_2, then calculate

$$\psi_2 = P_2 + \omega_1$$

$$\psi_1 = \sin^{-1} (\frac{V_1}{V_2} (\sin P_2)) + \omega_1$$

$$\alpha_2 = P_2 - \omega_1$$

$$\alpha_1 = \sin^{-1} (\frac{V_1}{V_2} \sin (_2 + \omega_1)) - \omega_1$$

When these four angles have been determined the following computations can be made: The derivation of these formulae were according to Clay and Rona (1965). The symbols refer to Figure 12.

$$X_{a1} = \frac{H_{a1}}{\frac{1}{\tan \alpha_1} - \tan \omega_1}$$

$$X_{a2} = \frac{H_{a2} + X_{a1} (\tan \omega_2 - \tan \omega_1)}{\frac{1}{\tan \alpha} + \tan \omega_2}$$

$$X_{p1} = \frac{H_{a1} + (X_{a1} + X_{a2} + X_{p2}) \tan \omega_1}{\frac{1}{\tan \psi_1}}$$

$$X_{p2} = \frac{H_{a2} - (X_{a1} + X_{a2}) \cdot (\tan \omega_1 + \tan \omega_2)}{\frac{1}{\tan \psi_2} + \tan \omega_1}$$

If the estimate of P_2 is acceptable then

$$X = \sum_{i=1}^{2} X_{ai} + X_{pi}$$

where X is the distance between the shotpoint and the recording site. If the sum of the partial distances does not agree with X, P_2 is adjusted and the distances are recomputed. The process follows until the best fit ray is found. Then the times of the partial rays paths are computed.

$$T_{AA'} = \frac{1}{V_1} \left(\frac{H_{a1} + X_a \tan \omega_1}{\cos \alpha_1}\right)$$

$$T_{BB'} = \frac{1}{V_1} \left(\frac{H_{a1} + (X_{a1} + X_{a2} + X_{p2}) \tan \omega_1}{\cos \psi_1}\right)$$

Knowing these

$$T_2' = T_2 - T_{AA'} - T_{BB'}$$

where

T_2' = the travel time in the second layer

T_2 = the arrival time

Correction = $CON_2 = T_{H2}^2 - 2T_{H2} \sin \omega_2 \, T_{A'B'}$

where

$$T_{H2} = 2 \frac{H_2}{V_{a2}}$$

$$T_{A'B'} = \frac{X_{a2} + X_{p2}}{V_{a2}}$$

$$T_M^{\,2} = (T_2')^2 - CON_2$$

Then the data is least square best fit to the equation

$$T_M^{\,2} = \frac{(X_{a2} + X_{p2})^2}{V_2^{\,2}}$$

The slope of this line gives the corrected V_2 velocity. The corrected slope is

$$\tan \omega_2 = \tan \omega_{a2} \frac{V_2}{V_{a2}}$$

At this point the process returns to the second equation and recomputes H_2. Then the entire computation is repeated. The iteration process is continued until convergence of V_2 velocity is achieved.

The actual computations for both the one layer or two layer case were carried out on digital computer. One program is available which computes only linear-least-square fit of data, the other can be used to fit the data to an nth order polynomial. The first program called SRTLFIT consists of two subroutines. The first fits the data to a straight line. The second squares the data and then fits it to a straight line. The second program STATS was taken from the Program Library of the Institute for Computer Studies. This program, numbered 19, is part of the Institute's Statistical package. The program is an extended form of the IBM Scientific Subroutine package program called Polynomial Regression. The necessary listing and description of these programs are presented in the Appendix.

Using the SRTLFIT program the PP or the observed reflection data from the continuous refraction profile gave V = 6.03 ± 0.05 km/sec. with ninety percentage of confidence limit of ± 0.0648.

The reflection data from the second interface was first least square best fitted to a straight line using the previous program. From this the intercept time was obtained. This value, as well as the distance and arrival times, were used in the program LEASTMO to find the interval velocity. This program is the Fortran IV form of the equations described in the previous section. Using the complete set of data the velocity V_2 in the second layer was found to be 6.91 ± 0.04 km/sec.

Straight Line Segments

As it was previously described, the field operations were carried out in three separate projects. The crustal refraction survey (Hall and Hajnal, 1964) had shot receiver directions through 360°. The continuous refraction profile along Provincial Highway no. 304 had twenty recording spreads in approximately an East-West direction and it had 31 recordings in close to a North-South direction. The vertical refraction survey had 11 miles continuous coverage, partly along Provincial Highway no. 304 and partly along the road which leads from this highway to Hole River Indian Reserve. Seismic arrivals were recognized on all the records. The arrival times and travel distances were determined and these data were plotted on travel-time graphs. As an indication of linear velocity relationships many of the points fell into a sequence of lines. The inverse slopes of these lines can provide velocities for the different sections of the crust. The data of some of these line segments were fed into computer program SRTLFIT.

(i) Crustal Survey

The line segments here represent Pg, P*, Pn, Sg, S*, Sn arrivals. These velocities were reported in Hall and Hajnal (1969). The velocities from

Pg $V_1 = 6.05 \pm 0.05$ km/sec. The compressional wave velocity in the upper layer of the crust.

P* $V_2 = 6.85 \pm 0.04$ km/sec. The refracted wave velocity in the intermediate layer

Pn $V_3 = 7.92 \pm 0.06$ km/sec. The velocity of compressional wave in the upper mantle.

Sg $V_{1s} = 3.46 \pm 0.05$ km/sec. The velocity of shear waves in the upper crustal layer.

S* $V_{2s} = 4.00 \pm 0.05$ km/sec. Shear wave velocity in the intermediate layer.

Sn V_{3s} = 4.60 ± 0.08 km/sec. Shear wave velocity in the mantle.

(ii) Continuous Refraction Profile

This provided arrival Pg. From Pg V_1 = 5.98 ± 0.06 km/sec. The slope is 0.1671 ± 0.0055 where the last figure represents the 90 percentage confidence limit.

(iii) Vertical Reflection

The first breaks in this eleven mile survey provided 132 geophone stations. These arrivals are from the upper-most portion of the crust. The results were velocity V_1 = 5.82 ± 0.016 km/sec. and slope 0.1719 ± 0.0048. The last term represents the 90 percentage confidence limit.

General Description

The crustal survey represents multidirectional recording. It is considered that this radial distribution of recording sites provides a significant reduction of the influence of the crustal structures in the velocity determination.

No reversed shots were recorded in the case of the continuous profile and the nearly-vertical reflection surveys. The velocity values obtained from these data thus cannot be corrected for structural deviations. Due to this possible error only the first arrival times were utilized as straight line segments for velocity detemrination from these surveys. Even these data would be considered reliable only if reversed profiles were observed.

Table 3 summarizes the velocity data obtained from the several techniques.

Although the tabled values show fluctuations, no significant changes could be observed which might be related to lateral or vertical velocity gradient. The data enforces the assumption that in the area of interest the velocities are relatively constant in certain segments of the crust; therefore, the layered model interpretation is acceptable. There are further evidences for the validity of this assumption. Simmons and Nur (1968) report results of in situ velocity and other physical parameter measurements in deep boreholes which penetrated Precambrian granitic rocks. Their results contradict the outcome of laboratory studies on samples from the same test holes. They have found that the longitudinal velocity in granite is quite high, 5.6 - 6.00 km/sec. near the surface. They did not observe an increase of velocity down to a depth of 1.5 km. which is contrary to predictions based on laboratory data. The compressional wave velocities in the samples, under pressure of a few bars, were found to be between 4 to 5 km/sec. The velocity values also increased with an increase of pressure. It was found that the amount of saturation and minute fractures or cracks in rock samples

TABLE III

VELOCITY DATA

Type Data and Velocity Determination	Upper Crustal Layer Velocity (km/sec)	Intermediate Layer Velocity (km/sec)	Upper Mantle Velocity (km/sec)
Reversed profile* South		$V_2 = 6.81$	$V_3 = 7.96$
Reversed profile* North		$V_2 = 6.85$	$V_3 = 7.99$
Station Pair*		$V_2 = 6.87 \pm 0.05$	$V_3 = 7.91 \pm 0.07$
Converted Waves*		$V_2 = 6.85 \pm 0.05$	$V_3 = 7.88 \pm 0.05$
Wide Angle Reflection	$V_1 = 6.03 \pm 0.05$	$V_2 = 6.91 \pm 0.04$	
Straight Line Segments			
Crustal Survey*	$V_1 = 6.05 \pm 0.05$	$V_2 = 6.85 \pm 0.04$	$V_3 + 7.92 \pm 0.06$
	$V_{1s} = 3.46 \pm 0.05$	$V_{2s} = 4.00 \pm 0.05$	$V_{3s} = 4.60 \pm 0.08$
Continuous Refraction Survey	$V_1 = 5.98 \pm 0.06$		
Vertical Reflection	$V_1 = 5.82 \pm 0.02$		

* From Hall-Hajnal, (1969).

have acute effects on the velocity of propogation. Samples taken from the studied boreholes showed velocity changes of 5.30 km/sec. dry and 5.95 km/sec. fully saturated. The changes in these physical parameters between the samples and the in situ rocks could cause the observed difference in the velocities when measured in situ and in the laboratory.

Steinhart et al (1962) investigate the relationships between the velocity gradient and the rock type, as well as the effects of temperature and pressure on the velocity. The temperature, pressure and constant velocity diagram of granitic type rocks reveal the following: If a velocity gradient of 0.05 km/sec. exists, no granitic rocks can exist deeper than 3 km. If the velocity gradient is 0.01 km/sec. or less and the temperature does not exceed 300 °C, it is possible to have granitic rocks at a depth of 20 km. If the temperature increases and no increase of mafic composition of the rock is considered, a velocity reversal must occur. The in situ measurements of Simmons and Nur (1968) do not show changes which would enforce the existence of physical conditions under which velocity gradient could exist. Neither the present investigations nor any other crustal studies on the Precambrian shield indicate velocity reversal in the upper portion of the crust. Therefore it is quite conceivable that a granitic type rock with uniform velocity exists down to a depth of 23 km. in the studied area.

Steinhart et al also described a temperature, pressure and constant velocity diagram of rock of gabroic composition. This diagram indicates that at a depth of 20 km. or more the velocity is quite constant with increasing pressure and temperature less than 300 °C. If the temperature increases over this figure a sudden drop of velocity will occur. The thermal measurements on the Precambrian Shield indicate anomalously low crustal temperature conditions. Thus a velocity gradient in the lower portion of the crust is very unlikely.

As was discussed by Hall and Hajnal (1969, p. 97) the upper mantle velocity of 7.92 km/sec. looks very anomalous in this area if Herrin (1966) or Kanasewich (1966) apparent Pn velocity distribution maps are studied. Both maps indicate an increase of Pn velocity toward the middle of the continent. Contour lines extended in Manitoba would require Pn velocities of 8.11 km/sec. or higher. The Project Early Rise survey, Iyer et al (1969) however further enforces the lower Pn velocity value in this region. This survey was part of the Vela Uniform project and it included the participation of twelve U.S. and Canadian research institutes. The Manitoba and Yukon lines cross the present area of interest. In both lines the Pn velocity was found very stable in distances not more than 1000 km. and the value of it was given by Mereu and Hunter

(1968) as 8.05 km/sec. Over this distance the Pn velocity jumped to 8.43 km/sec. The possibility of lower Pn velocity in the central part of the continent was further enforced by Stewart (1968). This survey was conducted by the U. S. Geological Survey in Missouri. The 300 km. long reversed profile showed the upper mantle velocity as 8.0 km/sec. This is again a much lower value than it is indicated by Herrin's map.

CHAPTER IX

PREPARATION OF DATA

General Description of Refraction-Reflection Interpretation

The present interpretation of the refraction and reflection data is based on the traditionally applied seismological practices. This means the acceptance of the following assumptions: The geological layers of the crust are considered as homogeneous isotropic media which are separated with sharp transition zones. The detonation of the explosion is represented for interpretation purposes with a point source, from this source elastic disturbances radiate spherically outward. At large distances from the source a portion of the wave front can be approximated with a plane. The normal to the wave front at any point is the wave ray. Fundamentally it is accepted here that the propogation of seismic waves follow the principles of geometrical optics. The theoretical aspects of this assumption as it is applied to seismic waves, were described first by Jeffreys (1926) and somewhat modified by Muskat (1933).

Using the principle of geometrical optics it can be proven that the propogated seismic energy is separated in refracted and reflected waves when the ray impinges on the interface which represents the contact of two materials with significantly different elastic properties.

The head wave ABC on Figure 13 is presented as the ray which changes its direction of propagation when it crosses a boundary. The reflected wave AD at the same time is the ray which returns when it encounters an interface.

Using these general theories as well as Snell's law and Fermat's principle from geometrical optics the geophysical exploration textbooks Nettleton (1940), Heiland (1963), Jakosky (1950), Dobrin (1960) illustrate the development of a set of working formulae which are used in the interpretation of the observed refraction and reflection data. Because of the well known nature of this formulae no derivation of them are attempted here. The ones which are used in the present calculations are listed and for explanational purposes they are referred to Figure 13.

Two-Layer Case Refraction Dobrin (1960, p. 72)

The travel time of the direct wave

$$T_{pg} = \frac{X}{V_1} \quad (1)$$

X = the distance between the shotpoint and the recording location.

The travel time of the critically refracted ray ABC is

$$T = \frac{X}{V_2} + 2\,H_1 \frac{\sqrt{V_2^{\,2} - V_1^{\,2}}}{V_2\,V_1} \quad (2)$$

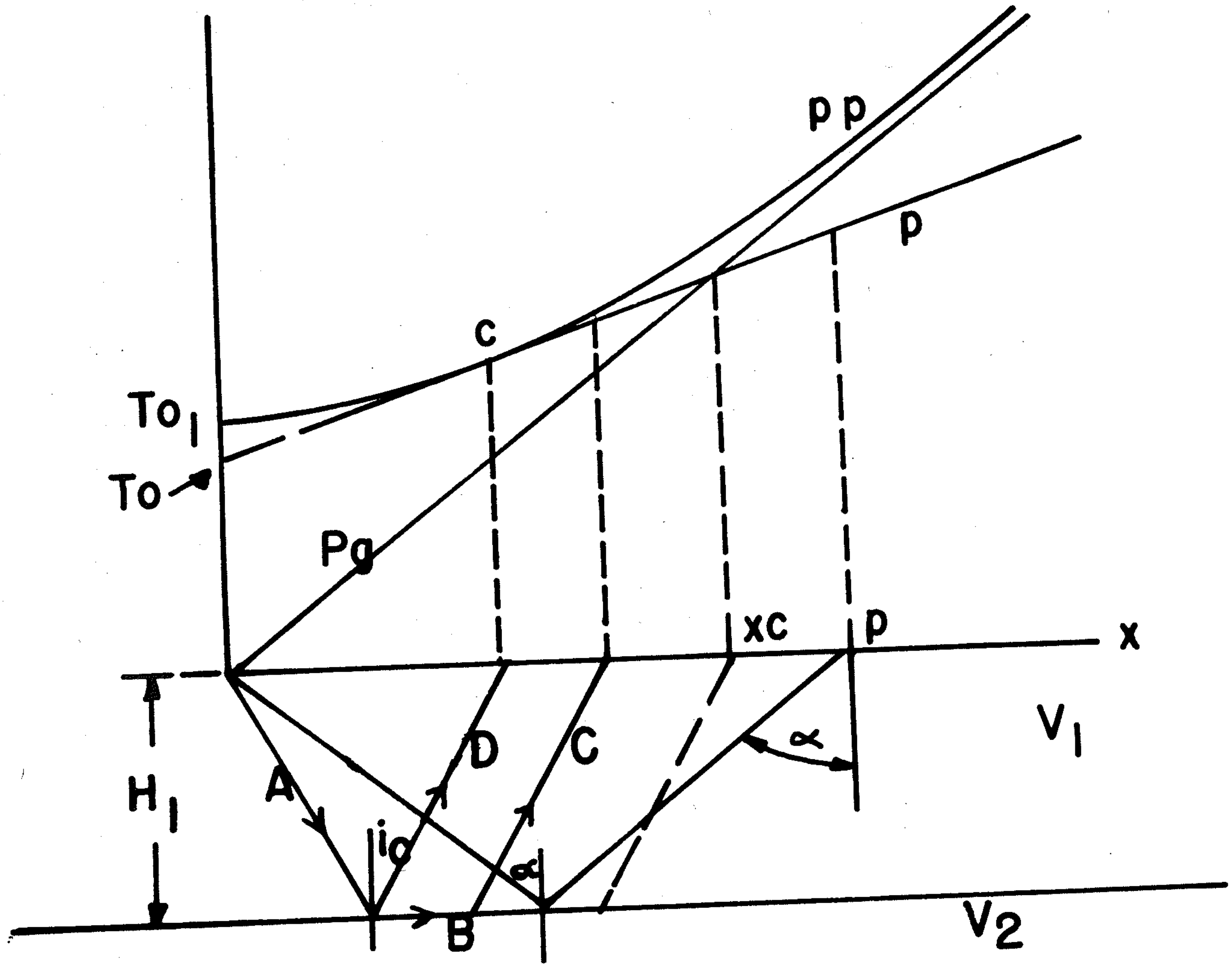


FIGURE 13. Theoretical time distance plot.

V_1 V_2 represent the velocity of propogation of the longitudinal waves in layer one and two respectively.

H_1 is the depth of the first interface

X_c is the critical distance. This is the point where the refracted wave becomes the first arrival on the observed record.

The travel time of the reflected ray AD is

$$T = \frac{\sqrt{4\,H_1^{\,2} + X^2}}{V_1} \qquad (2/a)$$

C on the diagram represents the critical point. This is the point of total reflection.

T_o, T_{o1} are known as intercept times.

The graph of T vs. X is the so called time distance plot. Equations 1 and 2 indicate that the slopes of the lines P_g and P* are $\frac{1-}{V_1}$ and $\frac{1}{V_2}$ respectively.

The previous description can be extended to three or more layer cases. It is assumed here that the velocity is increasing with the depth, that is

$$V_1 < V_2 < V_3 < V_4 \quad \text{etc.}$$

Three-Layer Case Refraction Dobrin (1960, p. 74)

$$T = \frac{X}{V_3} + \frac{2\,H_1\sqrt{V_3^{\,2} - V_1^{\,2}}}{V_3\,V_1} + \frac{2\,H_2\sqrt{V_3^{\,2} - V_2^{\,2}}}{V_3\,V_1} \qquad (3)$$

H_2 = thickness of the second layer

Reflection Slotnick (1959, p. 184)

$$T = 2 \left(\frac{H_1}{V_1 \cos \alpha_{12}}\right) + \frac{H_2}{V_2 \cos \alpha_{22}}) \qquad (4)$$

or in parametric form

$$T = 2 \left(\frac{H_1}{V_1(1-P^2V_1{}^2)^{\frac{1}{2}}} + \frac{H_2}{V_1(1-PV_2{}^2)^{\frac{1}{2}}} \qquad (5)$$

P = the ray parameter

$$P = \frac{\sin \alpha_{12}}{V_1}$$

$$P = \frac{\sin \alpha_{22}}{V_2}$$

The use of the ray path methods has its shortcomings. Its merits and limitations are discussed in Grant and West (1965). It is beyond the scope of this study to deal with them in any length. It should be mentioned however that the interpretation of the data was made with the awareness of the limits of the applied technique. It was the uniformity and linearity of the observed data which warranted the applied technique and not the interpreter who forced the technique on the data.

Distance Determination

The examination of the previously described five equations reveal that the computation of the depth of any of the interfaces requires the knowledge of the travel time and velocity of propogation as well as the shotpoint-recording distance. The travel time is determined from the observed records. The velocities obtained from the time distance graph, but only if the distance is known. Consequently the distance determination is a crucial part of the interpretation.

If the two sites are within a few miles the best distance determination is the direct survey. With the exception of the vertical reflection work all the present distances are in the range of a hundred kilometers or further. Obviously in these cases a simple survey is impossible. One alternative is the scaling of the distance from a topographic map. If good map coverage is available this technique provides distances with the estimated accuracy of ± .1 km. The larger the map scale the better the accuracy achieved.

There are areas however where no continuous map coverage is in existence or only maps with different scales can be used or the distances are so vast that too many maps have to be matched together to obtain the required distance. In these cases if the shotpoint and the recording site can be located on maps the scaling of the latitude and longitude of the two locations can provide the answer. From these data with the application of spherical geometry, the distance can be computed. In the present case equations provided by Bullen (1963, p. 154) were used for the creation of a computer program which can be used for computation. The description of this program named DISTAN can be found in the Appendix. This method provides distances with an accuracy of ± .1 km. if the error in the latitude and longitude determination is not more than ± 6 seconds. The present program uses equations which are most accurate if the arc distance is between 0° and 20°.

If map coverage is not obtainable in the surveyed area or the map is an older publication and the road where the observations were made is not located on it, the determination of latitude and longitude must be carried out by astronomical measurement. Gurley's 1968 ephemeris publishes the method, formulae and the necessary tables for the determination of the latitude and longitude from the measurement at a given point of the arimuth, altitude of the sun, Polaris, or a given star. The accuracy of the results depend on the precise measurement of the above two angles and the time, at the moment when the measurement of the two angles were made. Several measurements were carried using the Polaris during the summers of 1967 and 1968. Unvortunately the available instrument had an accuracy of only 20". This caused fluctuation in the longitude determination between ± .2 minutes. It was concluded therefore that without a better theodolite the astronomical measurements can be used only as a rough check of the map data. If it is unavoidable that this method is the main source of information and no better instrument is available. A large number of repeated measurements at the same site and the average of the obtained data may provide more accurate results.

The examination of equations one and two indicate that by combination of the two the distance "X" can be eliminated. This requires that the travel time for the direct wave and its velocity at the point of observation must be known. This technique also requires that no significant close surface velocity anomalies exist in the area or if they do their influence on the arrival time of the direct wave was eliminated.

Seismic Data Enhancement

The determination of the travel time of the seismic waves is taken from the record displays of the observed data. The criterion of a good record is the high signal to noise ratio. Even if the recording was made under favorable conditions extensive preparations in the laboratory are required before all the recognizable arrivals on a record are in such a shape that their arrival time can be picked. When the data are in analog form at least four separate playbacks with different gain, and sometimes with different filters settings, have to be prepared. One short record, usually with maximum gain, is concentrating on the first arrival. The second record is the section which usually consist of the head waves and the reflection arrival. In this case the reflection data generally have high amplitudes; therefore the original gain setting or somewhat smaller gain is required for playback. The part of the original record between the reflections and the first transverse wave contains the converted wave arrivals. These arrivals are quite weak in comparison to the first part of the record. Almost maximum gain and minimum frequency filtering is in order to obtain a good picture of them. The shear wave arrivals on the end of the record in all cases during the present program had low frequency and high amplitude characteristics. The display of this section almost always require low gain and minimum frequency filtering.

If the data are in digital form the different sections of the record must be prepared in the same manner as previously described. A more detailed description will be given later.

Using the prepared record segments the skilled interpreter will recognize the regular disturbance or arrivals. When all the arrivals are marked, their travel time is determined and plotted on the time distance graph.

The most crucial part of the interpretation is the correlation of the arrivals. This determines which points are tied together on the time distance graph and then what velocity determinations are made.

The correlation of arrivals depend on several criteria:

(a) The relative position on the time scale.

(b) The distance where the record was taken.

(c) Characteristics of arrival

(i) Frequency content

(ii) Relative amplitude

(iii) Periodicity

(iv) Phase relationship

(d) Best correlation found by application of numerical correlation techniques.

When several sets of points are joined together a group of line segments appear on the time distance graph. The position of these line segments and the velocity obtained from their slope will give definite indications as to what type of energy propogation these points represent. This condition is illustrated on the example time distance plot at the beginning of this section.

CHAPTER X

INTERPRETATION

Regional Refraction Survey

The results of this survey are presented on Figure 14 and Figure 15. The first represents the structure contour map of the intermediate discontinuity. The second is the structural picture of the top of the mantle or the so called Mohorovicic discontinuity. The compilation of these maps are based on fifty-four data points. Theses represent six shot points and forty-eight recording sites. A portion of the observed data as well as the final results of the depth calculations are listed in Tables IV and V. Because parts of these maps, sections between longitude 93° and longitude 95°, were already published by Hall and Hajnal (1969) the only data presented here is data which was not listed in the above publication. The interpretation technique was also described before and therefore no presentation of it is given here. These data and maps are included only as a background for the work of this thesis, and are to be published shortly as a separate study (Hall and Hajnal, 1970).

The intermediate discontinuity shows prominent structural features. It indicates an east-west trending

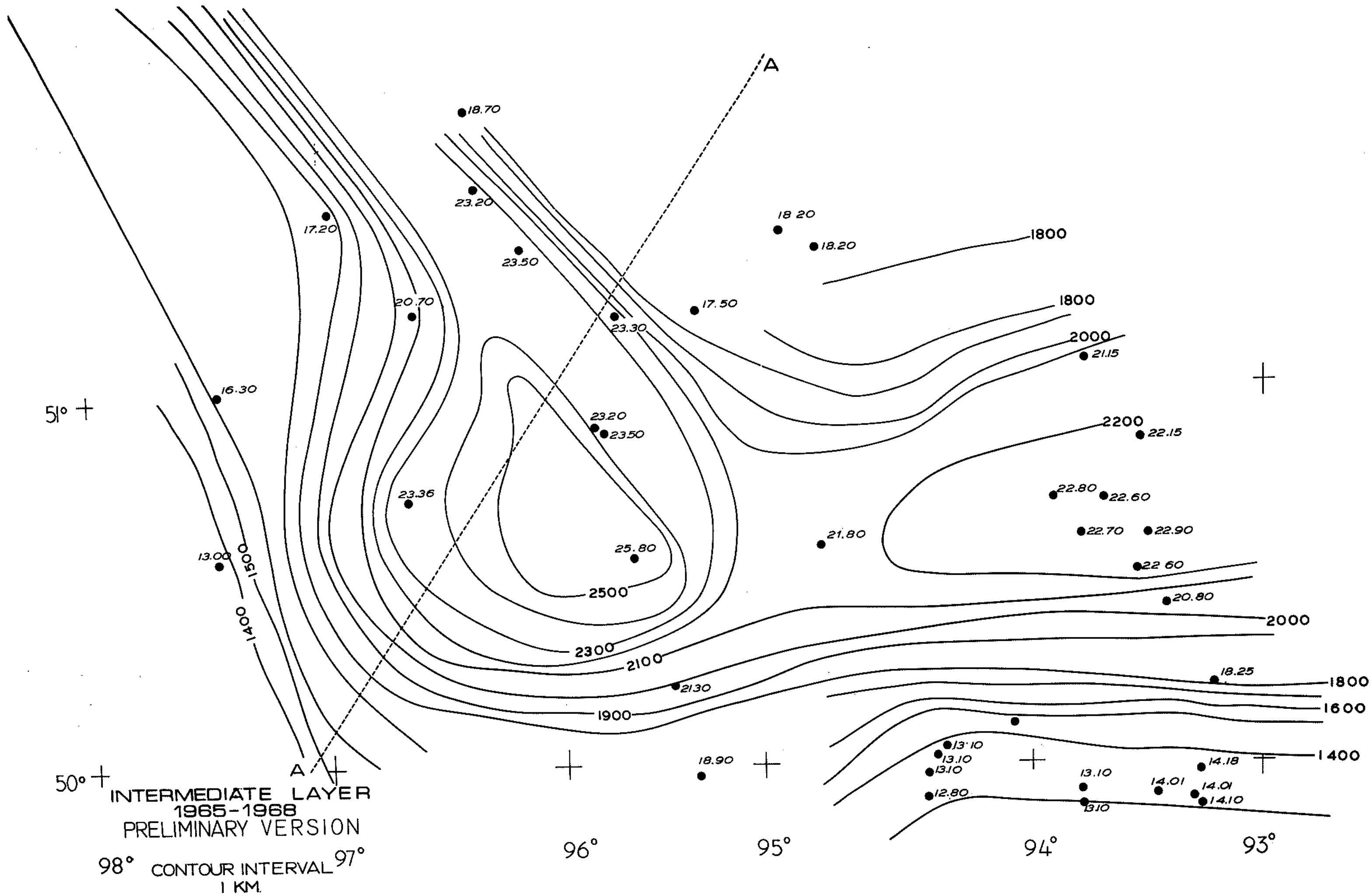


FIGURE 14. Contour map of the intermediate discontinuity.

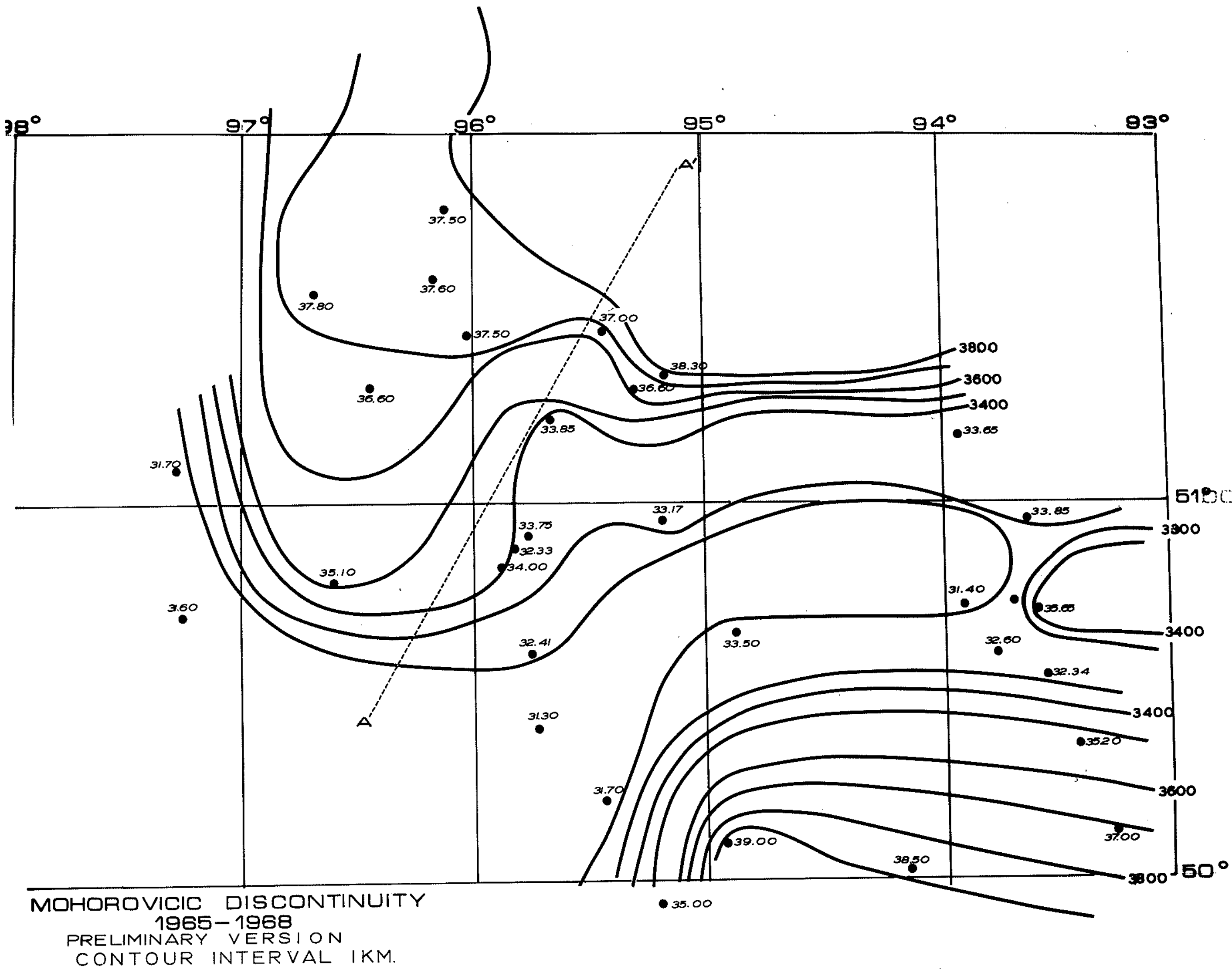


FIGURE 15. Contour map of the Mohorovicic discontinuity.

TABLE IV

REGIONAL REFRACTION DATA

Station No.	Distance km.	Pg	P*	PP	SPP	PPS	SPS	Sg	S*	Pn
28.5	163.75		26.86	27.70		31.57	33.21	46.85	46.06	27.17
29.2	125.50	20.75	20.65	-	23.16	24.12	26.28	-	-	22.22
30.5	203.01	-	32.88	34.11	36.25	-	39.15	-	56.23	32.18
31.2	145.40	-	23.81	-	26.07	27.64	-	-	-	24.65
32.5	137.00	22.42	22.91	23.63	26.03	27.28	29.45	38.68	36.27	23.83
33.5	157.85	25.85	26.08	26.65	-	30.63	32.43	45.18	44.47	26.61
34.2	185.00	-	29.85	-	32.28	-	36.79	-	51.99	29.85
35.5	105.56	17.23	18.01	18.66	21.08	22.10	24.67	30.11	31.45	19.91
36.6	132.73	21.65	22.40	22.85	25.51	26.65	28.67	37.95	38.15	23.39
37.2	209.00	-	33.15				-			32.81
38.6	176.88	29.03	29.03							29.03
39.6	213.06	37.86	34.13							33.58
40.6	249.39	-	38.63							37.51
41.6	136.16	22.31	22.98							24.01
42.6	168.38	27.50	27.50							27.95
43.6	221.49	-	35.20							34.09
44.6	134.64	22.14	22.80							23.76
45.6	172.23	27.80	27.82							28.53
46.6	127.20	20.95	21.47							22.75
47.6	243.47	-	36.87							-
48.7	284.76	-	-							42.70

TABLE IVa

REGIONAL REFRACTION DATA

Station No.		PSPSP	SSPSS	SPPPS	SSPPS	PSPSS	Sn	SSSS	PPPSS
28.5	27.95	-	-	-	35.80	34.91	-	47.80	31.55
29.2	26.96	-	-	-	-	-	-	39.41	-
30.5	33.36	35.88	43.08	-	40.40	40.25	-	56.70	-
31.2	-	-	-	-	-	33.55	-	-	
32.5	24.30	28.38	34.85	-	32.70	31.45	40.33	41.75	28.10
33.5	27.23	30.63	37.45	-	35.12	34.18	44.80	46.53	-
34.2	-	-	41.16	-	-	-	-	-	-
35.5	20.21	24.67	30.77	25.92	29.00	27.22	33.80	34.57	24.27
36.6	23.63	27.82	-	-	-	30.90	39.35	40.55	27.56
37.2									
38.6									
39.6									
40.6									
41.6									
42.6									
43.6									
44.6									
45.6									
46.6									
47.6									
48.7									

TABLE V

TIME-TERMS, DEPTH AND OFFSETS OF REGIONAL REFRACTION SURVEY

Station No.	Intermediate Time Term Sec.	Intermediate Depth km.	Intermediate Offset km.	Moho Time Term Sec.	Moho Depth km.	Moho Offset km.	Latitude	Longitude
Silver Lake 2	1.02	12.90	23.60	3.25	39.30	62.10	49°52.40'	94°08.00'
McCusker L 5	1.44	18.20	33.30	3.41	39.00	58.65	51°41.30'	94°40.63'
Malaher L 6	1.46	18.50	33.90	3.27	37.00	54.80	51°55.30'	95°04.10'
Gunisao L 7	1.51	19.10	35.00	3.38	38.30	56.90	53°32.40'	96°12.50'
28.5	1.72	21.80	39.90	3.07	32.50	45.05	50°13.60'	94°57.30'
29.2	1.49	18.90	34.60	3.09	34.20	49.70	49°59.20'	95°52.50'
30.5	1.94	24.50	44.90	3.07	31.30	41.25	50°04.00'	96°00.00'
31.2	1.68	21.30	39.00	3.00	31.70	43.90	50°20.10'	96°01.00'
32.5	1.62	20.50	37.55	3.07	33.17	46.90	50°34.10'	95°26.00'
33.5	1.84	23.50	43.00	3.20	33.65	46.00	50°37.20'	96°07.10'
34.2	2.04	25.80	47.20	3.20	32.41	42.45	50°49.10'	96°15.30'
35.5	1.37	17.60	31.70	3.14	36.38	53.10	51°02.50'	95°47.20'
36.6	1.76	22.30	40.60	3.18	33.85	47.00	51°00.00'	96°14.00'
37.2	1.84	23.50	43.00	3.19	33.50	45.80	51°06.10'	96°16.40'
38.6	1.97	25.00	45.06	3.35	34.30	47.30	50°32.06'	96°13.62'
39.6	1.83	23.30	42.60	3.31	35.10	48.60	50°26.30'	96°59.75'
40.6	1.07	13.60	24.90	2.72	31.60	48.20	50°26.25'	97°44.50'
41.6	1.84	23.50	43.00	3.48	37.50	53.00	51°10.00'	96°38.15'
42.6	1.63	20.70	37.80	3.33	36.60	52.90	51°04.05'	97°04.20'
43.6	1.63	20.70	37.80	3.29	31.70	46.70	50°53.34'	97°47.40'
44.6	1.83	23.20	42.45	3.48	37.60	53.20	51°25.85'	96°50.85'
45.6	1.36	17.20	31.40	3.17	36.20	54.60	51°25.20'	97°20.00'
46.6	1.56	19.70	36.00	3.41	37.50	55.00	51°41.75'	96°51.40'
47.6	1.34	16.90	30.90	-	-	-	51°42.76'	98°34.98'
48.7	1.39	17.60	32.20	3.42	37.10	55.60	51°01.80'	95°38.06'

downward from longitude 93° to longitude 95°. From this line it takes a turn in an approximately North 60° West direction. The deepest part of the trend is reached roughly in the centre of the mapped area. Topographically the extreme low zone of the structure is bordered by Wanipagow River on the North and by Winnipeg River on the south. The relationship between the greenstone belt in the area and the structural feature was already emphasized by Hall and Hajnal (1969).

The map also indicates an extensive uplift in the south-east corner of the studied area. The regularity of the contours seem to indicate an anticlinal structure but more information is required to the south before a complete understanding of this feature can be deducted. The surface geology does not indicate a similar structure.

Another significant local feature can be observed in the north-west portion of the map. Although it was built on only six observations they seem to reveal that the north-westerly boundary of the downward structure was a relatively steep gradient. The gently dipping platform from the north is interupted by a downward gradient of approximately 5 kilometers in a less than 10 kilometer zone. The south-eastern end of this trend is in an area which is part of the Project Pioneer combined geological and geophysical investigation. Because of the comprehensive scientific interests in the area the seismic investigations were extended to a detailed survey which was aimed at studying this major trend, and is the subject of the present thesis. The results of this study will be described in the following sections.

The map of the Mohorovicic discontinuity also shows structural variations on the crust-mantle interface. An east-west trending uplift is the most dominant feature between longitude 93° and 95°. South of this a downward trend can be observed indicating the thickening of the crust in this direction. West from longitude 95° the uplift broadens and it seems to take a slight turn toward the south-west. In the north-west it develops to a platform which has a gentle dip toward the north.

The implications of the structures on the two interfaces to the isostatic equilibrium in the area was mentioned by Hall and Hajnal (1969) and a detailed study of it was carried out by Hall (1969). The lack of detailed knowledge of the regional surface geology makes it impossible to give a full amount of the relationship of the described structures to the geology of the surveyed area.

Continuous Refraction Profile

The relationship between the regional crustal analysis and this detailed study was described in the previous section. The significance of this investigation is many fold. If it is able to prove that there is a major deep fracture zone in the earth's crust then this may have effects on the close surface geology which can lead to important economic possibilities. At the same time this experiment could indicate the technique which is best suited to find fracture zones.

The scientific aspects of it are also very important. This is the first continuous detailed crustal seismic experiment on this continent. The presently applied explosion studies in North America all follow the jump correlation techniques. The recording sites are always several miles apart. This method relies on the early assumptions that the deep interfaces of the crust are relatively smooth, therefore no closely spaced survey is necessary. Recent crustal seismic studies O'Brien (1968), Berry and West (1966), Smith et al (1969), Stewart (1968), Warren (1969), Cumming and Kanasewich (1966), Kanasewich et al (1968), Pakiser et al (1969) all indicate that there are significant and sudden structural disturbances in the crustal layers, not only here in Manitoba but also in other places on the continent. The European, especially the Russian literature, also show many sudden changing deep crustal structures, Beliayevsky et al (1968), Subbotin et al (1968), Dragasevic and Adric (1968) give examples of them. There is still some hesitancy by some to accept the recognizability of discontinuities within the crust. A detailed survey with continuous correlation of arrivals in a span of considerable distance should indicate a very definite answer to this question. This experiment attempts to point out that it is possible to combine refraction and reflection data from the same survey for interpretation purposes. This technique provides almost double coverage over the extent of either one of the methods separately.

The examination of the regional map of the intermediate discontinuity reveals that the approximate area of the major gradient is between longitude 95°30' to 96°30' and from latitude 51°00' to 51°40'. The best estimated direction of the profile is N 30° E. Considering the proper offset distance the survey should start thirty kilometers from the trend. The unaccesability of this area forced the survey to provincial highway no. 304. The shotpoint for the entire survey was located at Malaher Lake. The charge sizes varied between 300-500 pounds of SM Super X Ammonia Nitrate. The total number of fifty-two observations provided approximately 50 km. coverage over the intermediate discontinuity.

As the first attempt the data was prepared with the analog playback system and a section was made from the best quality records. The first arrivals were quite sharp and they could be correlated through the entire profile. Several other later arrivals were also recognizable but it became apparent that better correlation could be achieved if some of the low frequency noise was eliminated. Where it was possible arrival times were picked and using these data time distance curve was plotted. These data provided enough information that it was possible to identify a refracted and a reflected wave from the intermediate discontinuity and a dominant high amplitude event which was recognized as a reflection from the Moho. The depth calculations were in the same range as it was predicted by the regional survey.

At the later part of 1968 the University's computer IBM 360/65 reached the point where it could handle larger volume of data and with the acquisition of the analog to digital conversion system further processing of the seismic data became available. The details of the acquired instrumentation as well as the theory of the developed programs were described in the previous chapters. Although the developed programs can provide several types of filtering the experimental runs indicated that a 5-25 cps. band-pass filter would eliminate all the noise which hinders the continuous correlation of arrivals on the profile data. The final results are summarized in Table VI. The X-T plot of these arrival data is exhibited on Figure 16.

Figure 17 presents the final section after the process of the previously mentioned band-pass filter. The view of the first part of the profile reveals eight very distinct arrivals on the records. It becomes clear after record A-11 that the sixth or the PPPP arrival has the

TABLE VI

CONTINUOUS REFRACTION SURVEY DATA

Station Number	Distance km.	Intermediate Discontinuity Pg Sec.	P* Sec.	Depth km.	PP Sec.	Depth km.	Multiple Sec.	Sg Sec.	S* Sec.	Moho Pn Sec.	Depth km.	PPPP Sec.	Depth km.	P6 Sec.
A-1	109.72	18.12	18.75	17.60	19.14	18.51	21.17	31.61						
A-2	110.04	18.21	18.76	17.10	19.16	18.22	21.22	31.78						
A-3	110.35	18.25	18.82	17.30	19.20	18.14	21.31	31.83		20.10		20.55	34.84	20.95
A-4	110.72	18.31	18.94	18.20	19.29	18.44	21.36	31.95		20.18		20.61	34.90	21.04
A-5	111.11	18.44	19.00	18.20	19.33	18.24	21.46	32.04		20.19		20.57	34.25	21.09
A-6	111.66	18.51	19.08	18.20	19.43	18.37	21.57	32.24		20.29		20.71	34.65	21.14
A-7	112.26	18.58	19.17	18.30	19.93	18.43	21.68	32.37		20.35		20.70	34.89	21.21
A-8	112.90	18.67	19.29	18.60	19.60	18.13	21.78	32.59		20.38		20.88	34.94	21.32
A-9	113.44	18.74	19.35	18.40	19.74	18.66	21.87	32.74		20.46		21.00	34.71	21.38
A-10	113.49	18.77	19.40	18.89	19.74	18.59	21.91	32.76		20.47		20.85	35.00	21.40
A-11	113.53	18.80	19.41	18.93	19.75	18.62	21.94	32.84		20.49		20.92	34.96	21.40
A-12	113.78	18.87	19.43	18.72	19.76	18.34	21.97	32.84	33.82	20.51		21.06	34.50	21.41
A-13	114.65	18.91	19.56	18.68	19.91	18.47	22.12	33.08	34.02	20.62		21.09	34.59	21.52
A-14	115.28	19.04	19.63	18.60	20.05	18.87	22.25	33.22	34.18	20.70		21.16	33.80	21.60
A-15	115.90	19.13	19.74	18.80	20.10	18.40	22.38	33.41	34.28	20.80		21.27	33.91	21.70
A-16	116.02	19.14	19.75	18.71	20.16	18.81	22.39	-	34.37	20.82		21.31	33.89	21.72
A-17	116.10	19.15	19.75	18.50	20.17	18.78	22.39	-	34.38	20.84		21.27	34.45	21.73
A-18	116.53	19.22	19.79	18.20	20.23	18.71	22.45	-	34.51	20.93		21.36	34.82	21.78
A-19	117.62	19.39	19.96	18.50	20.38	18.49	22.65	33.92	34.78	21.07		21.52	34.10	21.91
A-20	118.87	19.54	20.19	18.95	20.55	18.21	22.89	34.28	35.15	21.19		21.63	34.30	22.07
A-21	119.90	19.73	20.30	18.60	20.70	18.08	23.08	34.55	35.36	21.31		21.70	34.20	22.21
A-22	121.14	19.95	20.53	19.20	20.90	18.12	23.34	34.88	35.75	21.44		21.86	34.00	22.40
A-23	122.73	20.20	20.77	19.40	21.15	18.10	23.68	35.41	36.17	21.66		22.21	34.09	22.61
A-24	123.18	20.38	20.99	20.50	21.23	18.19	23.75	35.48	36.45	21.72		22.34	34.90	22.64
A-25	124.80	20.53	21.25	21.00	21.53	18.54	23.95	35.97	36.92	21.95		22.62	35.92	22.89

TABLE VI (continued)

Station Number	Distance km.	Intermediate Discontinuity Pg Sec.	P* Sec.	Depth km.	PP Sec.	Depth km.	Multiple Sec.	Sg Sec.	S* Sec.	Moho Pn Sec.	Depth km.	PPPP Sec.	Depth km.	P6 Sec.
A-26	126.31	20.75	21.42	21.00	21.79	18.87	24.32	36.40	37.30	22.23		22.82	35.27	23.08
A-27	127.48	20.92	21.63	21.20	21.96	18.70		36.77	37.67	22.42		22.99	35.86	23.34
A-28	128.24	21.06	21.72	21.20	22.08	18.70		36.95	-	22.48		23.00	35.16	
A-29	128.49	21.09	21.72	21.50	22.12	18.70		37.01	37.91	22.55		23.06	35.65	
A-30	128.84	21.14	21.77	21.20	22.19	18.86		37.10	38.02	22.60		23.14	35.66	
A-31	129.20	21.29	22.01	22.60	22.23	18.67		37.08		22.65		23.20	34.50	
A-32	129.80	21.38	22.06	22.70	22.31	18.50		37.23		22.75		23.25	35.58	
A-33	130.90	21.54	22.22	22.70	22.51	18.78		37.54		22.87		23.40	35.32	
A-34	132.61	21.92	22.47	22.76	22.80	18.98		37.96		23.12		23.48	35.50	
A-35	133.40	22.06	22.58	22.70	22.91	18.05		38.00		23.21		23.68	35.54	
A-36	133.58	22.15	22.62	22.80	23.01	18.68		38.10		23.24		23.70	35.78	
A-37	134.19	22.21	22.70	22.70	23.05	18.97		38.42		23.35		23.98	33.89	
A-38	135.40	22.36	22.89	22.50	23.18	18.26		38.73				24.08	33.31	
A-39	137.09	22.70	23.15	22.80	23.50	18.84		39.10				24.36	33.50	
A-40	138.85	22.93	23.47	22.80	23.70	18.83		39.40				24.64	33.64	
A-48	149.62	24.71	25.07	24.00	25.45	18.17		42.46				26.03	35.23	
A-49	150.06	24.86	25.10	23.90	25.53	18.29		42.67				26.05	35.70	
A-50	150.16	24.92	25.16	23.90	25.60	18.97		42.74				26.08	35.91	
A-51	150.95	24.95	25.19	23.50	25.70	18.63		42.80				26.09	34.32	
A-52	151.10	25.00	25.24	23.80	25.73	18.71		42.92				26.19	35.28	
A-53	151.61	25.20	25.28	23.60	25.77	18.18		43.13				26.31	34.91	
A-54	152.46	25.31	25.42	23.66	25.95	18.73		43.42				26.45	33.92	
A-55	153.06	25.41	25.49	23.50	26.05	18.78		43.49				26.49	33.70	
A-56	154.16	25.53	25.65	23.50	26.23	18.82		43.58				26.55	33.98	
A-57	154.60	25.62	25.75	23.90	26.28	18.56		43.81				26.65	33.94	
A-58	155.64	25.81	25.89	23.70	26.42	18.20		44.04				26.83	33.70	
A-59	156.63	25.95	26.05	23.80	26.58	18.21		44.57				27.09	33.99	

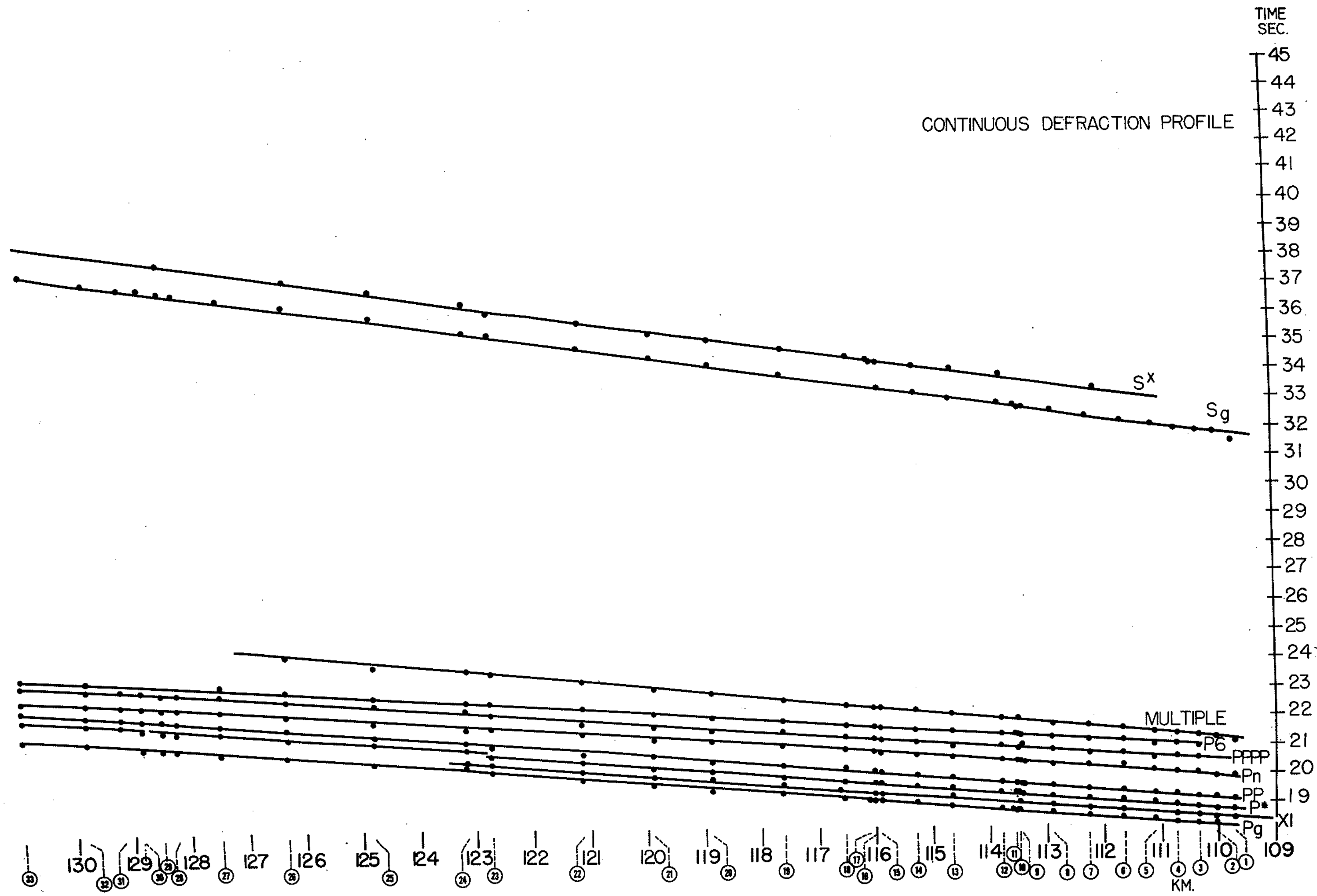


FIGURE 16. T-X plot of the Continuous Refraction Profile data.

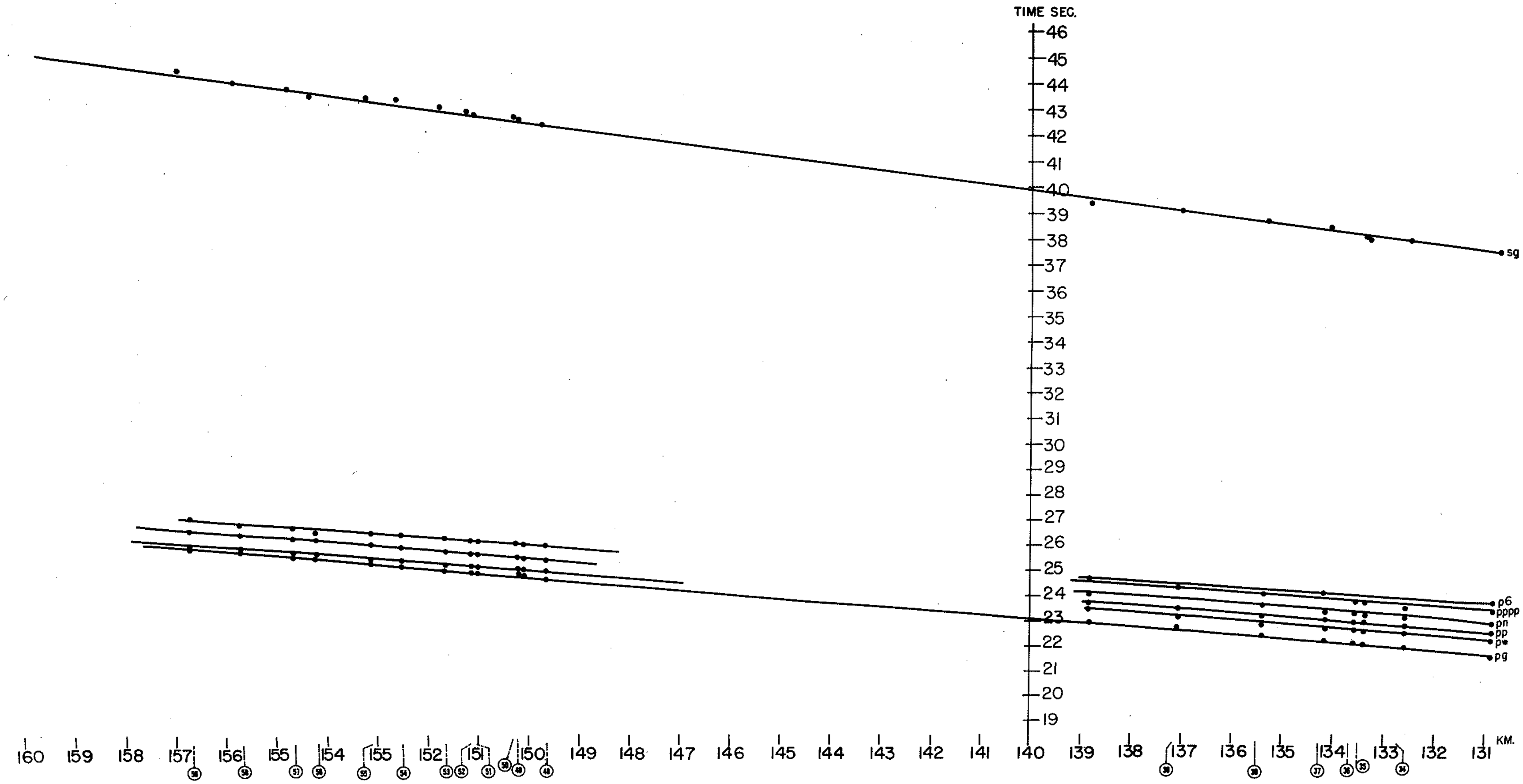


FIGURE 16. (continued)

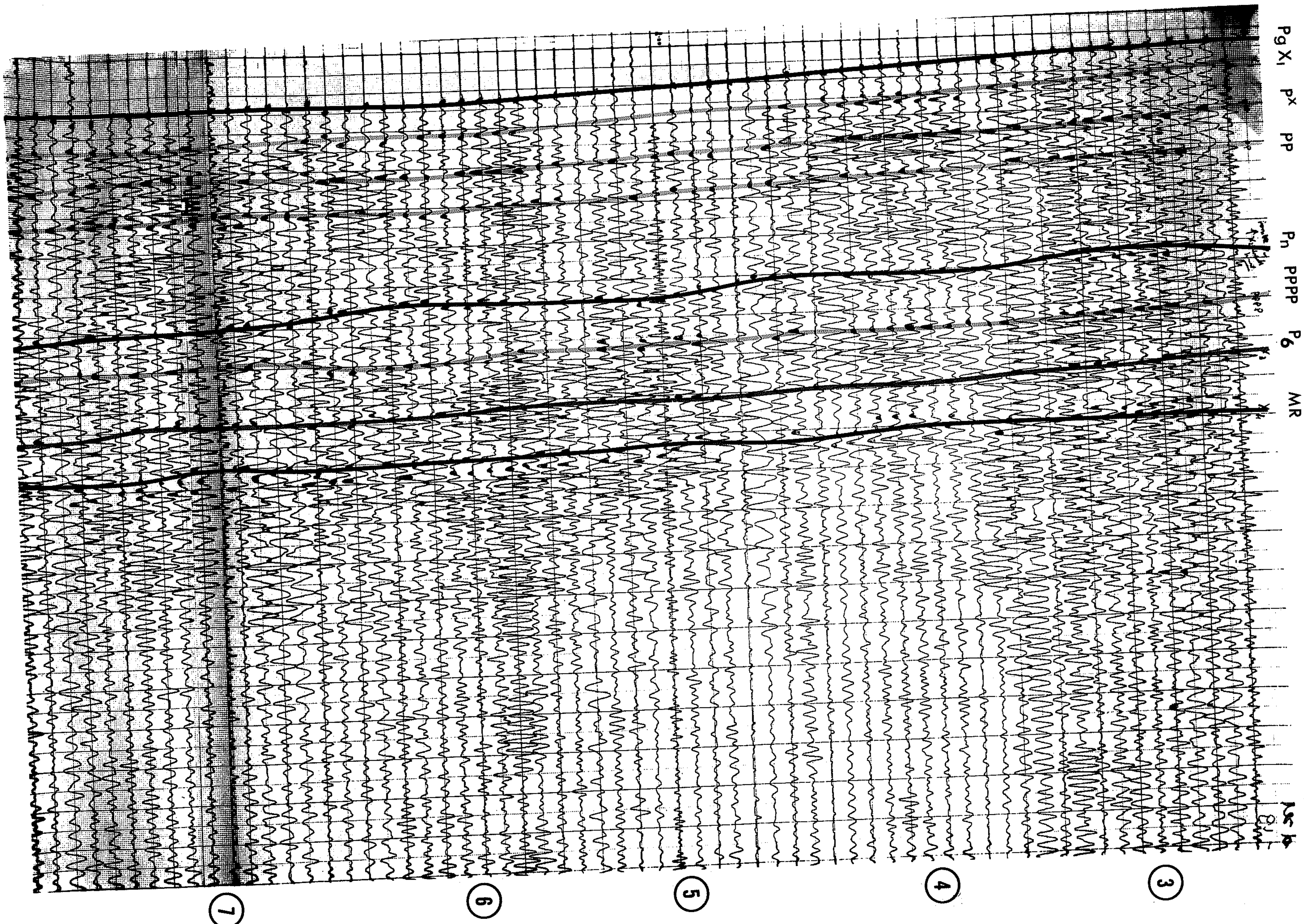
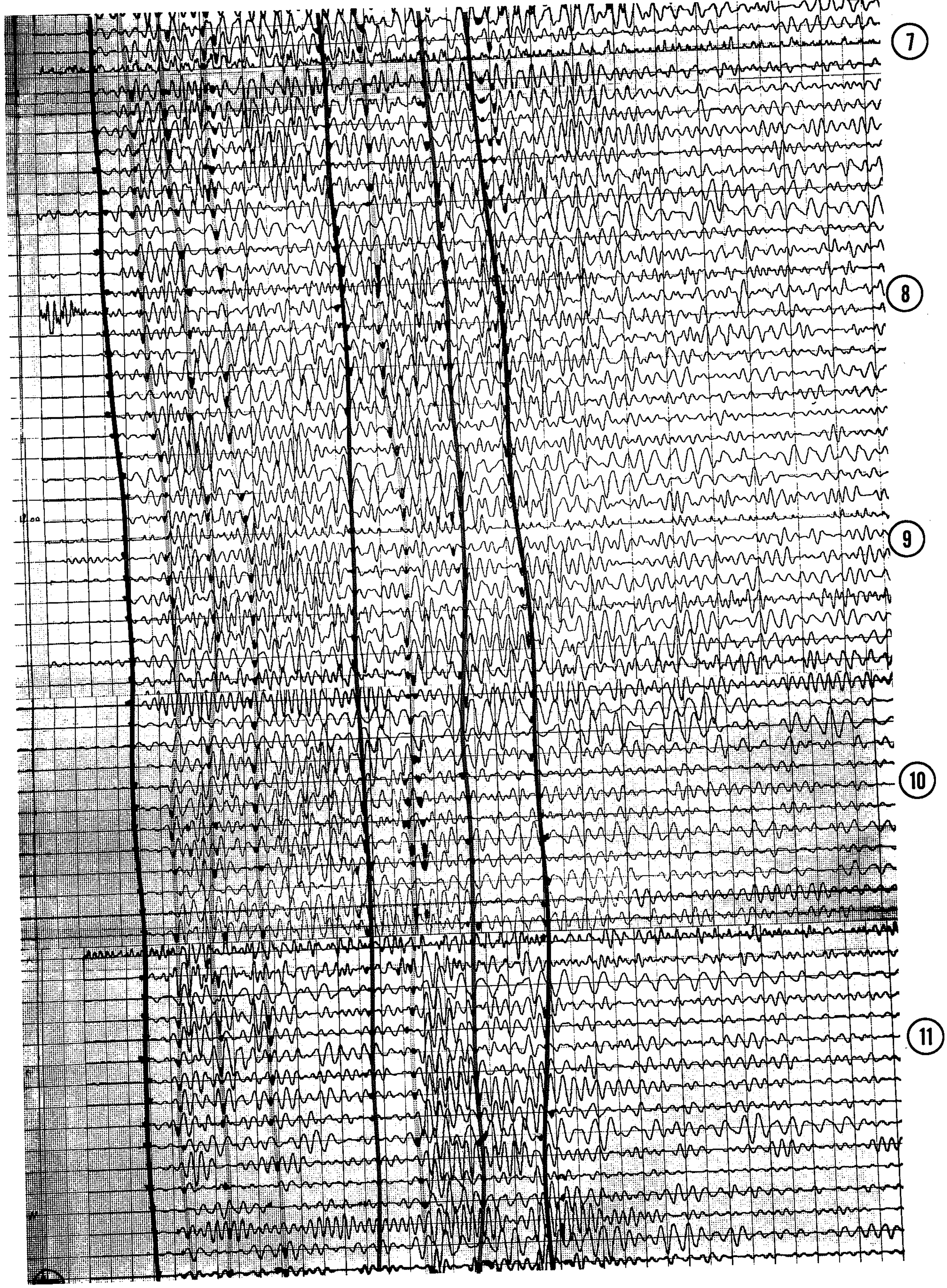
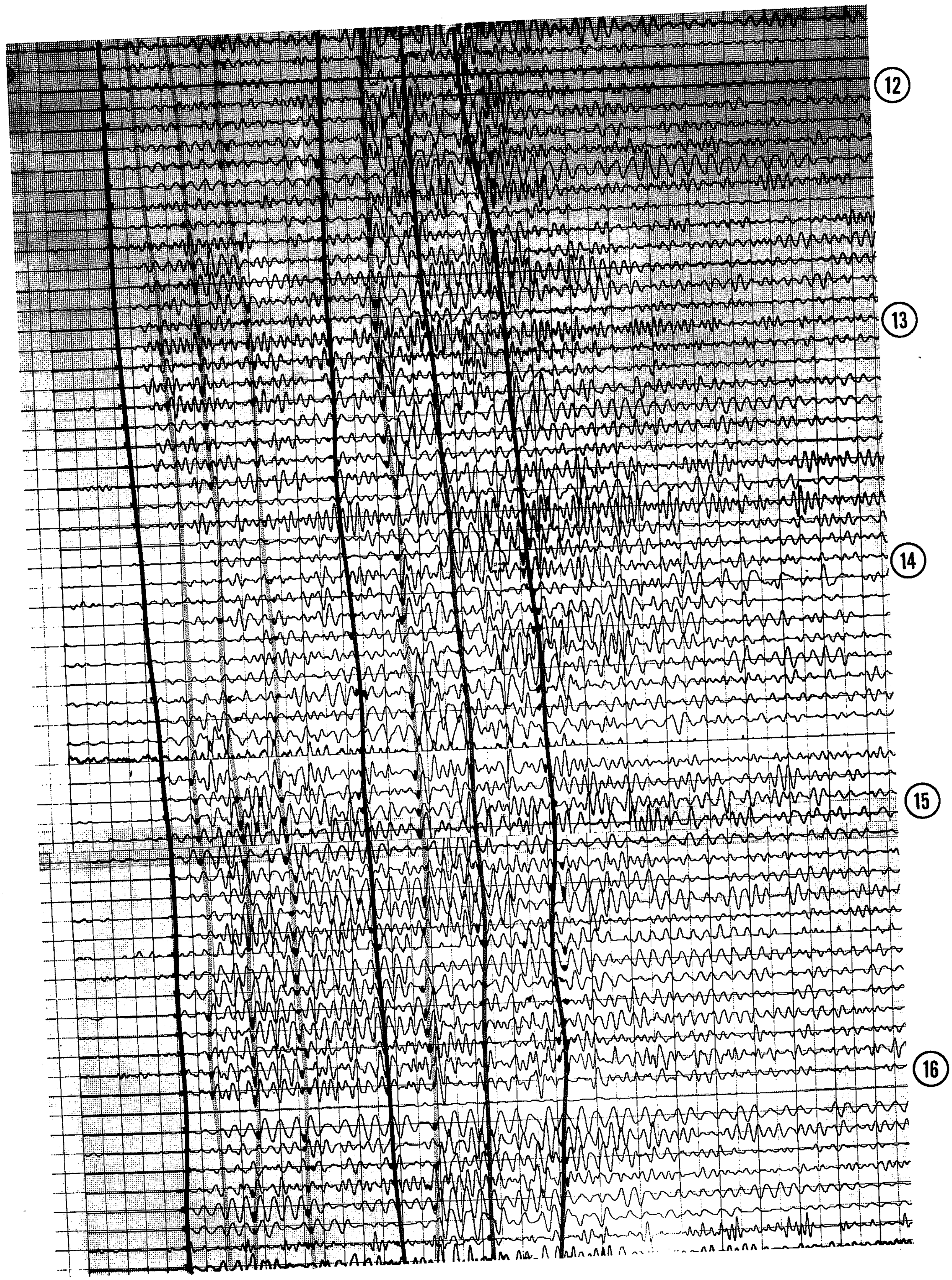
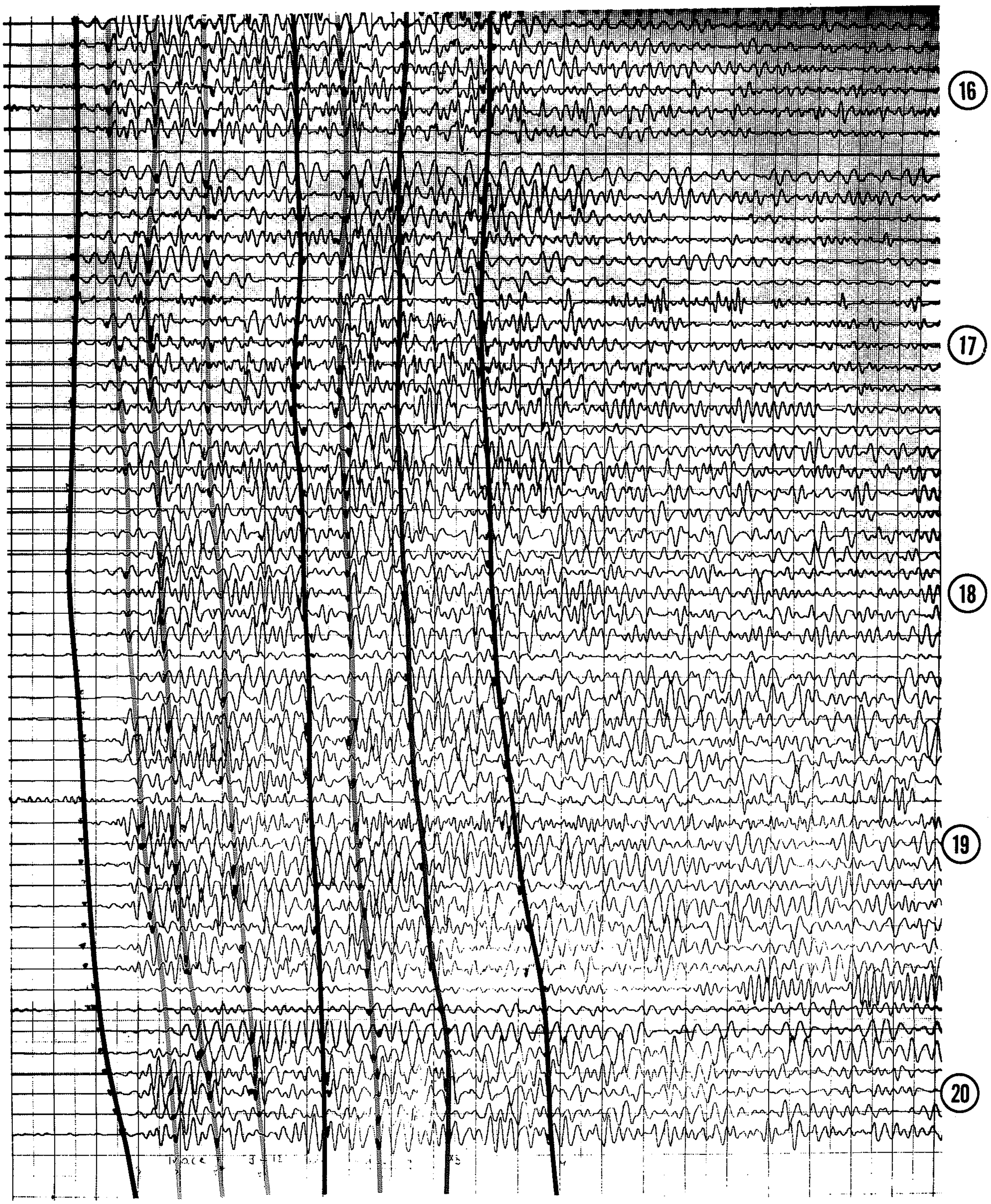
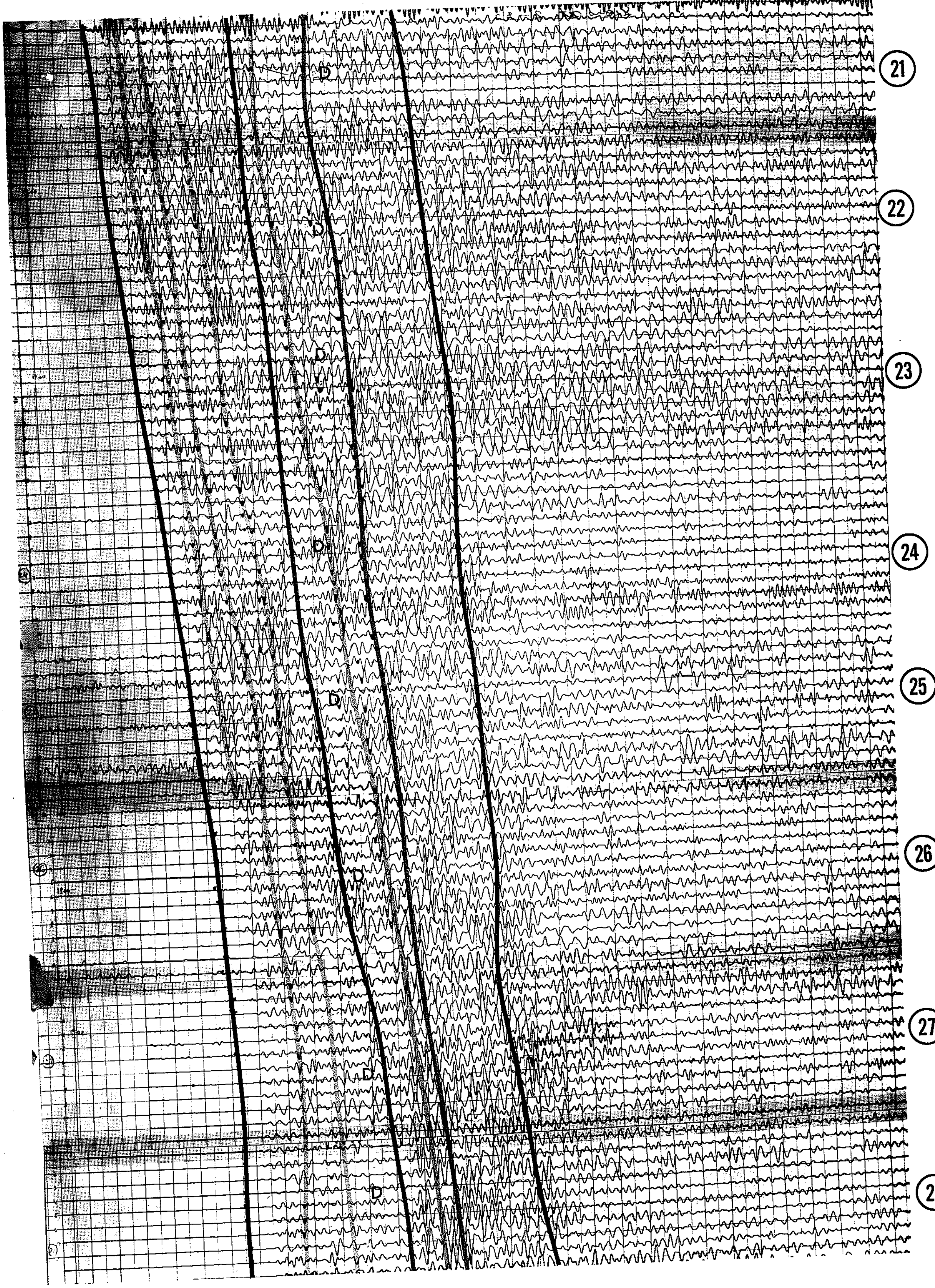


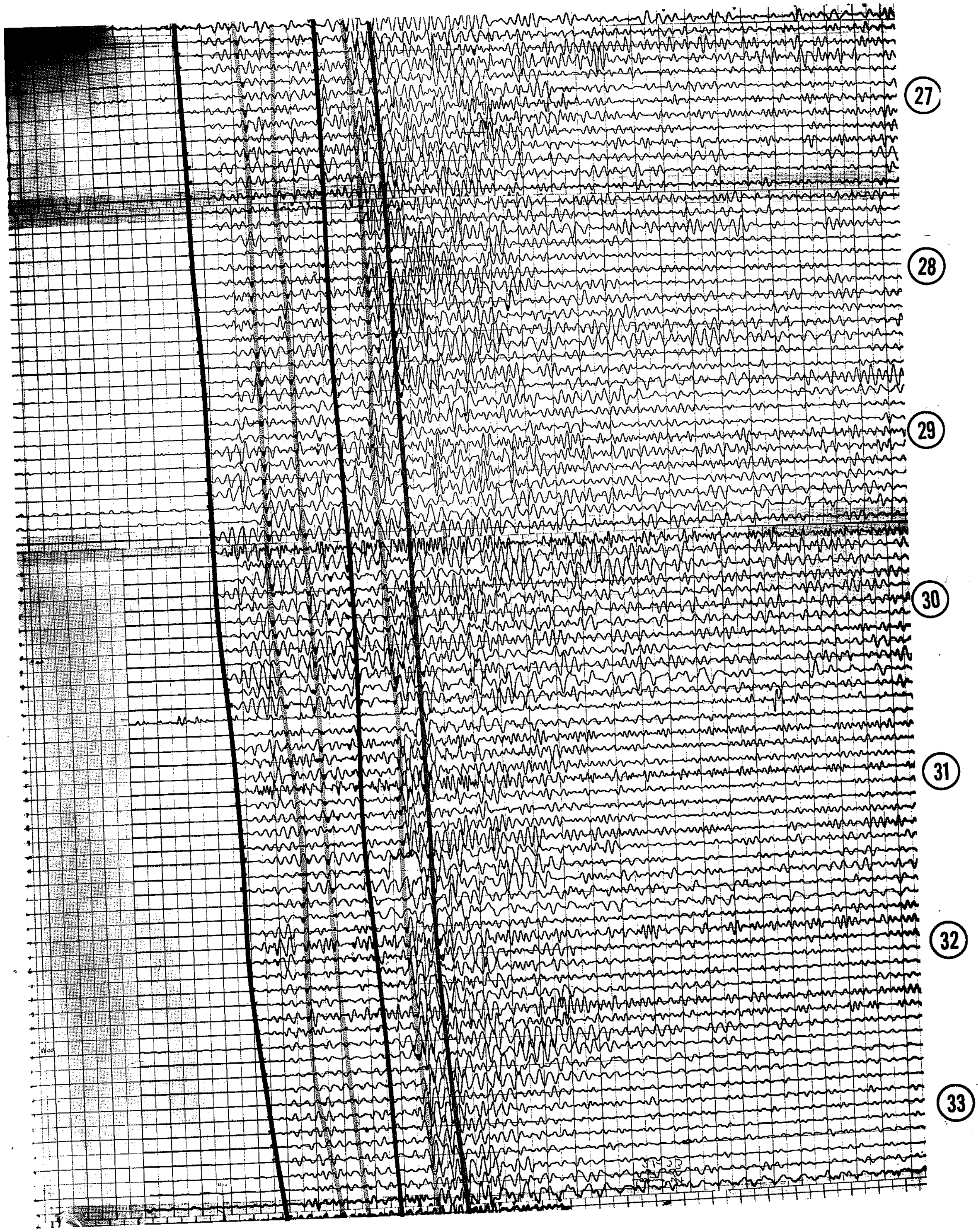
FIGURE 17. Seismic section of continuous refraction survey.

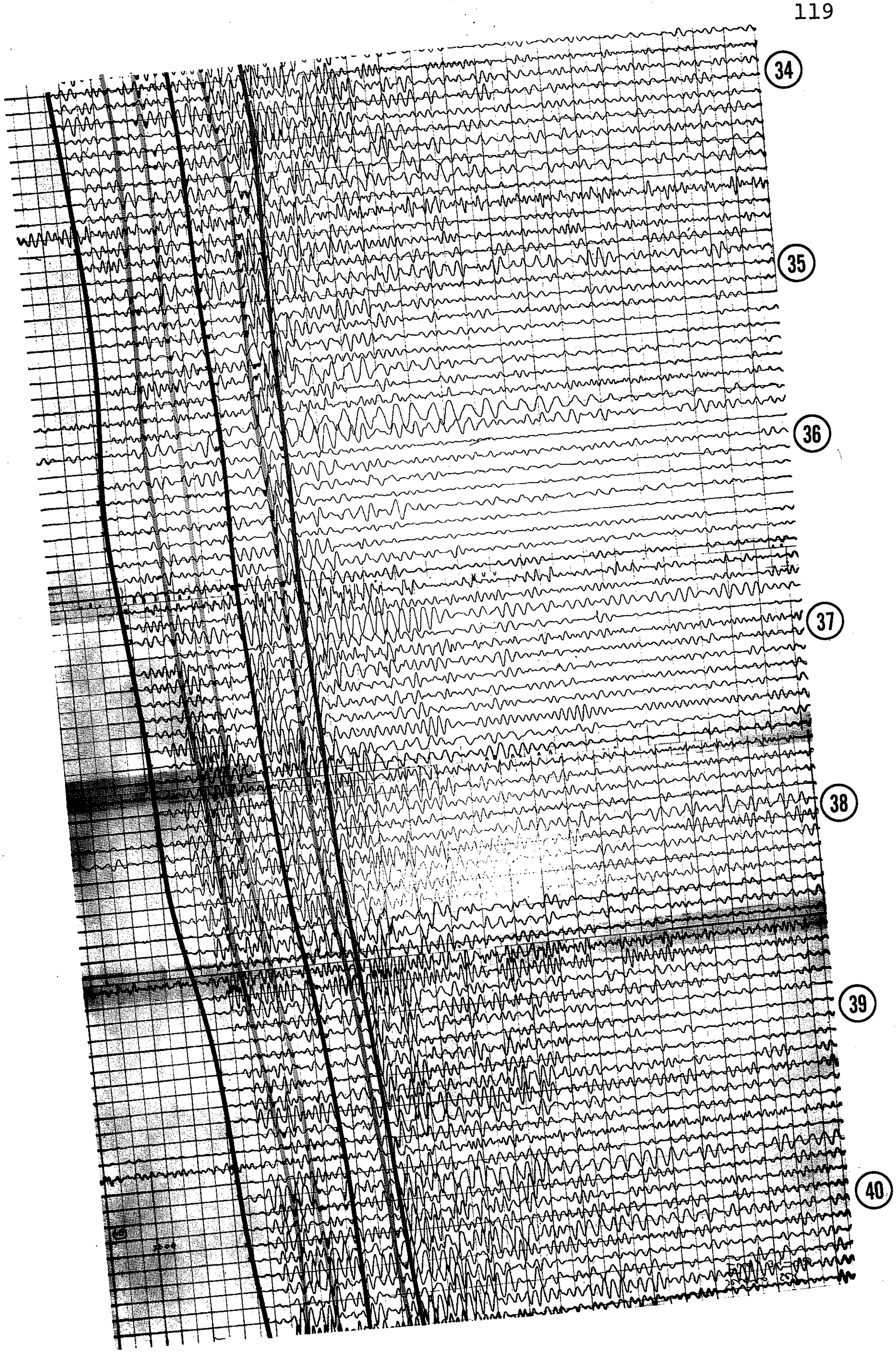

7
8
9
10
11

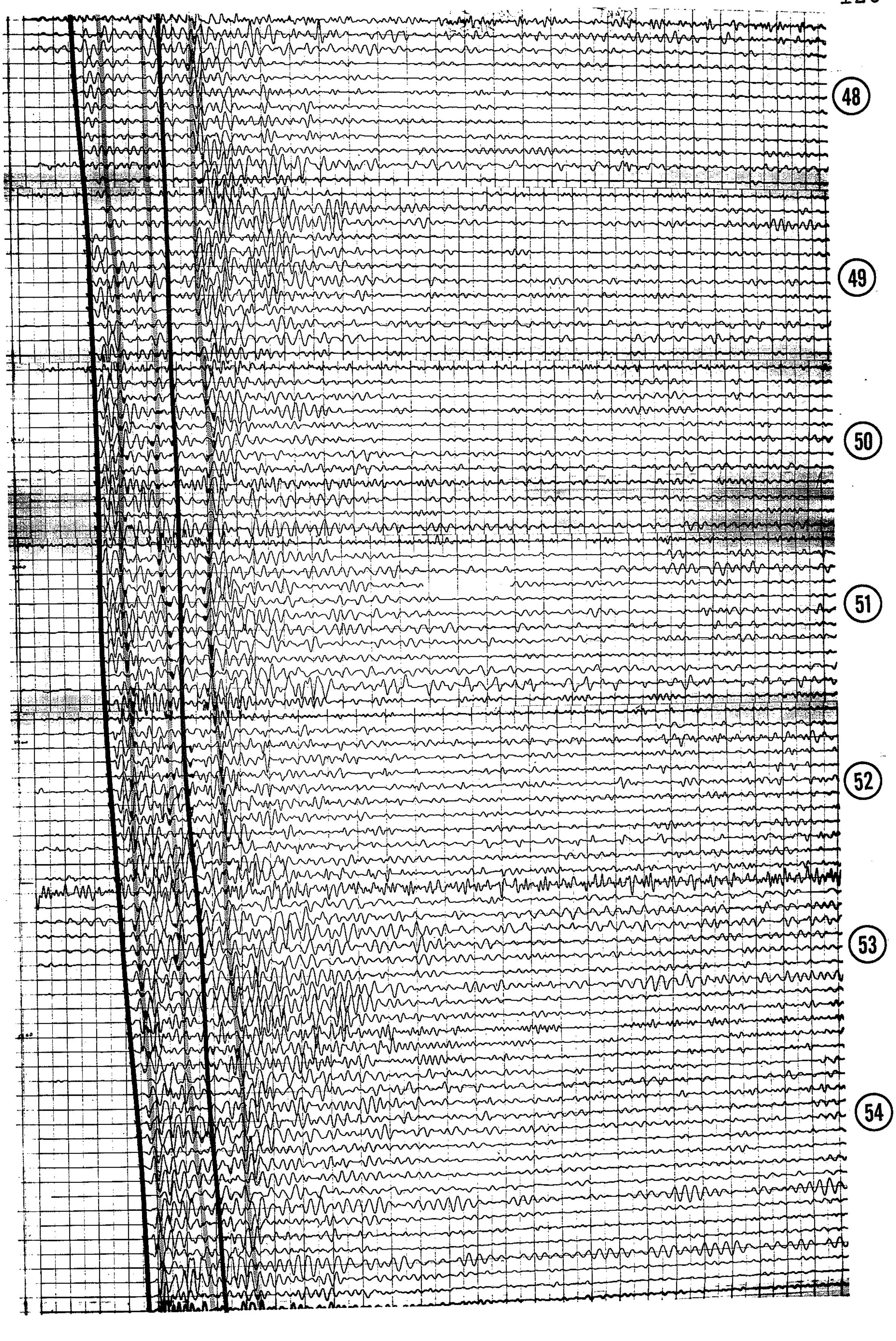

12
13
14
15
16

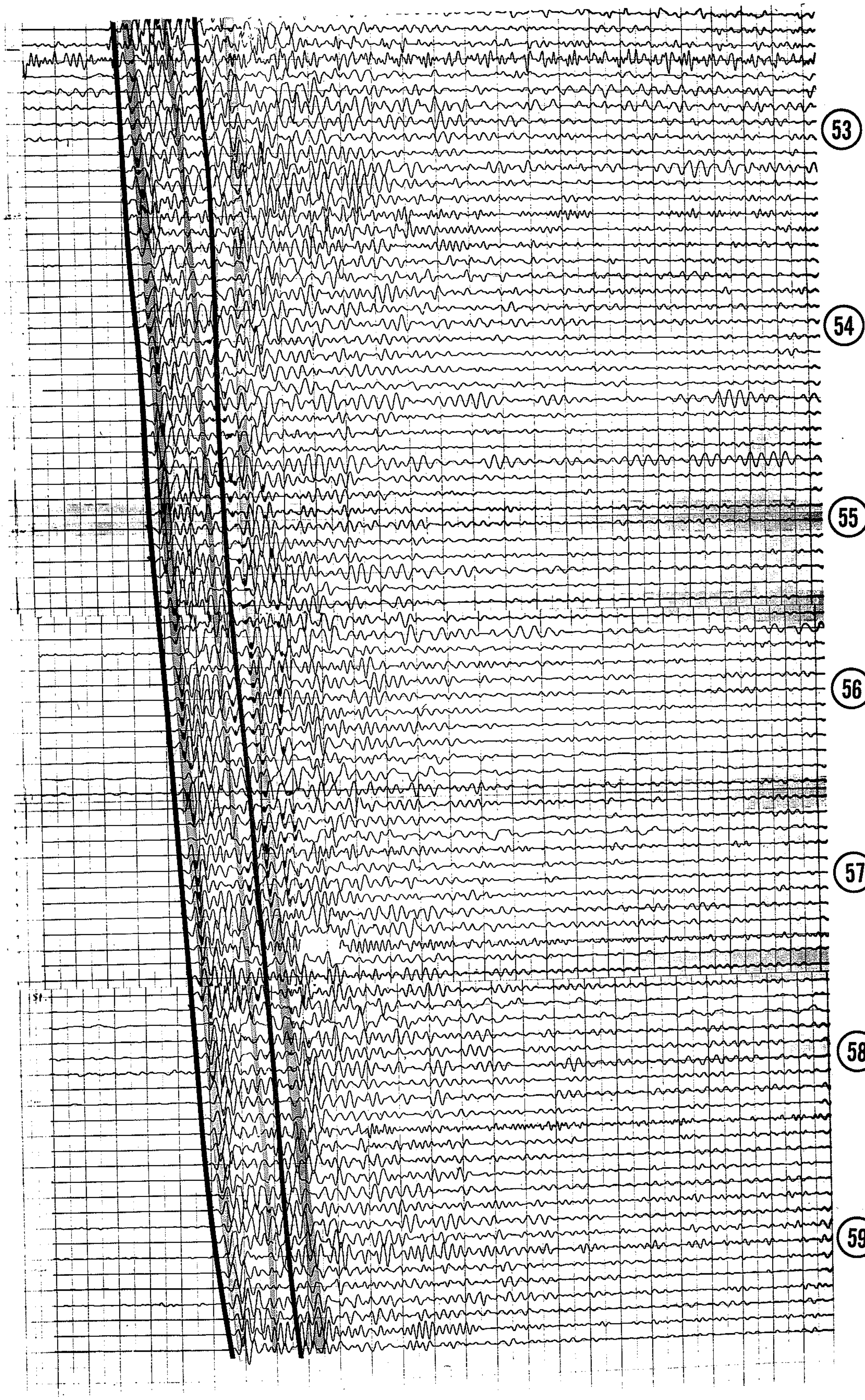

16
17
18
19
20


21
22
23
24
25
26
27
28
D


27
28
29
30
31
32
33


34
35
36
37
38
39
40


48
49
50
51
52
53
54


53
54
55
56
57
58
59

largest amplitude through the entire section. The extreme weakness of some of the arrivals example A-11 to A-14 is not the result of the disappearance of the particular event but the result in a change of the ratio of the weak arrival amplitude to the dominant PPPP. The plotting program was written to examine the largest amplitude on every trace and set this value to the scale of a half inch. As a result if the PPPP is very large the weaker events with small amplitude are suppressed by the program before plotting. Figure 18 attempts to illustrate this effect. Here record numbers 21 to 29 are replotted, but only the parts before PPPP. If this is compared to the original section in Figure 17 the improvement in the amplitude and the recognizability of the same arrivals become very clear. The development of an automatic amplitude control program would eliminate this problem. Because of the extremely variable nature of the amplitude of the arrivals in a crustal record the development of this program is rather complex. It was impossible to incorporate it in the present study. In areas where the correlation became a problem on this profile, the records were replotted with attention to obtain maximum amplitudes on arrivals with major interest.

The first arrivals or the first breaks indicated as Pg are interpreted as the direct wave. On most records the arrival starts with an up swing of the galvonometer. This is followed with two low amplitude peaks and the last

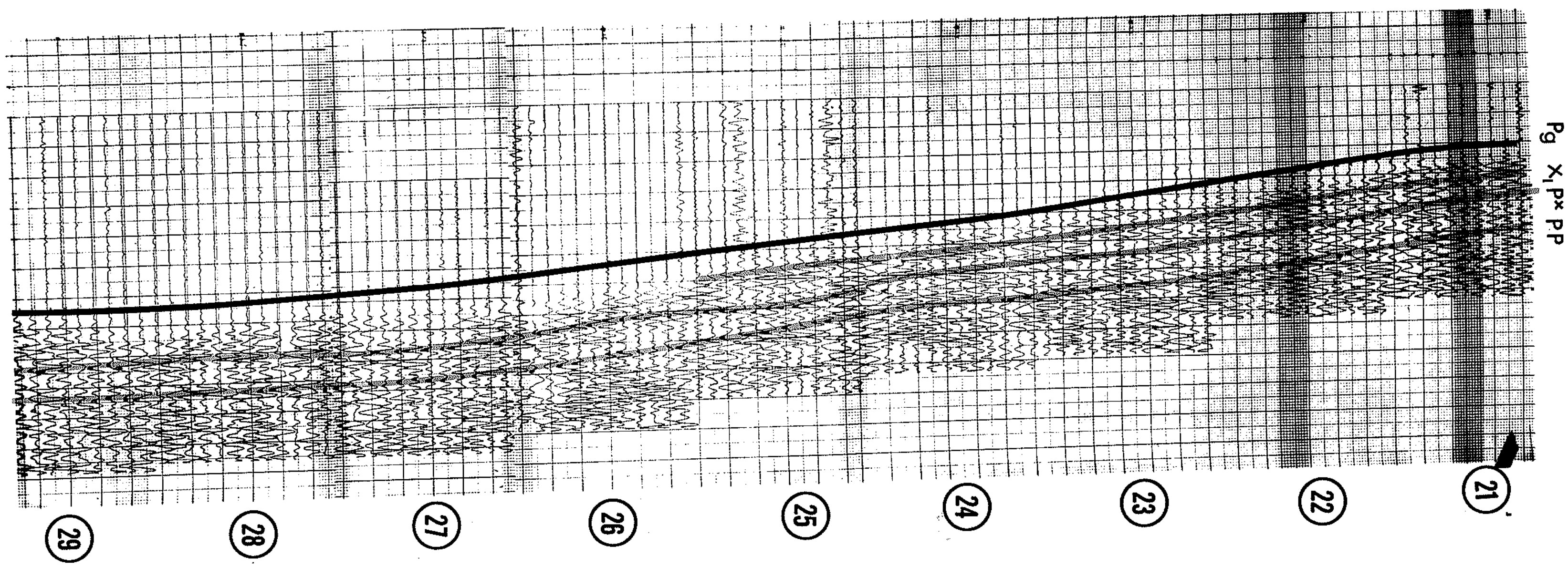


FIGURE 18. Detailed seismic section between site 21 and site 29.

part of the pulse is relatively strong. From record A-48 to A-59 the minor peaks disappeared; however the plot of the arrival times on the time-distance graph Figure 14 does not indicate recognizable ordinary shingling effect.

The next arrival, marked X_1 is not well separated from the previous one it can be correlated only to record number A-25. The recognition of this event and its interpretation will be discussed in the section dealing with the nearly-vertical reflection data.

The third event P* was recognized as the refraction event from the intermediate discontinuity. From record one to eighteen the arrivals fall on a straight line but from this they are somewhat delayed. The amplitude of the arrival is high up to record eleven. The frequency is between 8-10 cps. From record eleven to fifteen the amplitude is decreasing. On record nineteen the amplitude increases again and the event is very strong up to record twenty-six. In this interval the fundamental frequency is higher, around 12 cps. From record twenty-six the amplitude decreases again and a distinct change toward the lower frequencies occur.

The fourth arrival was interpreted as a wide angle reflection, PP, from the intermediate discontinuity. The amplitude of this event is generally larger than the P*, but its frequency does not seem to indicate too much variation.

The fifth event, P_n, represents the refracted ray from the Mohorovicic discontinuity. The amplitude of this arrival is rather strong up to record forty. From record 48 it is not recognized because of interference with serveral other arrivals.

The arrival marked PPPP or the sixth event on the first part of the section is the most dominant arrival on the entire section. The correlation of this becomes somewhat complex, only after record number fifty-three. It has the most energy among all the events and its frequency stays around 10 cps. The character of these events indicate that they are reflected longitudinal waves from the Moho.

The following set of arrivals, marked P_6, are also quite strong. No correlation of these to the regional data was observed. The arrivals can be correlates as far as record number 31. From this record the interference of the Moho reflection with this event makes further correlation impossible. The plotting of the arrival times indicates velocity close to 8 km. per second. It is late event. It indicates high velocity and it is observed relatively close to the shotpoint. Considering the crustal section derived from the interpretation of the previous data, this set of arrivals can be identified only as a reflection event coming from an interface within the mantle itself. Gurbuz (1969) interpreting the Project Early Rise data in this area indicates an interface in the mantle which could provide arrivals in the presently observed range.

The last set of arrivals, indicated PPM, show good correlation and high amplitude up to record number 28. The time-distance plot of these arrivals give a line segment which is very close to parallel with PP. If calculations are carried out using the depth and velocities from the previous data these arrivals fit in with the required travel time for a set of first order multiples from the intermediate discontinuity. The suddenly diminishing amplitudes seem to enforce these. The area of observations are close to twice the critical point distance for the intermediate discontinuity. The amplitude of the critically reflected wave has the most energy; therefore, its first order multiple may have recognizable amplitude.

The results of the depth calculations are plotted on Figure 19. The depth points are indicated at the computed offset distances. The zero point is located at the shotpoint. From fifty-five to seventy-five kilometers of the intermediate interface the depth values were computed from the wide angle, PP, reflection data. From here to ninety-seven kilometers the P* refraction data provided the depth. There is a gap from ninety-seven kilometers to one hundred five kilometers. This is a result of the discontinuity of the field survey between station number A-40

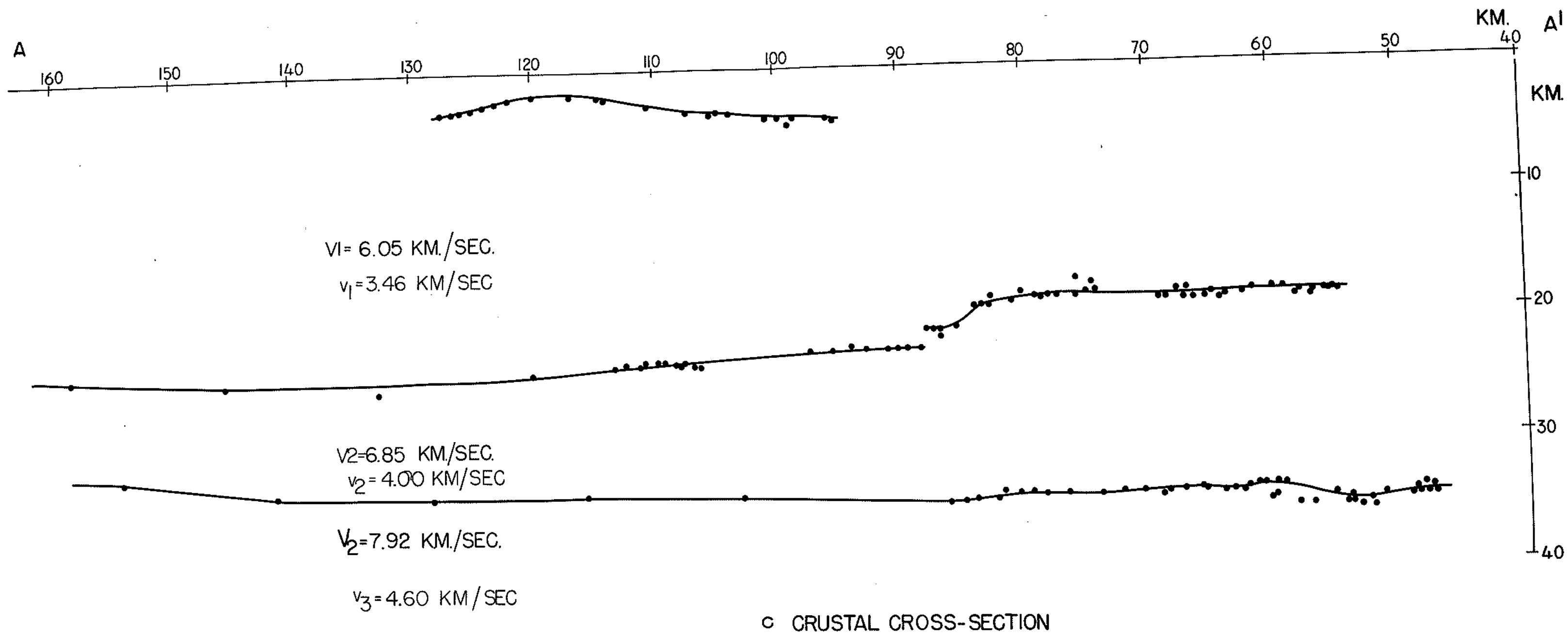


FIGURE 19. Crustal cross section

and A-48.

In the case of the Mohorovicic discontinuity the part between 47 and 60 kilometers is obtained from reflection data. From 60 km. to 95 km. the depth values were gained from the P_n arrivals. This cross section approximately fits the line indicated as AA' on the regional structure map.

The evaluation of the P_6 arrivals resulted in the deepest interface. The computation of these data were carried out with the aid of computer program THEORE. This program computes theoretical reflection arrival times if the interval velocities, the thickness of the layers at the shotpoint, and the slope of the interfaces are estimated. Detailed description of the program is attached in the Appendix. In the present process the depth of the intermediate and Moho discontinuities were provided as it is indicated on the cross-section. The applied velocities were also the same as this diagram exhibits, only the depth and the possible slope of the searched interface were varied. Using these conditions the best fit was obtained with an average thickness of 6.50 km. slope 1°. This indicates that the total average depth to this interface in the mantle is 43.17 km.

The most striking feature of this crustal cross-section is observable on the intermediate discontinuity. At 84 km. from the shotpoint it reveals a sudden change which is interpreted here as a deep fracture zone. According to the presented data the northern section was up thrown approximately three and a half km. relative to southern portion of the crust. This crustal movement seems to be associated with a slight uplift at the Moho. If these detailed results are associated with the regional picture the combined crustal data reveal a long relatively narrow depression in the crust which is connected to a relatively flat platform with considerable fracture zones.

The question arises of the criteria of the recognition of these fracture zones. Model experiments by Loster et al (1967), results of deep seismic sounding as Dragasevic and Andric (1968) indicate some conditions which may be applied in search of these features. The most important aspects are:

1. unusual attenuation of waves
2. variation in wave pattern
3. breaks in travel-time curves, delay of some segments
4. appearance of diffracted waves
5. appearance of non-regular waves with negative apparent velocity

Viewing these conditions the following observations can be made in the present case: Loster et al point out the amplitude is attenuated after the structure. A sudden decrease in amplitude can be observed on record 26, 27, 28 and 29. The examination of the seismic section between record 21 and 33 will show that there is a sudden change in frequency content of the signal after record no. 27. The arrivals after this record show lower frequency content. The local geological survey does not indicate anomoly in this area, which would explain this change in the nature of the signal. The time-distance graph shows a definite break after 123 km . The appearance of diffracted waves is not obvious on the seismic section. Arrivals, marked D, on the individual records fit in exactly with the computed travel time for rays which travel to the recording site if the uplift at 84 km. on the intermediate layer is considered as a point source. On records 23 to 26 especially between the Moho reflection and the multiple, there are several short arrivals with reversed time gradient. Because of the large distance from the fracture zone and the relatively small movement, the seismic section does not show as obvious characteristics as it can be observed on sections showing faults in shallow depth. The possible effect or extent of the surface of this fracture zone can be observed on the Tectonic Map of Canada, Stockwell (1968). This map indicates an abrupt stop of the general northwest pattern of surface geological trends at the same area as the location of the crustal gradient of the structural map of the intermediate discontinuity. Recently D. T. Anderson (personal communication) studying airphoto lineaments in the Bloodvein

River area found a large trend extending in northwest direction which he calls the Bloodvein River lineament. This surface feature is in the area of the crustal gradient and it follows the same direction.

Vertical Reflection Profile

The application of near-vertical reflection method in the course of the present study was planned to serve several purposes.

1. The observation of reflection arrivals from the Intermediate and Mohorovicic discontinuities would further enforce the layered nature of the crust in this area.
2. It is an aim of this study to investigate the possible applicability of the different seismic methods in mining exploration on the Precambrian Shield. More directly a technique is required which could give detailed information from the findings of regional crustal studies.
3. It is an attempt to determine the necessary modifications which would make the reflection method a successful survey tool in crustal and detailed studies on the Precambrian Shield.

Several very successful crustal reflection experiments are listed already in the literature, Junger (1951), Japan Research Group for Explosion Seismology (1955), Widess and Taylor (1959), Tuchev et al (1960), Beloussov et al (1962), Dix (1965), German Research Group for Explosion Seismology (1964), Kanasewich and Cumming (1965), Clowes et al (1968). However, not one of these was carried out in Precambrian Shield areas, therefore the present investigations faced some problems not encountered previously.

The details of the field operations were described in the previous sections. The preparation of data followed similar procedures as in the case of the continuous refraction profile survey. The first section was made using analog playback data and then digital processing was applied. Because of the very high frequency noise on the analog section the data was filtered with a 5-25 cps. band-pass filter. Table VII contains the numberical results.

Figure 20 shows the final seismic section of the survey. Although eleven recordings were made, only nine records were processed. The two closest records to the shotpoint had to be discarded because of the amplifier distortion. Only the first breaks were useful on these two records. Records numbered 577 to 580 were recorded with an energy source of 25 pounds SM Super X. For records 581 to 584 the amount of explosives were raised to 50 pounds. The last three shots used 100 pounds of explosives.

The first examination of the section reveals excellent first break arrivals as well as two distinct later arrivals. The arrival times of these events were plotted on time-distance graph, Figure 21. The first

TABLE VII

VERTICAL REFLECTION SURVEY DATA

Station &	Geophone #	Distance km.	First Brakes Sec.	Arrival # 1 Sec.	Arrival # 2 Sec.	Arrival # 3 Sec.	Sg Sec.	Rv Sec.
577	1	.181	.10					
	2	.261	.11					
	3	.374	.14					
	4	.494	.16					
	5	.615	.18					
	6	.756	.20					
	7	.869	.22					
	8	1.005	.24					
	9	1.134	.27					
	10	1.259	.30					
	11	1.388	.33					
	12	1.509	.33					
578	1	1.509	.34					
	2	1.642	.35					
	3	1.770	.36					
	4	1.899	.39					
	5	2.024	.41					
	6	2.140	.42					
	7	2.269	.44					
	8	2.394	.45					
	9	2.531	.47					
	10	2.631	.49					
	11	2.744	.50					
	12	2.861	.51					
579	1	2.861	.50	.80			.91	1.25
	2	2.933	.51	.81			.92	1.23
	3	3.018	.52	.83			.98	1.28
	4	3.122	.53	.84			1.01	1.30
	5	3.259	.56	.87			1.06	1.36
	6	3.388	.58	.89			1.10	1.40
	7	3.500	.61	.91			1.13	1.43
	8	3.637	.63	.93			1.16	1.50
	9	3.770	.66	.95			1.20	1.53
	10	3.903	.68	.98			-	1.57
	11	4.035	.70	1.00			1.27	1.62
	12	4.168	.73	1.01			1.31	1.69

TABLE VII (continued)

Station & Geophone #		Distance km.	First Brakes Sec.	Arrival # 1 Sec.	Arrival # 2 Sec.	Arrival # 3 Sec.	Sg Sec.	Rv Sec.
580	1	4.168	.73	1.01			1.34	1.69
	2	4.305	.78	1.04			1.37	1.70
	3	4.426	.81	1.05			1.41	1.73
	4	4.554	.83	1.09			1.43	1.77
	5	4.675	.86	1.09			1.48	1.81
	6	4.792	.87	1.12			1.53	1.86
	7	4.917	.90	1.15			1.54	1.93
	8	5.041	.91	1.16			1.59	1.94
	9	5.182	.93	1.18			1.63	2.01
	10	5.292	.95	1.20			1.65	2.03
	11	5.432	.98	1.23			1.70	2.10
	12	5.584	1.01	1.25			1.73	2.15
581	1	5.733	1.03	1.29			1.78	2.19
	2	5.810	1.05	1.29			1.80	2.23
	3	5.870	1.06	1.31			1.82	2.27
	4	5.987	1.08	1.32			1.85	2.31
	5	6.087	1.10	1.33			-	2.37
	6	6.188	1.12	1.35			1.92	2.33
	7	6.289	1.13	1.37			1.94	2.39
	8	6.389	1.16	1.40			-	2.40
	9	6.514	1.17	1.41			2.01	2.44
	10	6.614	1.19	1.43			2.03	2.49
	11	6.739	1.21	1.45			2.12	2.53
	12	6.876	1.23	1.48			2.13	2.56
582	1	6.952	1.23	1.48			2.14	2.61
	2	7.025	1.25	1.48			2.15	2.62
	3	7.178	1.27	1.50			2.20	2.65
	4	7.306	1.29	1.54			2.24	2.69
	5	7.419	1.31	1.55			2.28	2.74
	6	7.556	1.35	1.59			2.32	2.78
	7	7.697	1.37	1.61			2.30	2.84
	8	7.821	1.39	1.62			2.38	2.87
	9	7.946	1.42	1.64			2.43	2.90
	10	8.071	1.45	1.66			2.47	2.96
	11	8.200	1.46	1.70			2.53	3.00
	12	8.336	1.48	1.72			2.56	3.04

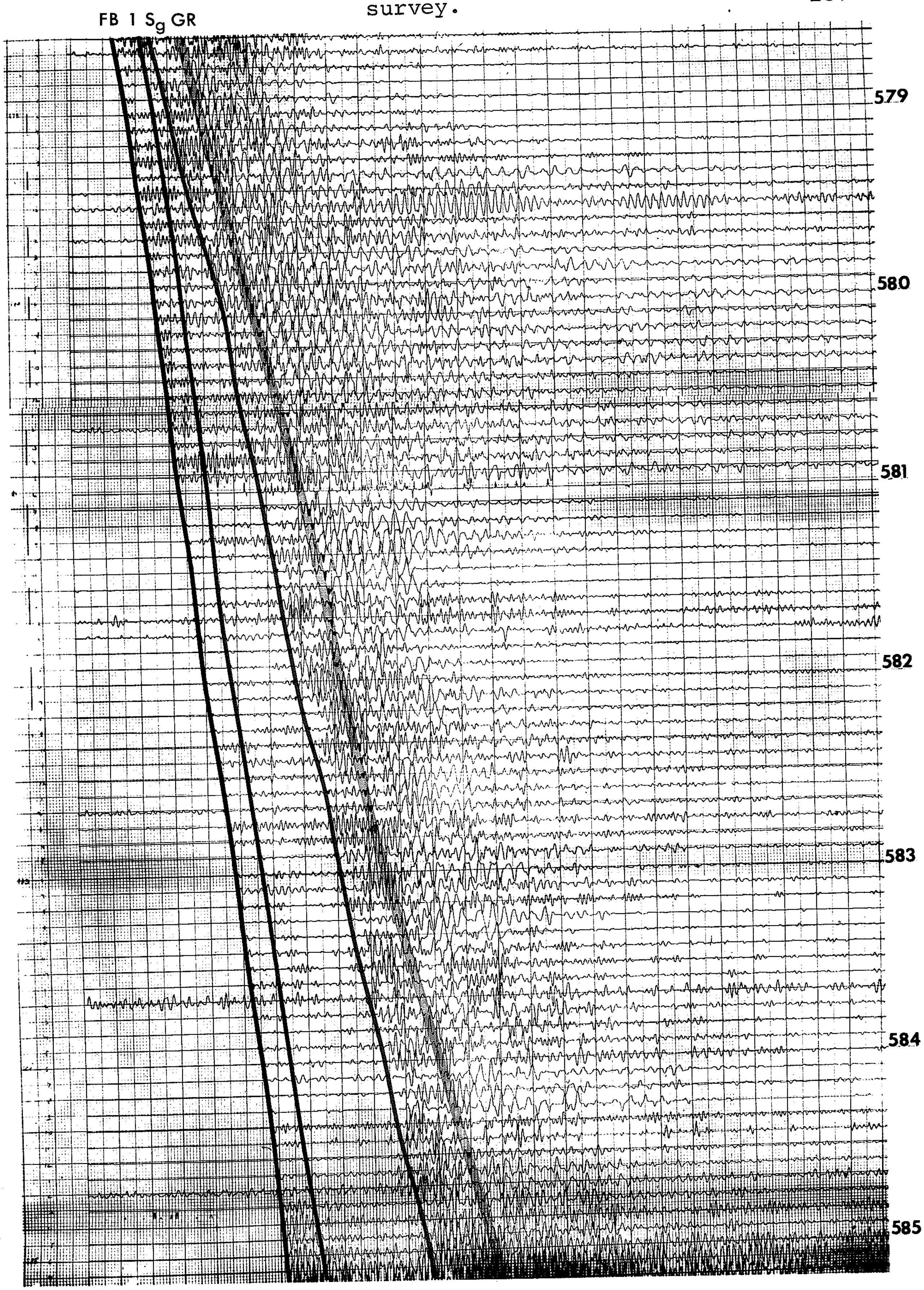
TABLE VII (continued)

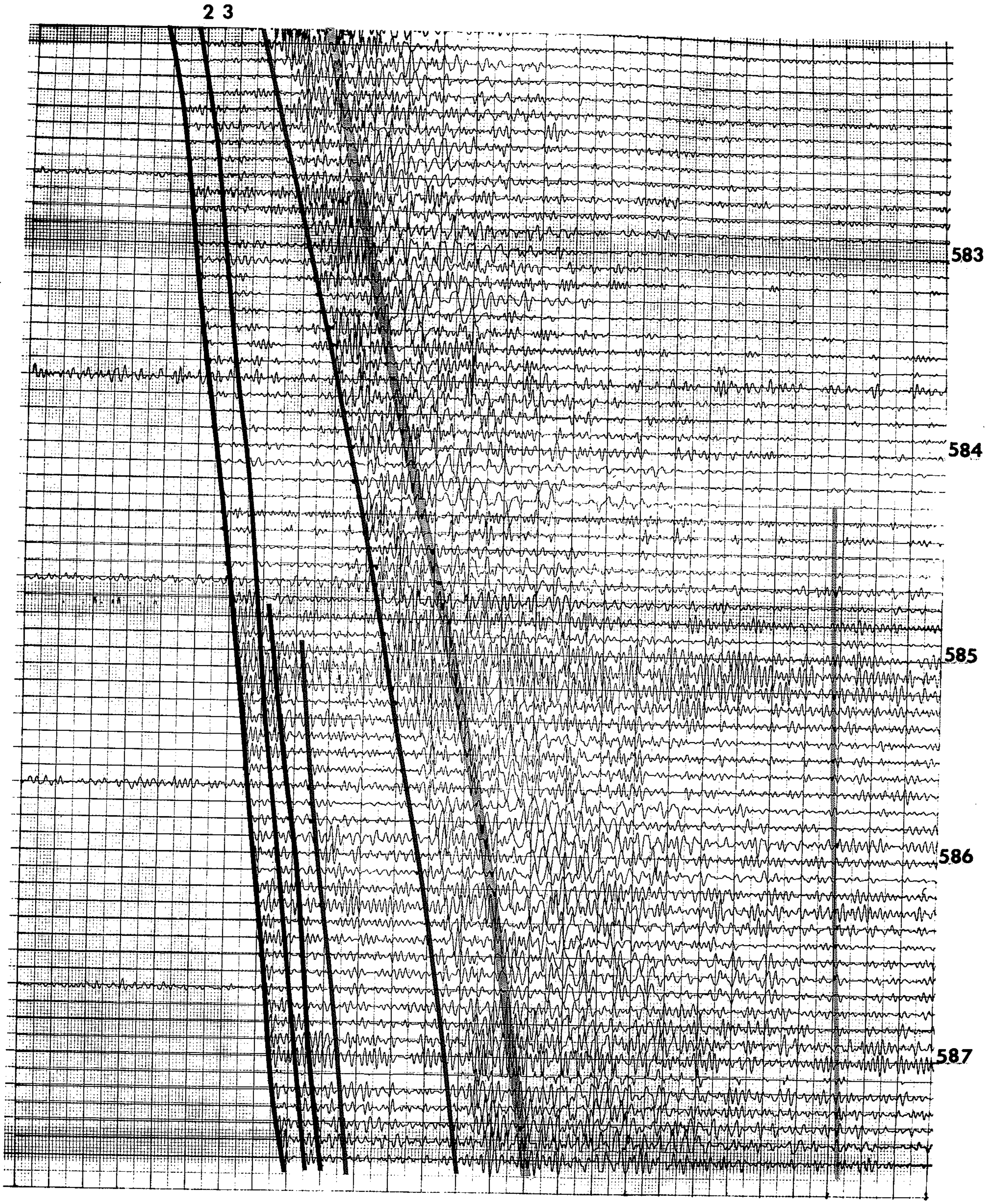
Station & Geophone #		Distance km.	First Brakes Sec.	Arrival # 1 Sec.	Arrival # 2 Sec.	Arrival # 3 Sec.	Sg Sec.	Rv Sec.
583	1	8.336	1.52	1.73			2.57	3.04
	2	8.473	1.55	1.74			2.59	3.09
	3	8.626	1.57	1.76			2.65	3.1
	4	8.750	1.58	1.78			2.67	3.19
	5	8.876	1.60	1.80			2.73	3.23
	6	9.029	1.62	1.82			2.76	3.28
	7	9.177	1.64	1.86			2.79	3.33
	8	9.318	1.66	1.89	2.04		2.83	3.38
	9	9.467	1.70	1.91	2.08		2.85	3.44
	10	9.608	1.70	1.93	2.08		2.92	3.47
	11	9.733	1.71	1.96	2.10		2.98	3.51
	12	9.857	1.74	1.97	2.11		3.02	3.57
584	1	9.857	1.74	1.96	2.13		3.02	3.59
	2	9.982	1.77	2.01	2.15		3.04	3.62
	3	10.094	1.79	2.00	2.17		3.09	3.64
	4	10.211	1.81	2.02	2.19		3.10	3.69
	5	10.336	1.83	2.05	2.21		3.15	3.74
	6	10.461	1.85	2.06	2.23		3.22	3.76
	7	10.561	1.89	2.07	2.25		3.24	3.79
	8	10.714	1.89	2.10	2.28		3.26	3.84
	9	10.839	1.93	2.13	2.31		3.29	3.89
	10	10.964	1.94	2.14	2.32		3.34	3.95
	11	11.101	1.94	2.16	2.36		3.38	3.97
	12	11.217	1.98	2.18	2.36		3.41	4.01
585	1	11.217	1.98	2.18	2.36		3.42	4.04
	2	11.330	2.01	2.20	2.38		3.46	4.07
	3	11.430	2.03	2.23	2.39		3.47	4.10
	4	11.531	2.04	2.25	2.42		3.52	4.15
	5	11.632	2.05	2.27	2.43		3.52	4.17
	6	11.720	2.08	2.27	2.44		3.56	4.20
	7	11.821	2.09	2.28	2.45		3.58	4.22
	8	11.893	2.11	2.30	2.47		3.60	4.26
	9	11.994	2.13	2.30	2.48		3.65	4.28
	10	12.106	2.15	2.33	2.51		3.65	4.33
	11	12.223	2.16	2.34	2.51		3.70	4.35
	12	12.324	2.18	2.35	2.52	2.79	3.73	4.39

TABLE VII (continued)

Station & Geophone #		Distance km.	First Brakes Sec.	Arrival # 1 Sec.	Arrival # 2 Sec.	Arrival # 3 Sec.	Sg Sec.	Rv Sec.
586	1	12.420	2.19	2.39	2.54	2.79	3.74	4.45
	2	12.590	2.22	2.43	2.57	2.82	3.80	4.49
	3	12.690	2.24	2.45	2.60	2.82	–	4.49
	4	12.800	2.26	2.47	2.61	2.83	3.86	4.55
	5	12.940	2.28	2.47	2.64	2.86	3.91	4.59
	6	13.000	2.29	2.49	2.65	2.89	3.92	4.62
	7	13.020	2.29	2.50	2.65	2.90	3.93	4.68
	8	13.110	2.32	2.51	2.66	2.92	3.94	4.69
	9	13.250	2.33	2.54	2.68	2.93	4.00	4.70
	10	13.350	2.35	2.56	2.70	2.94	4.03	4.71
	11	13.450	2.37	2.59	2.71	2.95	4.05	4.75
	12	13.620	2.39	2.60	2.74	2.98	4.11	4.81
587	1	13.620	2.41	2.61	2.74	2.98	4.11	4.86
	2	13.840	2.43	2.62	2.78	3.02	4.17	4.87
	3	13.940	2.45	2.64	2.79	3.04	4.19	4.89
	4	13.950	2.46	2.66	2.79	3.04	4.23	4.93
	5	14.020	2.47	2.20	2.81	3.06	4.23	4.94
	6	14.100	2.49	2.70	2.82	3.08	4.25	4.98
	7	14.250	2.52	2.71	2.84	3.11		
	8	14.320	2.52	2.73	2.85	3.12		
	9	14.500	2.54	2.74	2.88	3.15		
	10	14.600	2.56	2.75	2.90	3.17		
	11	14.700	2.58	2.75	2.91	3.19		
	12	14.740	2.59	2.76	2.92	3.20	4.45	5.02

FIGURE 20. Complete seismic section of vertical reflection survey.




2 3
583
584
585
586
587

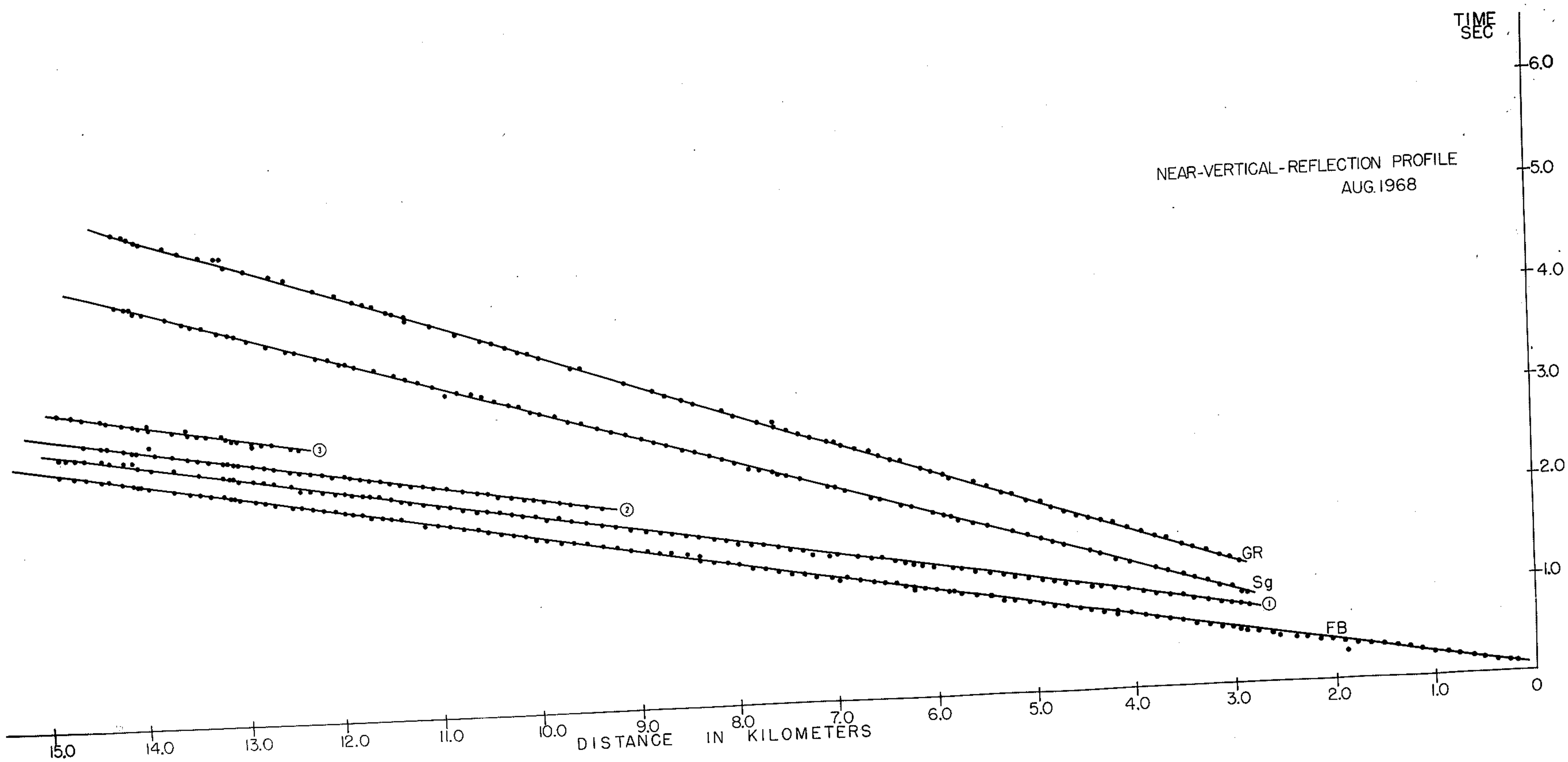


FIGURE 21. T-X plot of vertical reflection data.

arrivals were recognized as the travelling direct wave in the uppermost layer of the crust. The slope of the line segments of the two large amplitude later arrivals represent the shear wave and the surface waves respectively. Both the shear waves and the surface waves show higher frequency content on this section. This is the result of the filtering and the characteristics of the seismic detectors. Similar shots recorded with 1 cps. detectors in the same area revealed surface waves with frequency components less than 5 cps. A closer study of the last three records show a possibility of arrivals between the first arrival and the shear wave as well as some weak events around 8 seconds. The theoretical reflection times computed from the crustal section, as a result of the refraction studies, are 7.783 seconds at number one detector position on record number 579 and 8.141 seconds at the twelfth detector position on record number 587. The closeness of the weak events to the theoretical reflection time from the intermediate discontinuity warranted some further processing of the data.

Figure 22 is a six to one stack of the same set of data. The data was normalized and a 0.002 sec. move out correction was applied from trace to trace. The arrows are drawn at the points where the computed arrival times should fall using the crustal section of Figure 19. There are no recognizable events on records 579 to 581 in the expected range. Records 582 to 584 show an increase in

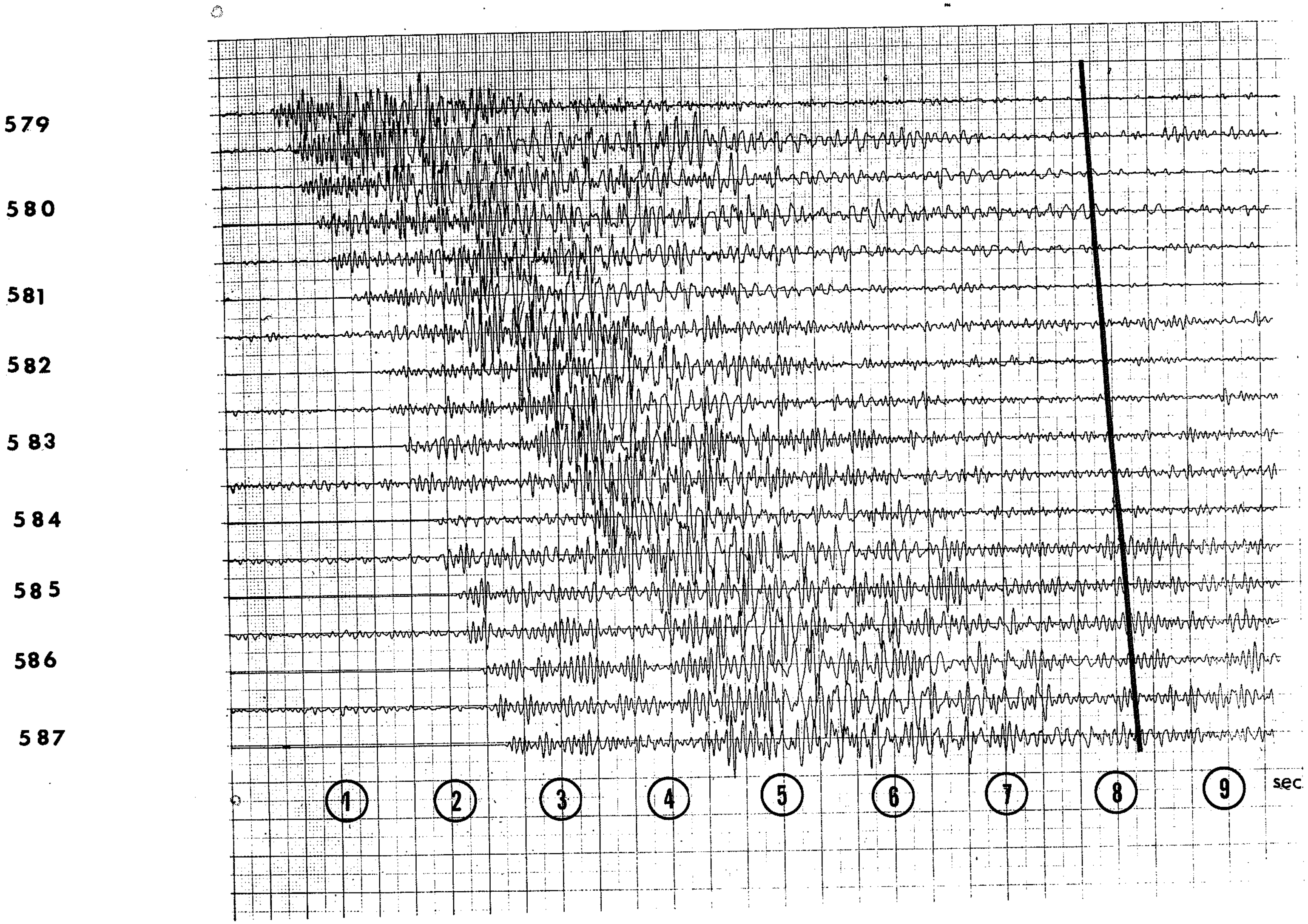


FIGURE 22. Velocity filtered vertical reflection section.

frequency content and some of the traces indicate possible weak arrivals. The last three records are much more encouraging, but the closeness of the surface waves makes the questionable. The change in characteristics of the records with the increase of the amount of explosives is quite apparent. A repetition of the same experiment with better shotpoint conditions is required to make further correlation of these arrivals to the intermediate discontinuity.

Figure 23 exhibits the multiple correlation process on the nearly vertical reflection data. The theory and details of the application of this method was described in the section on Digital Processing. The nine traces here present a six to one stack and a continuous integration with integration arrival of 0.20 seconds. Although there are good indications of arrivals after 8 seconds on records 585 to 587, this method does not provide better results than it can be observed from the six to one stacked traces.

This section however indicates clearly the problems of the applied technique. Because of the small number of traces, no complete elimination was achieved of the noise and the unwanted signals. As the straight lines indicate, even though they are out of phase, the first breaks, the shear wave and the ground roll are still identifiable after the process. The elimination of trace number two from the record, as well as other very poor traces would increase

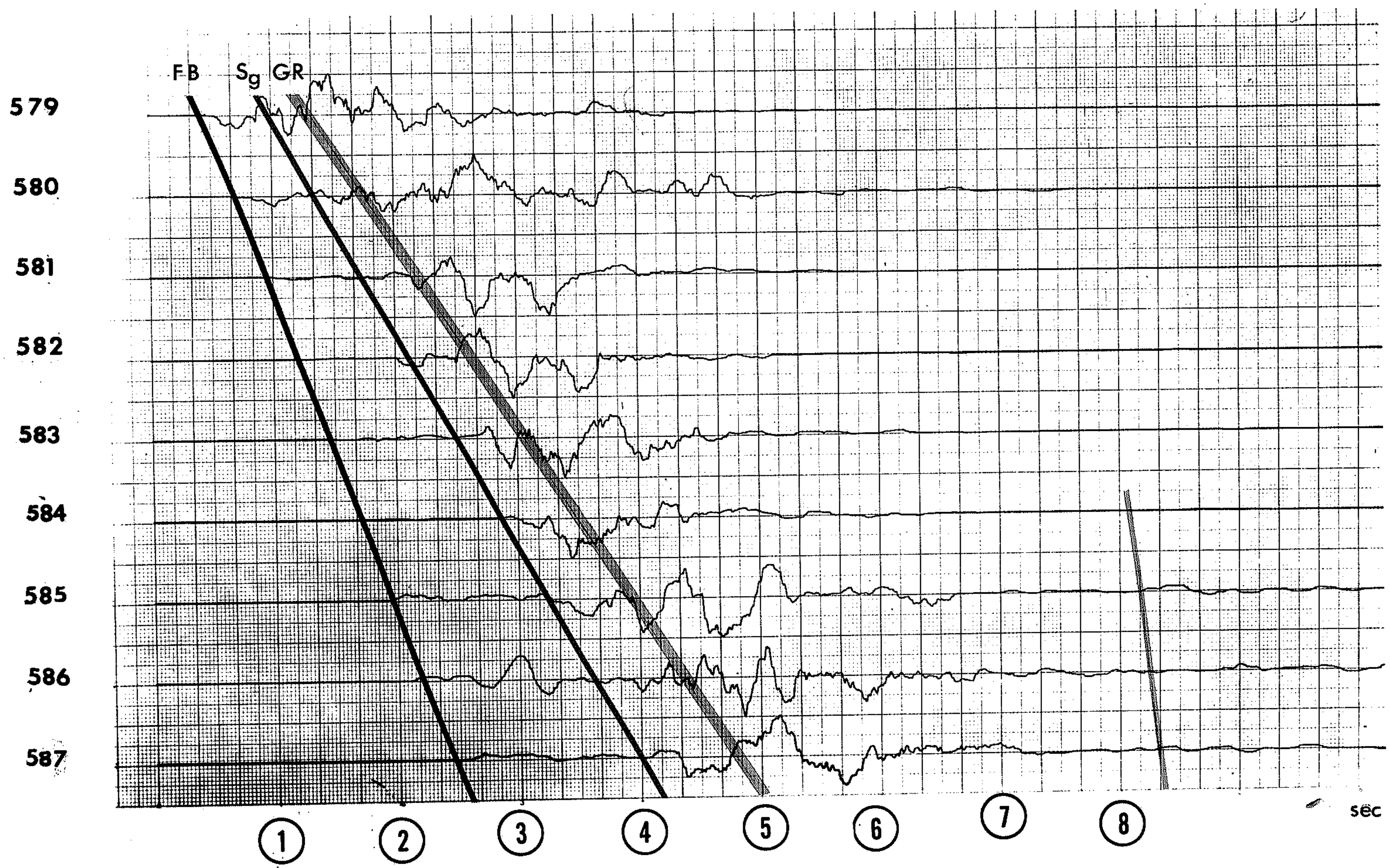


FIGURE 23. Multiple correlated seismic section.

the effect of noise suppression. Spieker (1961) points out that only carefully selected traces should be applied to make the technique more powerful.

Figure 24 displays the first part of the seismic section. The data presented here is from zero to the approximate arrival time of the shear wave on the individual trace. There are three sets of recognizable arrivals on this section after the first breaks. The first set of arrivals can be correlated from record 579 to 587. The second can be distinguished from detector number 8 on record 583 to the end of the section. The third set starts at trace number 12 of record 585 and it can be traced to the end of record 587. Although the travel time data is plotted on the time distance graph, because of the only one direction shooting, and only one single profile, no definite interpretation concerning the velocity and the nature of these data can be made.

One explanation, which is following here, is based only on the available limited amount of information. It should be emphasized here that the experiment was aimed for an investigation of arrivals from greater depth, therefore the detector spacing camera speed were set accordingly. Thus these factors cause further complications in the interpretation of the present set of later arrivals. The straight line least square best fit of the first break times provide velocity of 5.82 km/sec. This best fit

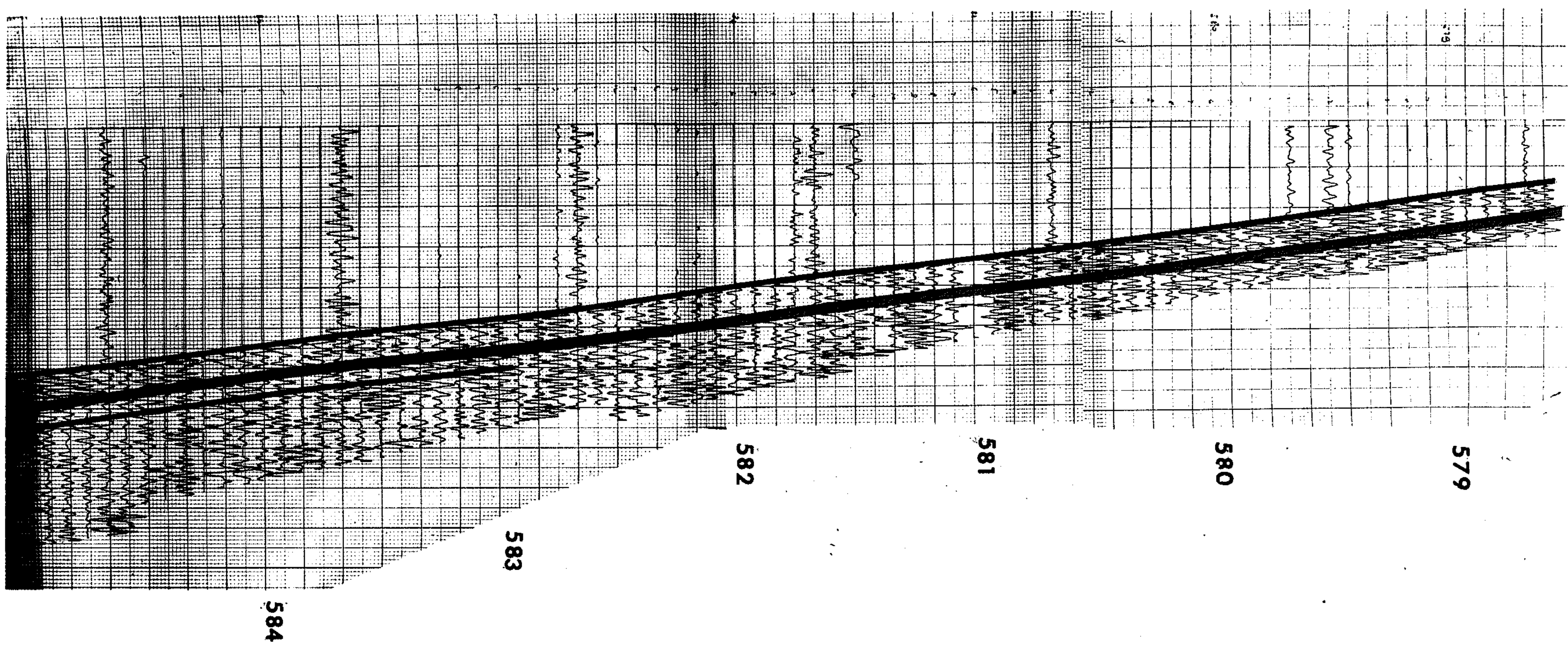
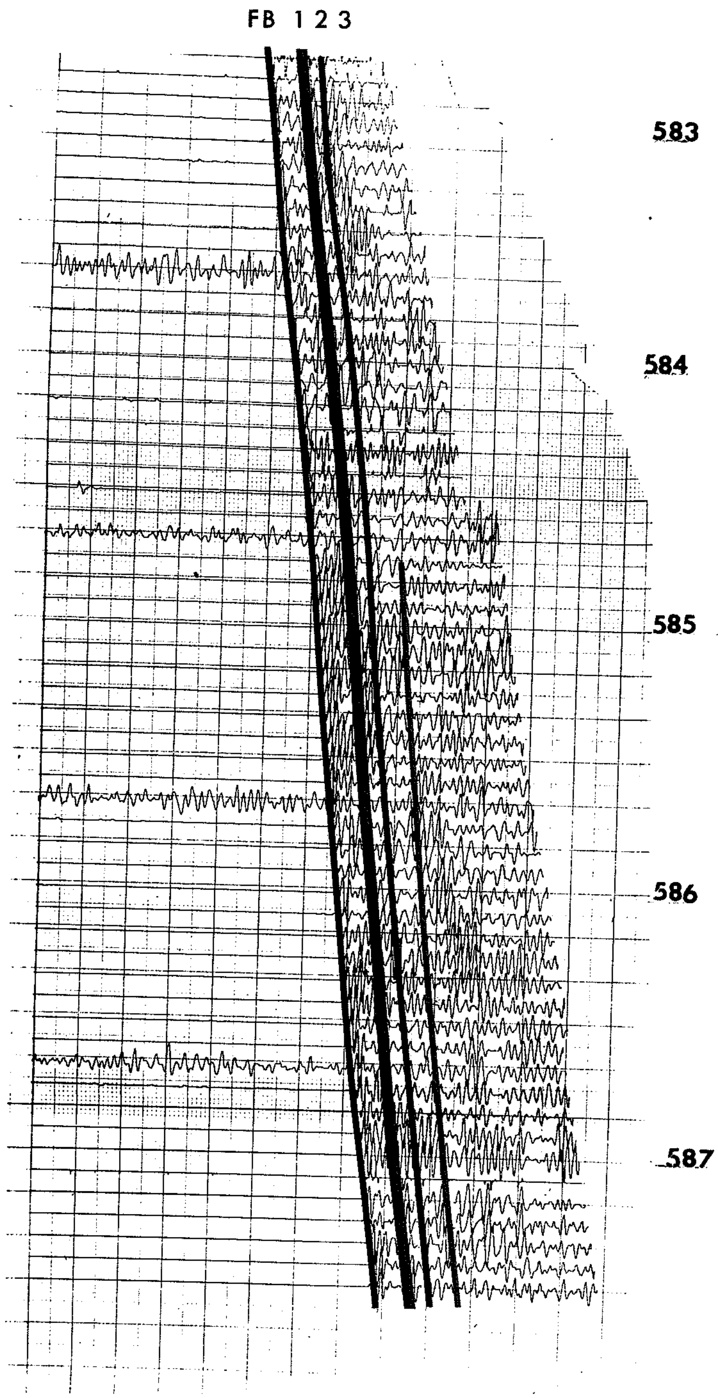


FIGURE 24. Detailed seismic section of vertical reflection survey.


FB 1 2 3
583
584
585
586
587

straight line intercepts the time axis at 0.055 sec. This indicates a weathering layer. Because the first detector is 0.180 km. from the shotpoint the estimate of this weathered layer was attempted by drawing a straight line on the time distance graph between the origin and the first point of the observed first break time. This crude approximation gives a velocity of 1.82 km/sec. which is very close to the velocity of propogation of seismic waves in glacial till or wet sand. Using the above mentioned intercept time depth calculations of the weathered layer was carried out using formula (Dobrin 1960, p. 73)

$$Z = \frac{T_i}{2} \frac{V_1 V_0}{\sqrt{V_1^2 - V_0^2}}$$

where

T_i = intercept time

V_0 = 1.82 km/sec.

V_1 = 5.82 km/sec.

These calculations indicate a depth of 0.0527 km. Examination of surface geological data in the area Davis (1951) indicate glacial drift cover around the shotpoint locality in the same order of magnitude.

The least square best fit of the arrival times just after the first breaks give velocity of 5.97 km/sec. considering linear fit. The intercept time is 0.3029 sec. Using this velocity and the intercept time a second layer with thickness of 3.47 km. and a total depth of 3.99km. can be computed. Applying this depth figure, the estimate of the critical point is around 16 km. Because these arrivals were observed far before this distance this fact would eliminate the possibility of recognizing this set of arrivals as refraction travel times from a shallow layer.

Considering reflections, the data was fitted to a $x^2 - t^2$ curve. The obtained velocity was 5.41 km/sec., This is a smaller value than the figure reached from the first break data. The decrease of velocity may indicate a downward dip of a layer south from the shotpoint. If it is assumed that the 5.82 km/sec. represents the velocity of the uppermost weathered section of the precambrian rocks and 6.05 km/sec. is the true velocity of upper crustal layer, then this geological condition would provide an interface of 1.43 km. close to the shotpoint and a figure of 7.37 km. at the end of the profile. These depth values were plotted on the crustal cross-section Figure 19 between 118 km. and 127.5 km. The above assumptions can be further extended by the interpretation of the XI arrivals from the continuous refraction survey. These data fit to a line segment of 5.84 km/sec. Depth calculations from these data were plotted between 95 km. and 117 km. It has to be pointed out that geographically the location of these data is approximately 3-4 km. north-east of the nearly-vertical reflection survey area.

The extent of the glacial till coverage around the shotpoint is not known exactly, therefore, no estimate of possible multiples can be made which could also be the origin of the later arrival sets on the records. The zone of 4 km. to approximately 8 km. from the shotpoint is interpreted by Davis (1951) as a shear zone of a fault which represents the southern end of the greenstone belt. The second and third set of arrivals on the vertical reflection profile show changes in amplitude and in frequency content and they are observed at distances which would indicate that these arrivals can be considered as diffraction events from the above fault zone.

The real significance of these observed later arrivals on the seismic section is that they cannot be explained with the bubble pulse phenomena. They seem to be related to the near surface geological anomalies. Thus they indicate that a modified version of the present technique could be a useful tool to deliniate certain geological contacts and structural anomalies on the Precambrian Shield.

Accuracy of the Crustal Section

The source of errors in crustal refraction surveys are not too clearly defined. Steinhart and Meyer (1961) devote considerable attention to this problem. They also point out that previous investigations, as for example

Zirbel (1954) show the effects of omission of surface layers, Hales and Sacks (1958) indicate the effect of omitting the intermediate layer, Gutenberg (1954) describes the effects of the low velocity layers, are all directed toward only one specific source of error. They felt that the application of Acton (1958) probability statements give a better understanding of the limits of the results. This would indicate that the model which provides the smallest uncertainty region with a high percentage of confidence limits is the best fit to the data. This approach was applied to the Lake Superior experiment by Smith et al (1966) but due to the unexpected large crustal structure in the area, the fitting of the data with the complete Acron's conditions could not be carried out.

As the above problem indicates, if the structural conditions in the crust are quite abrupt, even the profile shooting could lead to poor velocity determinations. The station pair method at the same time is multidirectional, therefore the effects of the structure on velocity determinations are minimized.

The one directional nature as well as the possible structure on the intermediate discontinuity eliminate the use of the continuous refraction data for velocity determination in the present case, but the wide angle reflection arrivals at the same time provide reliable velocity data because the points of reflection are located away from the structurally anomalous zone.

If no variations in velocities are expected, the other two factors which affect the depth calculations are the accuracy of the travel times, and the accuracy of the distance determination. The comparison of the results of the three described techniques for distance determinations has shown a fluctuation of ± .15 km. for a given site. The arrival times have error of ± 0.03 seconds. If these values are applied to the formulae which are used for depth calculations the maximum error is ± .65 km. in the determined depth. Considering an average depth of 20 km. the above fluctuation indicates a 3 % error.

Pakiser and Steinhart (1964) using information theory and channel capacity arrive at the conclusion that in the case of the signal to noise ratio of 2:1 the first arrivals have an error of ± 0.03 sec. but for later events they estimate time uncertainty of ± 0.2 sec. or more. The last figure was mainly built on the reasoning that the identification of the arrival depends on how it fits to the particular model. This problem may occur when the stations are a certain distance apart and jump correlation of the events is required. This is not the case for the present continuous profile. Pakiser and Steinhart claim that the channel capacity drops from 32 bits/sec. to 20 bits/sec. for later arrivals. According to their formula this drop of channel capacity represents a decrease of signal to noise ratio from two to one. These calculations represent only a single channel situation. If all twelve channels of the seismic system is considered, then this system represents redundancy of the transmitted information. There is no well developed theory which describes this situation but Goldman (1955) indicates that redundancy increases the reliability of the transmitted signal. The examination of the later arrivals on the seismic section will indicate identification uncertainties closer to ± 0.04 sec. than ± .2 sec. indicated by Pakiser and Steinhart. It is also easy to see that the signal to noise ratio is better than one.

Just as good correlation can be made with the later arrivals as with the first breaks. In the case of most arrivals 0.2 sec. represents one and a half cycles. The examination of the seismic sections indicate that correlation becomes impossible if it is attempted at such an interval left and right from the present picks.

The presently estimated 2-3% error is much smaller than the indicated structure. The described first order astronomical survey for distance determination as well as the application of the present generation digital recording systems would provide data with even less than the above error. With the advances of the digital processing the identification of arrivals does not depend on travel times alone, but other significant characteristics of the seismic event.

CHAPTER XI

CONCLUSION

The present recording system and the laboratory analog to digital conversion provides a smooth and reliable operation. Modifications which were described in the relevant sections would provide some improvement. However, the results of the present study indicate that the crustal seismic experiments require higher accuracy than the upper limits of this system. The investigation of later arrivals as well as reliable amplitude studies demands distortionless recording of very weak signals in a wide range of frequencies. The last generation of digital recording equipment, widely used by the exploration industries, has these qualities, and at the same time provides the data in a format which is ready for further processing.

The field operational procedures provided very significant results. It is shown that higher accuracy of depth determination may require sophisticated distance determination techniques. This is especially important in areas were significant structural changes occur in the crust. It is possible to combine refraction and wide angle reflection surveys with no change of technique and instrumentation. The combined technique provides double coverage with the cost of one operation. The combination of station pair, refraction and reflection survey procedures are necessary to obtain the best possible velocity and model conditions in the studied area.

The nearly-vertical reflection survey techniques in the Precambrian Shield require extensive experimentation. It is difficult to find good shotpoints for this work in the area of interest. Shallow lakes usually do not have favorable bottom conditions and it is difficult to control the energy for close shots. Because of the relatively small section of weathered layer, or the lack of it, energy sources other than explosives may provide sufficient energy for this type of work. All the successful crustal vertical reflection seismic experiments indicated that well designed detector arrays are necessary for observation of reliable data. This may require a completely new survey procedure on the Precambrian Shield.

Digital Processing is a necessity for significant crustal projects. To obtain a unique solution would require an understanding and identification of all the later arrivals. This can be achieved only with a well developed optimum filter system which cannot be applied without high speed large size computers. The problem of handling the seismic data and extracting from it the vital information in an efficient manner is just as great as that of interpreting and presenting results. The present study relied on 116 seismic records. If all the possible arrivals were examined there would have been 2990 data points to consider. In addition to this several playbacks and print-outs are made with different gains and filters. There is no way to eliminate some events and emphasize the others. During the course of the interpretation the interpreter must return to the previously studied sets and compare calculations or revise assumptions to find the best possible model. The solution of this problem is impossible without the computer. Although the present set of computer programs are able to carry out many of the necessary computations, a further automation is required to achieve an efficient production level. This would require a large set of subroutines which would compare partial results to the observed but not yet interpreted data. This would help to eliminate wrong assumptions at the early part of the interpretation.

The regional crustal survey provided structural maps of the Intermediate and Mohorovicic discontinuities. The technique applied here works very smoothly and provides enough details that locations of possible local crustal features can be delineated. It is an excellent reconnaissance technique to obtain a broad scale regional picture of an area.

The results of the continuous refraction profile exhibit a major fracture zone in the earth's crust. The apparent relationship of this feature to the surface geology could be very significant for explorational purposes. This type of local feature very likely exists in other parts of the continent. This study therefore provides that a completely new approach is required for further crustal investigations. The previously described reconnaissance survey must be followed with detailed studies where high density of observations are required to achieve unambiguous interpretation. The survey technique must employ both refraction and reflection methods. It is quite possible that the reflection techniques, as in oil exploration, will develop to be superior in providing details of crustal structure. The large offset distances of the refraction technique makes it more difficult to locate at strategic points. The refraction technique does not provide a good picture of the velocity conditions alone. It may not indicate low velocity zones or thinner high velocity layers, if the survey distances are not right for it. The application of the time term method alone can be very dangerous. O'Brien (1968), Hajnal (1969) pointed out that this technique displaces the structural relief quite substantially and can lead to erroneous depth figures, even though the velocities of the different interpretation techniques are the same.

The continuous correlation of the events, and the linearity of the observed data strongly support the simple layered model continental crust criteria. Until visual evidences like drill core smaples will be available down to the Mohorovicic discontinuity, it will always be possible however to create a velocity gradient which can explain most of the observed arrivals. But this concept is alien to all the other observed geophysical data. As it was pointed out in the section on velocity determination, the field observations do not follow the predicted gradient values. The observed gravity data Innes et al (1967), Weber and Goodacre (1969) cannot be explained by the single layer model. When the same seismic and gravity data was reinterpreted by Hall (1969) and Hajnal (1969) in the view of a layered model, the results of the two studies showed excellent correlation. Similar problems exist in the comparison of magnetic and thermal survey data to the single layer continental model Francis (1968).

The nearly vertical reflection experiment did not reach the stage that a definite final conclusion can be made. The 6:1 stacked data indicate very encouraging results. The multiple correlation traces are not as definite. Spieker (1961) compares the two methods and feels that the stacking improves the amplitude $\sqrt{n}$ times where n is the number of traces summed. This report also pointed out that for small values of signal to noise ratio the stacking provides better improvement than the other method considered. The instrumentation, especially the detector arrays, require drastic improvement. New energy sources should be tried, mainly in the cases of very close shot-observation distances. The arrival from the shallow zone of the crust indicates that a well designed reflection method can be used for exploration purposes on the Precambrian Shield. The experiment also pointed out that a detailed understanding of the close surface conditions are necessary if a crustal near-vertical experiment is attempted in a given area of the Precambrian Shield.

BIBLIOGRAPHY

BIBLIOGRAPHY

Acton, F. S.
1959 Analysis of Straight-Line Data, Wiley, New York, 267 pp.

Barnhard, P.
1967 Signal Strength of Marine Seismograph Explosives, Geophysics, v. 33, p. 827.

Barr, K. G.
1967 Upper Mantle Structure in Canada from Seismic Observations Using Chemical Explosions, Can. J. Earth Sci., v. 4, no. 5, p. 961.

Beliayevsky, N. A., A. A. Borisov, Schukin Volvovsky and K. Yu.
1968 Transcontinental Crustal Sections of the U.S.S.R., and Adjacent Areas, Can. J. Earth Sci., v. 5, p. 1067.

Beloussov, V. G., B. S. Volvovsky, I. S. Volvovsky and V. Z. Riaboi
1962 Experimental Investigation of the Recording of Deep Reflected Waves, Bull. Acad. Sci. U.S.S.R., Geophy. Ser., English Translation, no. 8.

Berry, M. T. and G. F. West
1966 An Interpretation of the First Arrival Data of the Lake Superior Experiment by Time-Term Method, Bull. Seis, Soc. of Am., v. 56, p. 141.

Bowker, A. H. and G. J. Libberman
1959 Engineering Statistics, Prentice Hall Inc., Englewood Cliffs, N. J., 585 pp.

Cale, R. H.
1948 Underwater Explosions, Dover Publications Inc., New York, 437 pp.

Clay, C. S. and P. A. Rona
1965 Studies of Seismic Reflections from Thin Layers on the Ocean Bottom in the Western North Atlantic, J. Geophys. Res., v. 70, no. 4, p. 855.

Clowes, R. M., E. R. Kanasewich and G. L. Cumming
1968 Deep Crustal Seismic Reflections at Near Vertical Incidence, Geophysics, v. 33, p. 441.

Cumming, G. L. and E. R. Kanasewich
1966 Crustal Structure in Western Canada, Project Vela Uniform, Contract No. AE 19 (628)-2835, Project No. 8652, Tosh No. 865 202, ARPA order no. 292, 126 pp.

Davies, J. F.
1950 Geology of Wanipigow River Area, Rice Lake Mining Division, Publication 49-3, Department of Mines and Natural Resources, Mines Branch, Province of Manitoba.

________.
1951 Geology of the Manigotagan River Area, Rice Lake Mining Division, Publication 50-2, Department of Mines and Natural Resources, Mines Branch, Province of Manitoba

________.
1953 Geology and Gold Deposits of Southern Rice Lake Area, Publication 52-1, Department of Mines and Natural Resources, Mines Branch, Province of Manitoba.

________, B. B. Bannatyne, G. S. Barry, and H. R. McCabe.
1962 Geology and Mineral Resources of Manitoba, Department of Mines and Natural Resources, Mines Branch, Province of Manitoba.

Dix, C. H.
1955 Seismic Velocities from Surface Measurements, Geophysics, v. 20, no. 1, p. 68.

________.
1965 Reflection Seismic Crustal Studies, Geophysics, v. 30, no. 6, p. 1068.

Dobrin, B. M.
1960 Introduction to Geophysical Prospecting, McGraw-Hill, 446 pp.

Dragasevic, T. and B. Andric
1968 Deep Seismic Sounding of the Earth's Crust in the Area of the Dinarides and the Adriatic Sea, Geophys. Prosp., v. 16, p. 54.

Durbaum, H.
1954 Zur Bestimmung von Wellengeschwindigkeiten aus Reflexion Seismischen Messungen, Geophys. Prosp., v. 2, p. 125.

Embree, P., I. B. Burg and M. M. Backus
1963 Wide Band Filtering - the "pie-slice" process, Geophysics, v. 28, p. 948.

Ermanovics, I. F.
1968 Hecla-Carroll Lake Map Area Manitoba-Ontario 62P (East-Half) 52M (West-Half), Project 680020, Report of Activities, Part A, Paper 69-1, Geol. Surv. Can.

Fail, I. P. and G. Grau
1963 Les Filtres en Eventail, Geophys. Prosp, v. 11, p. 131.

Foster, M. R., R. L. Sengbush and R. I. Watson
1964 Design of Sub-optimum Filter System for Multiface Seismic Data Processing, Geophys. Prosp., v. 12, p. 173.

Galbraith, J. N. and R. A. Wiggins
1968 Characteristics of Optimum Multichannel Stacking Filters, Geophysics, v. 33, p. 36.

German Research Group for the Explosion Seismology
1964 Crustal Structure in Western Germany, Z. Geophys, v. 30, p. 209.

Goldman, S.
1955 Information Theory, Prentice Hall Inc., New York 385 pp.

Grant, F. S. and G. E. West
1965 Interpretation Theory in Applied Geophysics, McGraw Hill, 583 pp.

Gurley Engineering Instruments
1968 Gurley Ephemeris, W. & L. E. Gurley, Troy, New York, 94 pp.

Gutenberg, B.
1954 Effects of Low Velocity Layers, Geophys. Pura Appl., p. 1.

Hajnal, Z.
1969 A Two-Layer Model for the Earth's Crust under Hudson Bay, Geol. Surv. Can., Paper 68-53, p. 326.

Hales, A. L. and F. S. Sacks
1958 Evidence of an Intermediate Layer from Crustal Structure Studies in the Eastern Tranvaal, Geophys. Jour., v. 2, p. 15.

Hall, D. H.
1964 Converted Waves in Refraction Surveys over Markers with Variable Depth, Geophysics, v. 29, p. 733.

________.
1966 The Converted Wave Method of Seismic Refraction Interpretation, Can. J. Earth Sci., v. 3.

________.
1969 A Seismic Isostatic Analysis of Crustal Data from Hudson Bay, Geol. Surv. Can., Paper 68-53, p. 337.

________ and W. C. Brisbin
1961 A Study of the Mohorovicic Discontinuity near Flin Flon, Manitoba;Final Report, Geophysics Research Directorate, Air Force, Cambridge Research Laboratories, U. S. Dept. of Commerce, Officeoof Technical Services, Washington 25, D. C.

________, and ________.
1965 Crustal Structure from Converted Head Waves in Central Western Manitoba, Geophysics, v. 30, p. 1053.

________ and Z. Hajnal
1969 Crustal Structure of North Western Ontario: Refraction Seismology, Can. J. Earth Sci., v. 6, no. 1, p.81.

________ and ________.
1970 In preparation.

Heiland, C. A.
1963 Geophysical Exploration, Hafner, 1013 pp.

Herrin, E. T.
1966 Travel-Time Anomalies and Structure of the Upper Mantle (Abstract), Trans. Am. Geophys. Union, v. 47, no. 1.

Hobson, G. D.
1967a Hudson Bay Crustal Seismic Experiment: Time and Distance Data, Can. J. Earth Sci., v. 4, no. 5, p. 879.

________, A. Overton, D. N. Clay and W. Thatcher
1967 Crustal Structure under Hudson Bay, Can. J. Earth Sci., v. 4, no. 5, p. 929.

Hunter, F. A. and R. F. Mereu
1967 The Crust of the Earth under Hudson Bay, Can. J. Earth Sci., v. 4, no. 5, p. 949.

Innes, M. J., A. K. Goodacre, J. R. Weber and R. K. McConnell
1967 Structural Implications of the Gravity Field in Hudson Bay and Vicinity, Can. J. Earth Sci., v. 4, no. 5, p. 977.

Iyer, H. M., L. C. Pakiser, D. J. Stuart and D. H. Warren
1969 Project Early Rise; Probing of the Upper Mantle, J. Geophys. Res., v. 74, p. 4409.

Jakosky, J. J.
1957 Exploration Geophysics, Trija Pub. Co., Calif., 1195 pp.

James, D. E. and J. S. Steinhart
1966 Structure Beneath Continents: A Critical Review of Explosion Studies 1960-1965, Geophysical Monograph No. 10, Am. Geophys. Union, Washington, D. C.

The Japanese Research Group for Explosion Seismology
1951-1959 Tokyo Univ. Earthquake Inst. Bull., v. 29 - v. 37.

Jeffreys, H.
1926a Camb. Phil. Soc. Proc., v. 23, p. 472.

________.
1926b On Near Earthquakes Monthly Notices, Roy. Astron. Soc. Geophys. Suppl., v. 1.

Johnston, A. W.
1938 Carroll Lake Sheet (West-Half) Manitoba and Ontario; Lat. 51°00' to 52°00', long. 95°00' to 96°00', Geol. Surv. Canada, Map 428A.

1938 Hecla Sheet (East-Half), Lat. 51°00' to 52°00', long. 96°00' to 97°00',Geol. Surv. Canada, Map 429A.

Junger, A.
1951 Deep Reflections in Big Horn Country, Montana, Geophysics, v. 16, no. 3, p. 499.

Kanasewich, E. R.
1966 Deep Crustal Structure under the Plains and Rocky Mountain, Can. J. Earth Sci., v. 3, p. 937.

Kanasewich, E. R., R. M. Clowes and C. H. Claughan
1968 A Buried Precambrian Rift in Western Canada, Department of Physics, Univ. of Alta., 30 pp.

________ and G. L. Cumming
1965 Near Vertical Incidence Seismic Reflections from the Conrad Discontinuity, J. Geophys. Res., v. 70, p. 3441.

Lanczos, C.
1956 Applied Analysis, Prentice Hall Inc., 539 pp.

Laster, S. J., M. M. Backus and R. Schell
1967 Analog Modes Studies of the Simple Refraction Problem; Seismic Refraction Prospecting, Society of Exploration Geophysicists, 604 pp.

________ and A. F. Linvillie
1968 Preferential Excitation of Refracting Interfaces by use of Source Array, Geophysics, v. 33, p. 49.

Lee, Y. W.
1966 Statistical Theory of Communication, John Wiley and Sons, Inc., New York, 509 pp.

Le Pichon, X., J. Ewing and R. E. Houtz
1968 Deep Sea Sediment Velocity Determination Made While Reflection Profiling, J. Geophys. Res., v. 73, no. 8, p. 2597.

Mereu, R. F. and J. A. Hunter
1969 Crustal and Upper Mantle Structure under the Canadian Shield from Project Early Rise Data, Bull. Seis. Soc. Amer., v. 59, no. 1, p. 147.

Muskat, M.
1933 The Theory of Refraction Shooting, Physics, v. 4, p. 14.

Nettleton, L. L.
1940 Geophysical Prospecting for Oil, McGraw-Hill, 444 pp.

O'Brien, P. N. S.
1959 Seismic Energy from Explosions, Geophys. J., v. 3, p. 29.

________. 1967 The Efficient Use of Large Charges; Seismic Refraction Prospecting, S.E.G., 604 pp.

________. 1968 Lake Superior Crustal Structure, A Reinterpretation of the 1963 Seismic Experiment, J. Geophys. Res. v. 73, p. 2669.

Ormsky, J. F. A.
1961 Design of Numerical Filters with Applications to Missile Data Processing, J. Assoc. Computing Mach., v. 8, no. 4, p. 440.

Pakiser, L. C. and J. S. Steinhart
1964 Explosion Seismology in the Western Hemisphere, Research in Geophysics, v. 2, M.I.T. Press, p. 123.

Papoulis, A.
1962 The Fourier Integral and its Applications, McGraw-Hill, New York, 318 pp.

________. 1966 Error Analysis in Sampling Theory, Proceedings of the I.E.E.E., v. 54, no. 7, p. 947.

Pierou, H. and O. Rosenbach
1960 Comparitive Considerations on the Energy Content of Seismic Waves in Central and Linear Pattern Shooting, Geophys. Prosp., v. 8, p. 164.

Robertson, H. H.
1965 Approximate Design of Digital Filters, Technometrics, v. 7, no. 3, p. 387.

Robinson, E. A.
1966 Collection of Fortran II PRograms for Filtering and Spectral Analysis of Single Channel Time Series, Geophys. Prosp., v. 14, supplement no. 1, p. 32.

________. 1967a Multichannel Time Series Analysis with Digital Computer Programs, Holden Ray, San Francisco, 298 pp.

________. 1967b Statistical Communication and Detection with Special Reference to Digital Data Processing of Radar and Seismic Signals, Hafner Pub., New York, 362 pp.

Ruffman, A. and M. J. Keen
1967 A Time-Term Analysis of the First Arrival Data from the Seismic Experiment in Hudson Bay, Can. J. Earth Sci., v. 4, p. 901.

Ryall, A.
1964 Improvement of Array Seismic Recordings by Digital P Processing, Bull of Seis. Soc. Am., v. 54, p. 277.

Scheidegger, A. E. and P. L. Willmore
1957 The use of a Least Squares Method for the Interpretation of Data from Seismic Surveys, Geophysics, v. 22, no. 1, p. 9.

Simmons, G. and A. Nur
1968 Granites: Relations of Properties In Situ to Laboratory Measurements, Science, p. 789.

Singleton, R. C.
1967 A Method for Computing the Fast Fourier Transform with Auxiliary Memory and Limited High Speed Storage, I.E.E.E., Trans. on Audio and Electro-acoustics, AU-15.

Slotnick, M. M.
1959 Lessons in Seismic Computing, Soc. of Exp. Geophys., 268 pp.

Smilk, F. T., J. S. Steinhart and L. T. Aldrich
1966 Lake Superior Crustal Structure, J. Geophys. Res., v. 71, p. 1141.

Spieker, L. J.
1961 Project Manager, Seismometer Array and Data Processing Systems, Texas Instruments, Inc., Project Vela Univorm, AFTAC Project VT/077, Final Report.

Starkwell, C. H.
1968 Tectonic Map of Canada, No. 1251A, Geological Survey of Canada.

Steinhart, J. S.
1964 Lake Superior Seismic Experiment: Shots and Travel Times, J. Geophys. Res., v. 69, p. 5535.

________, R. Green, T. Asoda, B. Rodriguez, L. T. Aldrich and M. A. Tuve
1962 The Earth's Crust Seismic Studies; Annual Report of the Director of the Department of Terrestial Magnetism, Carnegie Institute of Washington.

_______ and R. P. Meyer
1961 Explosion Studies of Continental Structure, Carnegie Institute of Washington, Publication 622, 409 pp.

Stewart, S. W.
1968 Crustal Structure in Missouri by Seismic Refraction Methods, Bull. Seis. Soc. of Am., v. 58, p. 291.

Subbotin, S. I., D. Prosen, K. Posgay, E. Mituch, and T. Dragasevic.
1968 Junction of Deep Structures of the Carpatho-Balkan Regions with those of the Black and Adriatic Seas, Can. J. Earth Sci., v. 5, p. 1027.

Tucker, P. M., J. A. Westphal, R. D. Lynn, J. J. Roark and C. H. Dix.
1960 Earth Crust Measurements in Oklahoma, Proc. Geophys. Soc., Tulsa, v. 7, p. 25.

Warren, D. H.
1969 A Seismic Refraction Survey of Crustal Structure in Central Arizona, Geol. Soc. of Am. Bull., v. 80, p. 257.

Weber, J. R. and A. K. Goodacre
1969 An Analysis of the Crust-Mantle Boundary in Hudson Bay from Gravity and Seismic Observations, Geol. Surv. Can. Paper 68-53, p. 270.

Weston, P. E.
1960 Underwater Explosion as Acoustic Sources, Proc. Phys. Soc., v. 76, p. 233.

Whittlesey, J. R.
1964 A Rapid Method for Digital Filtering, Communication of the ACM, v. 7, no. 9, p. 552.

Widess, M. B. and G. L. Taylor
1959 Seismic Reflections from Layering within the Precambrian Basement Complex, Oklahoma, Geophysics, v. 24, no. 3, p. 417.

Willmore, P. L. and A. M. Bancroff
1960 The Time-Term Approach to Refraction Seismology, Geophys. J., v. 3, p. 419.

Wood, L. C.
1968 A Review of Digital Pass Filtering, Review of Geophysics, v. 6, no. 1, p. 73.

Zirbel, N. N.
1954 Comparison of Breakpoint and Time Intercept Methods in Refraction Calculations, Geophysics, v. 19, no. 4, p. 716.

APPENDIX - A

PROGRAM DESCRIPTION AND LISTING

PROGRAM: BINBIN

A. IDENTIFICATION

Title: Binary to binary conversion

Programer: D. R. Sprague

Date: September 1968

Language: COBOL

B. PURPOSE

To convert a 12 bit signed binary number on 7 track tape to a 16 bit signed binary number on 9 track tape.

C. USAGE

1. Operational Procedure: Only one program, no subroutines are required. Three optional features

   a. conversion

   b. conversion and print out of the converted tape

   c. print out only of previous conversion

2. Parameters: Must be provided on computer card.

   Column 1: 1 = convert only

   2 = convert and print out

   3 = print out only

   Column 2-4: Number of blocks of data to be printed out (999 maximum).

   Column 5-6: Number of multiplexor channel used (16 maximum).

3. Space Requirement: 104 K
4. Temporary Storage Required: none
5. Printout: optional
6. Input Tape: 7 track seismic data
7. Output Tape: 9 track seismic data
8. Time: 0.005 seconds per one 12 channel digital block.
9. Reference: none

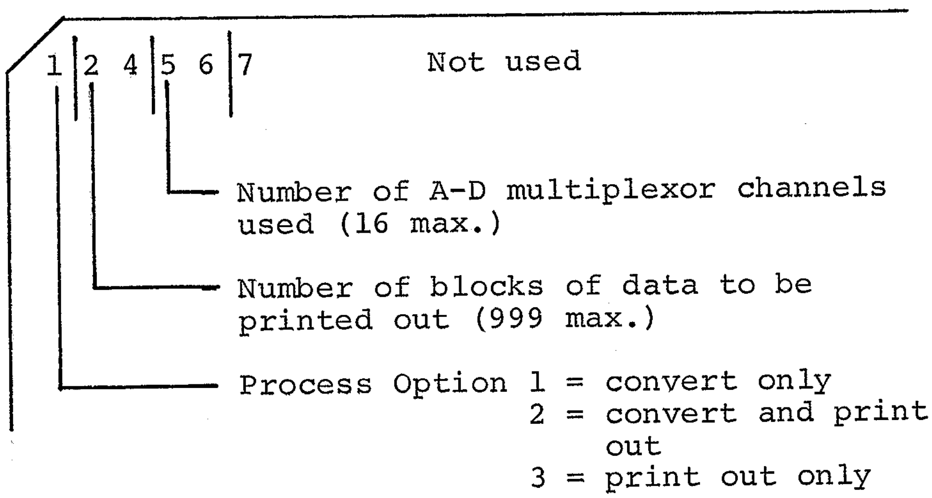
BINBIN PROGRAM DESCRIPTION

The program "BINBIN" will convert a 12 bit signed binary number on 7 track tape to a 16 bit signed binary number on 9 track tape. The 12 bit number is recorded as an 11 bit magnitude plus a sign designated by the high order twelfth bit while the 16 bit number is recorded in 2's complement notation. Depending upon the options chosen, the "BINBIN" program will do one of these three things: it will convert a 7 track binary tape to a 9 track binary tape, it will make the same conversion and then print out the converted tape, or it will simply print out a 9 track binary tape that has been previously converted. The binary data on the 7 track tape was generated by an A-D converter Model supplied by Radiation Incorporated of Melbourne, Florida. Two tape characters are required to make one 12 bit binary number and there are 2404 characters or 1202 numbers in each block of the 7 track tape. The "BINBIN" program reads in a block of this data, reformats the first character as the low order 6 bits of a 16 bit binary number and reformats the second character as the seventh to eleventh bit in the converted number. The sign of the 12 bit number (that is, the twelfth bit) is tested and if the number is negative the sign bit is reset to zero and the converted number multiplied by minus one to put it in 2's complement notation for standard recording in the IBM 9 track format.

The printed output displays the record number and the block number of the input data and the data itself. Since the data was generated by the digitizer working with a 16 channel multiplexor, up to 16 strings of data corresponding to each multiplexor channel can be generated. The number of channels of the multiplexor which were used in the original recording of data is indicated on a parameter control card which in turn causes the output format to be columns of numbers corresponding to the numbers of the multiplexor channels used. In displaying the converted data, it is possible that only a few blocks of data rather than the entire record is desired. This is especially desirable during debug stages to sample the nature of the data being obtained. A variable number of blocks may be specified to be printed out with the upper limit being 999. The number of blocks to be displayed is defined in the parameter control card.

Since considerable bit manipulation is being done, this program is highly dependent upon the IBM 360 system structure and conventions. It is further dependent upon the format and the conventions of the device which is creating the binary input tape.

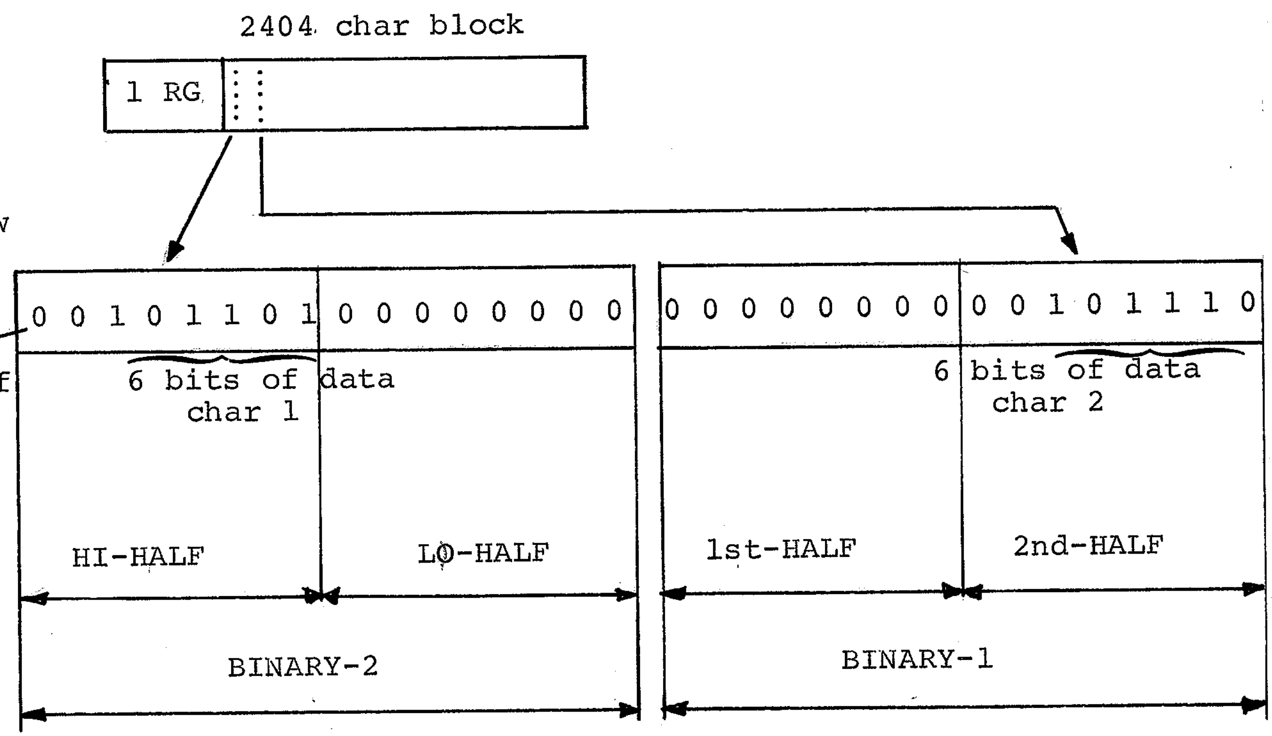
Parameter Control Card (all fields are numeric-no. blanks)



ASSUME the number expressed as two characters on the 7-track tape is: 101101101110 which is -878 in "magnitude plus sign" convention.

1. READ 7-TRACK TAPE

First character goes to high order byte of field called BINARY-2 and the second character goes to the low order byte of the field called BINARY-1.



2. Shift contents of BINARY-2 right, 2 bits by dividing BINARY-2 by 4.

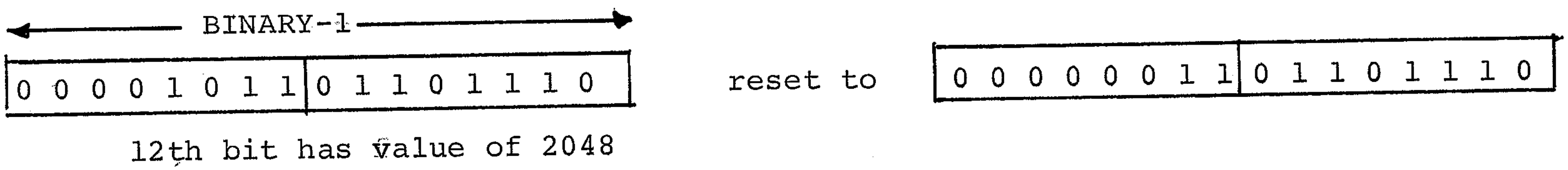
⟨BINARY -2⟩ /4 | 0 0 0 0 1 0 1 1 | 0 1 0 0 0 0 0 0 |

3. Add contents of BINARY-2 to contents of BINARY-1 to obtain the 16 bit "equivalent" of the input number.

⟨BINARY-1 + BINARY-2/4⟩ | 0 0 0 0 1 0 1 1 0 | 1 1 0 1 1 1 0 |

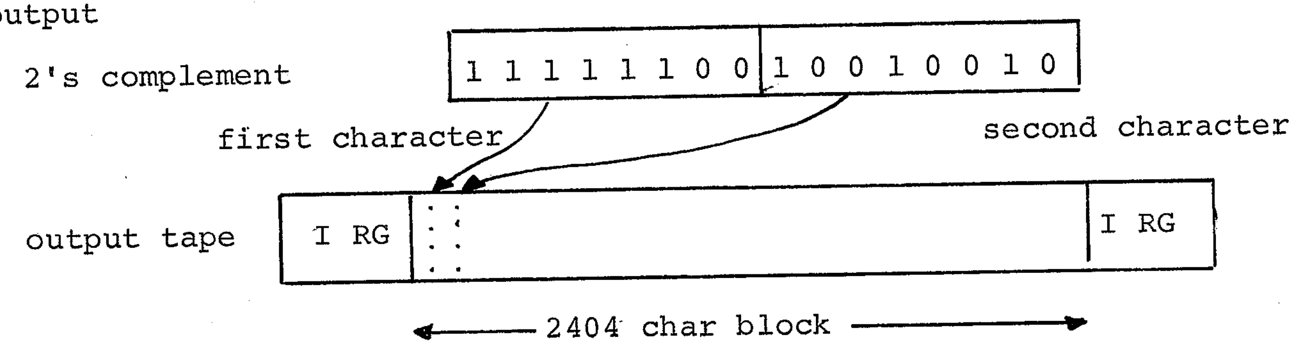
BINARY-1

4.



If the digitized input data is negative, the 12th bit of BINARY-1 will now be a "1" and therefore BINARY-1 will be greater than 2047. Reset 12th bit to "0" by subtracting 2048 from BINARY-1, if required, and multiply BINARY-1 by -1 to get 2's complement notation for writing on 9 track tape.

5. Write output



```
IDENTIFICATION DIVISION.
PROGRAM-ID. 'BINBIN'.
AUTHOR.  D.R.SPRACUE.
DATE-WRITTEN. NOV.15,1967.
DATE-COMPILED. JAN  7,1970
REMARKS. THIS PROGRAM CONVERTS A 12-BIT SIGNED BINARY NUMBER ON
         7-TRACK TAPE TO A 16-BIT SIGNED BINARY NUMBER ON 9-TRACK
ENVIRONMENT DIVISION.
CONFIGURATION SECTION.
SOURCE-COMPUTER. IBM-360 H65.
OBJECT-COMPUTER. IBM-360 H65.
INPUT-OUTPUT SECTION.
FILE-CONTROL.
    SELECT OCT-TAPE ASSIGN TO 'TAPEIN' UTILITY 2400 UNIT, RESERVE
        1 ALTERNATE AREA.
    SELECT HEX-TAPE ASSIGN TO 'TAPEOUT' UTILITY 2400 UNIT
        RESERVE 1 ALTERNATE AREA.
    SELECT PRINTER ASSIGN TO 'SYSOUT' UNIT-RECORD 1403 UNIT.
DATA DIVISION.
FILE SECTION.
FD  OCT-TAPE LABEL RECORD IS OMITTED, RECORDING MODE IS F,
        BLOCK CONTAINS 2404 CHARACTERS, DATA RECORD IS REC-IN.
01  REC-IN.
    02  IN-GUTS                                 PICTURE X(2404).
FD  HEX-TAPE LABEL RECORD IS STANDARD, RECORDING MODE IS F,
        BLOCK CONTAINS 2404 CHARACTERS, DATA RECORD IS REC-OUT.
01  REC-OUT.
    02  OUT-GUTS                                PICTURE X(2404).
FD  PRINTER  DATA RECORDS ARE LINE-OUT, TITLE-1
        LABEL RECORD IS OMITTED, RECORDING MODE IS F.
01  LINE-OUT.
    02  FILLER                                  PICTURE X.
    02  NUMBER-FLD   OCCURS 16 TIMES            PICTURE -(7)9.
    02  FILLER                                  PICTURE X(15).
01  TITLE-1.
    02  FILLER                                  PICTURE X.
    02  NAME-1                                  PICTURE X(135).
WORKING-STORAGE SECTION.
77  X       COMPUTATIONAL   VALUE 0             PICTURE S9999.
77  Y       COMPUTATIONAL   VALUE 0             PICTURE S9999.
77  Z       COMPUTATIONAL   VALUE 0             PICTURE S9999.
77  LINE-CNT                                    PICTURE S999.
01  OPTIONS.
    02  BRANCH-OPT                              PICTURE 9.
    02  BLK-CNT-OPT                             PICTURE 999.
    02  CHANNEL-OPT                             PICTURE 99.
01  WORK-IN.
    02  IN-CHAR      OCCURS 2404 TIMES          PICTURE X.
01  WORK-OUT.
    02  OUT-CHAR     OCCURS 1202 TIMES
            USAGE IS COMPUTATIONAL              PICTURE S9999.
01  RECEIVES.
    02  HOLD-ON.
        03  1ST-HALF                            PICTURE X.
        03  2ND-HALF                            PICTURE X.
    02  BINARY-1 REDEFINES HOLD-ON
                  USAGE IS COMPUTATIONAL        PICTURE S9999.
```

```
           02  SHIFTER.
                03  HI-HALF                             PICTURE X.
                03  LO-HALF                             PICTURE X.
           02  BINARY-2 REDEFINES SHIFTER
                         USAGE IS COMPUTATIONAL         PICTURE S9999.
       01  BLOCK-CNTR.
           02  FILLER        VALUE 'RUN NO. '           PICTURE X(8).
           02  R-CNTR                                   PICTURE ZZ9.
           02  FILLER    VALUE SPACE                    PICTURE X(8).
           02  FILLER    VALUE 'BLOCK NO. '             PICTURE X(10).
           02  B-CNTR                                   PICTURE ZZZ9.
       PROCEDURE DIVISION.
       INITIALIZE.
           ACCEPT OPTIONS.
           GO TO READ-IN, WRITE-READ, READ-BACK DEPENDING ON BRANCH-OPT.
       READ-IN.
           OPEN INPUT OCT-TAPE, OUTPUT HEX-TAPE.
       READ-IT.
           READ OCT-TAPE INTO WORK-IN AT END GO TO EOF-7T.
           MOVE 0 TO Z.
           MOVE -1 TO X. MOVE 0 TO Y.
           PERFORM CONV-RTN 1202 TIMES.
           WRITE REC-OUT FROM WORK-OUT.
           GO TO READ-IT.
       CONV-RTN.
           ADD 2 TO X.   ADD 2 TO Y.   ADD 1 TO Z.
           MOVE 0 TO BINARY-1, BINARY-2.
           MOVE IN-CHAR (Y) TO 2ND-HALF.
           MOVE IN-CHAR (X) TO HI-HALF.
           COMPUTE BINARY-1 = BINARY-1 + (BINARY-2 / 4).
           IF BINARY-1 NOT < 2048, COMPUTE BINARY-1 = -1 * (BINARY-1
               - 2048).
           MOVE BINARY-1 TO OUT-CHAR (Z).
       EOF-7T.
           CLOSE OCT-TAPE, HEX-TAPE.
       SWITCH-1.
           GO TO CLOSE-OUT.
       WRITE-READ.
           ALTER SWITCH-1 TO PROCEED TO READ-BACK.
           GO TO READ-IN.
       READ-BACK.
           OPEN INPUT HEX-TAPE, OUTPUT PRINTER.
           MOVE 1 TO Y.
       GO-ON.
           MOVE 2 TO Z.
           READ HEX-TAPE INTO WORK-OUT AT END GO TO CLOSE-2.
           MOVE OUT-CHAR (1) TO R-CNTR.
           MOVE OUT-CHAR (2) TO B-CNTR.
           MOVE BLOCK-CNTR TO NAME-1.
           WRITE TITLE-1 AFTER ADVANCING 0 LINES.
           MOVE SPACES TO TITLE-1.
           IF OUT-CHAR (2) > BLK-CNT-OPT GO TO CLOSE-2.
           PERFORM MOVE-PRINT UNTIL Z > 1201.
           GO TO GO-ON.
       CLOSE-2.
           CLOSE PRINTER, HEX-TAPE.
       CLOSE-OUT.
```

```
           STOP RUN.
       MOVE-PRINT.
           PERFORM LOAD-UP THRU E1 VARYING X FROM 1 BY 1
               UNTIL X > CHANNEL-OPT.
           WRITE LINE-OUT AFTER ADVANCING 1 LINES.
           MOVE SPACES TO LINE-OUT.
       LOAD-UP.
           ADD 1 TO Z.
           MOVE OUT-CHAR (Z) TO NUMBER-FLD (X).
           IF Z > 1201 THEN IF X = CHANNEL-OPT MOVE 1 TO Y
               ELSE COMPUTE Y = X + 1  COMPUTE X = CHANNEL-OPT + 1
               ELSE NEXT SENTENCE.
       E1.
           EXIT.
```

PROGRAM: BLOCK 50

A. IDENTIFICATION

Title: Printout and block number determination of digital seismic records

Programmer: Z. Hajnal

Date: October 1968

Language: FORTRAN IV

B. PURPOSE

To printout a given segment of the digital seismic record for the first break time recognition. To determine the total length of a digital seismic record.

C. USAGE

1. Operational Procedure: Main program calls subroutine ENT. This moves tape to the required record. Main program prints the necessary data. Subroutine INPUT counts the total number of digital blocks in the seismic record.

2. Parameters: A1 = the number of the first required seismic record

   L = total number of records examined

   MM = total number of blocks printed from a record

3. Space Requirement: 120 K

4. Temporary Storage Required: none

5. Printout: (100 x 12) matrix of integer numbers

6. Input Tape: 9 track

7. Output Tape: none

8. Time: 1.30 seconds per digital block

9. Reference: none

BLOCK 50 PROGRAM DESCRIPTION

This program consists of one main program and two subroutines. The program requires three input cards. The input parameters were indicated in the program write-up.

When all the data are given, subroutine ENT will start to read the tape and compare the record number of the first block with the given number A1. If they are not equal, the tape is read until equality of the two numbers are found. At this point the system moved the tape to the beginning of the record which will be examined. Now the main part of the program takes over. This will read and print in a (100, 12) matrix order as many blocks as required by the number MM. After this subroutine INPUT is called. This will continue to read the above record and to count the number of blocks in the record. When the subroutine senses that the record number is changed, the program prints out the total number of blocks read in the record. Now the action again returns to the main programs and it prints out the MM number of blocks in the new digital record. This procedure is continued until L number of records were read by the computer.

If no print out of blocks is required for some records, by making MM = 0 the process is immediately transferred to subroutine INPUT which will read the whole record and print out the total number of blocks in one record.

```
C MAIN PROGRAM PRINTS .171*MM SEC FROM EVRY DESIRED RECORD ON TAPE
C A1=NUMBER OF THE FIRST RECORD USED IN THE PROGRAM
C  L=NUMBER OF RECORDS WANTED TO BE PRINTED
C MM= NUMBER OF BLOCKS PRINTED IN ONE RECORD TO FIND FIRST BREAK
      INTEGER*2 A,B,A1
      INTEGER*2 T(12,100)
      A1=1
      L=1
      MM=50
      CALL ENT (A,B,T,A1)
      DO 60 M=1,L
      NN=0
      IF (MM.EQ.0) GO TO 800
      DO 55 K=1,MM
      READ (8,2) A,B,((T(I,J),I=1,12),J=1,100)
    2 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      NN=NN+1
      WRITE (6,17)A,B
   17 FORMAT (1H ,2I5)
      WRITE (6,4) ((T(I,J),I=1,12),J=1,100)
    4 FORMAT (1H ,12I5)
   55 CONTINUE
  800 CALL INPUT (A,B,T,A1,MM,NN)
      A1=A1+1
   60 CONTINUE
   70 CALL EXIT
      END
```

```
      SUBROUTINE ENT (A,B,T,A1)
      INTEGER*2 A,B,A1
      INTEGER*2 T(12,100)
      DO 58 MS=1,6000
      READ (8,12) A,B,((T(I,J),I=1,12),J=1,100)
   12 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      IF (A.EQ.A1) GO TO 65
   58 CONTINUE
   65 BACKSPACE 8
      RETURN
      END
```

```
      SUBROUTINE INPUT (A,B,T,A1,MM,NN)
      INTEGER*2 A,B,A1
      INTEGER*2 T(12,100)
      DO 18 K=1,8000
      READ (8,2) A,B, ((T(I,J),I=1,12),J=1,100)
    2 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      NN=NN+1
      WRITE (6,4) A,B
    4 FORMAT (1H ,2I5)
      IF (A.GT.A1) GO TO 48
   18 CONTINUE
   48 NN=NN-1
      WRITE (6,16) A,NN
   16 FORMAT (' ','RECORD NO.=',I2,'NUMBER OF BLOCKS=',I2)
      BACKSPACE 8
      RETURN
      END
```

PROGRAM: BAND-PASS

A. IDENTIFICATION

Title: Calculations of impulse response and frequency response of band-pass filter

Programmer: Z. Hajnal

Date: October 1968

Language: FORTRAN IV

B. PURPOSE

To compute weighting coefficients of a band-pass filter. To determine the frequency response of the computed band-pass filter.

C. USAGE

1. Operational Procedure: Subroutine FEJERT computes the smoothed coefficients. Subroutine BNDPSS computes the ideal band-pass filter coefficients. Subroutine FRERE computes the frequency response.

2. Parameters: N = total number of coefficients of one lobe plus one center lobe

   DT = sampling interval in seconds

   FL = low frequency cut off

   FH = high frequency cut off

   M = total number of points of frequency response

3. Space Requirement: 120 K
4. Temporary Storage Required: none
5. Printout: weighting coefficients and the frequency response
6. Input Tape: none
7. Output Tape: none
8. Time: 30.25 seconds for a 200 coefficient filter
9. Reference: Robinson (1966)

BAND-PASS PROGRAM DESCRIPTION

The program consists of a main part and the following subroutines:

1. Subroutine BNDPSS
2. Subroutine FEJERT
3. Subroutine FRERE

The input data are provided by a computer card. The format of these data is indicated by statement ninety in the main program.

Subroutine BNDPSS computes the filter weighting coefficients considering the ideal filter case. The program converts the data to a two sided filter.

Subroutine FEJERT determines the linear operators of the filter and corrects them with Fejer's formula. This also prepares a two-sided filter.

Subroutine FRERE calculates the frequency response of one lobe of a symmetric filter. The present program is set up to compute the response of both the ideal and corrected filter coefficients.

```
C THE PROGRAM COMPUTES THE COEFFICIENTS OF A BNDPSS FILTER  188
C SUBROUTINE FRERE COMPUTES THE FREQ. RESPONCE OF THE BNDPSS FILTER
C PROGRAM TO COMPARE FILTER COEFFICIENTS FOR TWO FREQUENCY BANDPASS
C FILTERS
      DIMENSION FILT(210),CT(210),FILT2(410),CC(410)
      READ(5,90) N,DT,FL,FH,M
   90 FORMAT(I4,F6.4,F3.1,F4.1,I4)
      NT=N+N-1
      WRITE(6,99)
   99 FORMAT(1H1,T58,'TEST PROGRAM FOR BANDPASS FILTERS',/,1H0,T58,
     1'BNDPSS',T78,'FEJERF')
      CALL BNDPSS(N,DT,FL,FH,FILT,FILT2)
      CALL FEJERF(N,DT,FL,FH,CT,CC)
      DO 200 I=1,NT
      WRITE (6,100) FILT2(I),CC(I)
  100 FORMAT(1H ,T58,F10.4,T78,F10.4)
  200 CONTINUE
      WRITE (6,101)
  101 FORMAT (1H1,T45,'FREQUENCY RESPONSE OF IDEAL BNDPSS FILTER')
      CALL FRERE (FILT,N,M,DT)
      WRITE (6,205)
  205 FORMAT (1H1,T45,'FREQUENCY RESPONSE OF FEJER FILTER')
      CALL FRERE (CT,N,M,DT)
      WRITE (6,110) N,DT,FL,FH,M
  110 FORMAT (1H ,T45,'INPUT PARAMETERS',/,1H ,'NO.OF W.COEFF=',I4,'DT=
     1',F10.5,'FL=',F10.5,'FH=',F10.5,'M=',I4)
      CALL EXIT
      END
```

```
      SUBROUTINE BNDPSS(N,DT,FL,FH,FILT,FILT2)
 SUBROUTINE BNDPSS COMPUTES A TWO-SIDED SYMMETRIC BANDPASS FILTER
 FOR SINGLE CHANNEL PROCESSING  (AUTH. ENDERS A. ROBINSON).
 FOR INPUT PARAMETERS SEE FESERF.
      DIMENSION FILT(210),FILT2(410)
      FN=N
      CHK=FH*DT-0.5
      IF(CHK.GT.0.0) RETURN
      CHK=(FH-FL)-1.0/(DT*FN)
      IF(CHK.GE.0.0) GO TO 100
      FC=(FH+FL)/2.0
      WL=6.2831853*(FC*DT-0.5/FN)
      WH=6.2831853*(FC*DT+0.5/FN)
      GO TO 200
  100 WL=FL*DT*6.2831853
      WH=FH*DT*6.2831853
  200 FILT(1)=WH-WL
      DO 300 I=2,N
      FI=I-1
      FILT(I)= (SIN(WH*FI)-SIN(WL*FI))/FI
  300 CONTINUE
      DO 400 I=1,N
      FILT(I)=FILT(I)/3.14159265
  400 CONTINUE
      NN=N+1
      DO 600 I=1,N
      J=NN-I
  600 FILT2(I)=FILT(J)
      MM=N+N
      DO 601 L=1,N
      K=MM-L
      I=NN-L
  601 FILT2(K)=FILT(I)
      WRITE (6,204) (FILT2(L),L=1,99)
  204 FORMAT (1H ,10F10.7)
      RETURN
      END
```

```
      SUBROUTINE  FEJERF(N,DT,FL,FH,CT,CC)                                    190
C     SUBROUTINE FEJERF COMPUTES THE COEFFICIENTS OF A FINITE FEJER-WEIGHTED
C     DIFITAL BANDPASS FILTER FOR SINGLE CHANNEL PROCESSING
C     INPUT PARAMETERS ARE:  FH   HIGHCUT FREQUENCY (CPS)
C                            FL   LOWCUT FREQUENCY (CPS)
C                            DT   SAMPLE RATE (SECS)
C                            N    LENGTH OF FILTER OPERATOR
C     NOTE: FH-FL MUST BE POSITIVE AND GREATER THAN  1.0/DT*N,(N EVEN NO.)
      DIMENSION CT (210),CC(410)
      NZ=N
      X=6.2835853*FH*DT
      Y=6.2831853*FL*DT
      TV=1.0/FLOAT(NZ)
      CT(1)=X-Y
      DO 100 I=2,N
      TI=I-1
  100 CT(I)=(1.0-TV*TI)*(SIN(X*TI)-SIN(Y*TI))/TI
      DO 101 L=1,N
  101 CT(L)=CT(L)/3.14159365
      NN=N+1
      DO 200 I=1,N
      J=NN-I
  200 CC(I)=CT(J)
      MM=N+N
      DO 201 L=1,N
      K=MM-L
      I=NN-L
  201 CC(K)=CT(I)
      WRITE (6,203) (CC(I),I=1,99)
  203 FORMAT (1H ,10F10.7)
      RETURN
      END
```

```
      SUBROUTINE FRERE (CF,N,M,DT)
C     COMPUTES FREQUENCY RESPONSE OF SYMMETRIC BANDPASS FILTER
      DIMENSION CF(210),C(210),H(210),TF(210)
      FNQ=1./(2*0.00171)
      DF=FNQ/N
      DO 2 K=1,M
      C(K)=0.0
      TF(K)=DF*((K-1.)/5.)
      DO 4 I=2,N
      S=6.2831853*TF(K)*DT*I
    4 C(K)=C(K)+(COS(S))*CF(I)*2
      H(K)=CF(1)*2.+C(K)
    2 CONTINUE
      WRITE (6,7) (CF(KK),KK=1,N)
    7 FORMAT (1H ,T50,F7.5)
      WRITE (6,5)(TF(K),H(K),K=1,M)
    5 FORMAT (1H ,T50,'FREQ=',F8.3,'FREQRES=',F10.7)
      RETURN
      END
```

PROGRAM: CONVOLV

A. IDENTIFICATION

Title: Convolution of two time series

Programmer: Z. Hajnal

Date: November 1968

Language: FORTRAN IV

B. PURPOSE

To filter seismic data with a set of weighting coefficients

C. USAGE

1. Operational Procedure: Subroutine ENT moves the tape to the required record on the tape. Subroutine SUPUL locates the required portion of the record. Subroutine FOLD carries out the process of convolution.

2. Parameters: A1 = first record used for process

   L = number of records used in the process

   N = number of channels involved in the process

   LM = number of filter coefficients

   N3 = total number of digital blocks

processed per record

NC = number of channels per output

M = number of filtered output point per run of subroutine FOLD

ST = time delay in seconds for the filtering process from the beginning of the digital seismic record

C = amplification factor

3. Space Requirement: 120 K
4. Temporary Storage Required: none
5. Printout: time delay in seconds, record number, number of blocks per record.
6. Input Tape: 9 track containing seismic data
7. Output Tape: 9 track filtered data
8. Time: 13.20 seconds per digital block
9. Reference: none

CONVOLV PROGRAM DESCRIPTION

This program controls the digital filtering of any time series. It was designed for multichannel systems. The program requires that the filter operators are read in from punch cards and the data is fed from a nine track magnetic tape.

As the first step the main program determines from ST the number of digital blocks rejected from the beginning of the seismic record.

The application of subroutine ENT moves the tape to the first desired record. This subroutine was described in detail with program Block 50. The next subroutine SUPUL is called. This reads and rejects a certain number of blocks from the beginning of the digital record if this is requested by the input data ST.

The operation of these two subprograms moves the tape to the exact point where the filtering process can be initiated. The call of subroutine FOLD will start the convolution process. An attempt was made to improve the efficiency of the convolution operation by reading in as mcuh data in the core as the computer system can take without interruption of the general computer operation. At the present time five blocks of data are processed at one time.

This represents .855 sec. of seismic data per trace or M = 500 digital samples per trace.

The actual folded output is M + LM samples, where LM is the number of filter coefficients. To make the filtering process continuous, before the next five blocks is read in the core, the LM number of partially filtered samples are moved in the core to a location where they are easily accessible when the next set of data is processed.

The units of filtered data are written continuously on a disk or tape during the filtering process. For this setp the same format was applied as it was used for the writing of data to the nine track tape. This way only one input and output format is required for the entire digital processing.

Subroutine ZERO is also part of subroutine FOLD. This subprogram, which was taken from Robinson (1967b), prepares the core locations for the filtered output data.

In the present form program CONVOLV writes the processed data on a nine track tape. For plotting purposes this data may need slight modifications. If subroutine DAVE is incorporated with the program then the data can be adjusted for any type of plotting formats before it reached the final output. Because the format of plotting of seismic data is changing from one technique of interpretation to the other it was felt that it will be more efficient to locate the final output on a tape using a general format and when plotting is required this tape is read back and the data is prepared for the necessary plotting format. This last procedure can be carried out using the PLOTMOD program. This program was written to serve any of the plotting needs which may occur with seismic data.

```
C PROGRAM CONVOLVES BADPASS FILTER WITH SEISMIC DATA
C SUBRT.ENT.AND SUPUL MOVES THE TAPE TO ANY PART OF A WANTED RECORD
C THE PROGRAM RUNS THROUGH ANY NUMBER OF FILES ON TAPE
C       A1=FILE NO.THE NO.OF THE FIRST FILE USED
C       N = NO.OF TACES USED IN THE PROCESS
C       L=NO.OF RECORDS TO BE PROCESSED
C       MB = NO OF BLOCKS WHERE PROCESS START ON IDIVIDUAL FILE
C       BC = FILTER WEIGHING FACTORS
C       XC = CONVOLVED OUTPUT
C       LM = NUMBER OF FILTER COEFFECIENS
C       NC = NO.OF TRACES IN ONE OUTPUT RECORD
C       MC = NO.OF DATA POINT PER OUTPUT TRACE
C       N3=NO.OF (12,500) BLOCKS PROCESSED PER RECORD
C      C= CONSTANT MULTIPLIER FOR AMPLIFICATION BEFOR FILTERING
      INTEGER*2 A,B,A1,MB(15),XC(12,700),NST(15)
      INTEGER*2 T(12,600),LOT(12,100),GAR(12,100)
      COMMON /NAME/ LOT
      EQUIVALENCE (LOT(1,1),GAR(1,1))
      DIMENSION ST(15)
      DIMENSION BC(100)
      LM=99
      A1=41
      L=12
      N3=24
      N =12
      M=500
      C=4
      NC=12
      MC=M+LM
      READ (5,17) (ST(J),J=1,L)
   17 FORMAT (12F6.3)
      DO 18 IS=1,L
      MB(IS)=ST(IS)/.171
      DZ=ST(IS)-(MB(IS)*.171)
      WRITE (6,21) DZ
   21 FORMAT (' ','DZ=',E10.3)
      NST(IS)=DZ/.00171
   18 CONTINUE
      WRITE (6,22) (MB(IG),IG=1,L)
   22 FORMAT (1H ,12I4)
      WRITE (6,23) (NST(IGG),IGG=1,L)
   23 FORMAT (1H ,12I3)
      READ (5,47) (BC(MZ),MZ=1,LM)
   47 FORMAT(10F7.4)
      DO 50 J2=1,L
      CALL ENT (A,B,A1)
      CALL SUPUL (A,B,MB,J2)
      CALL FOLD (A,B,T,N,M,BC,LM,XC,NC,MC,N3,C)
      A1=A1+1
   50 CONTINUE
      REWIND 8
      REWIND 14
      CALL EXIT
      END
```

```
      SUBROUTINE ENT (A,B,A1)
      INTEGER*2 A,B,A1
      INTEGER*2 LOT (12,100)
      COMMON /NAME/ LOT
      DO 58 MS=1,6000
      READ(8,12) A,B,((LOT(I,J),I=1,12),J=1,100)
   12 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      IF(A.EQ.A1) GO TO 65
   58 CONTINUE
   65 BACKSPACE 8
      RETURN
      END
```

```
      SUBROUTINE SUPUL (A,B,MB,J2)
      INTEGER*2 A,B
      INTEGER*2 GAR(12,100),MB(15)
      COMMON /NAME/ GAR
      II=0
      DO 42 K=1,100
      IF (MB(J2)) 43,43,45
   45 READ (8,5) A,B,((GAR(I,J),I=1,12),J=1,100)
    5 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      II=II+1
      IF (II.EQ.MB(J2)) GO TO 43
   42 CONTINUE
   43 RETURN
      END
```

```
      SUBROUTINE FOLD (A,B,T,N,M,BC,LM,XC,NC,MC,N3,C)
      INTEGER*2 A,B,T(N,M),W,XC(NC,MC)
      DIMENSION BC(LM)
      MI=M+LM-1
      NS=1
      W=0
      DO 19 L7=1,N3
      DO 18 K=1,M,100
      L=K+99
   18 READ (8,2) A,B,((T(I,J),I=1,12),J=K,L)
    2 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      CALL ZERO (XC,NC,MC,NS)
      DO 1 IB=1,N
      DO 1 LB=1,M
      DO 1 MB=1,LM
      KB=LB+MB-1
    1 XC(IB,KB)=XC(IB,KB)+(T(IB,LB)*C)*BC(MB)
      DO 25 LL=1,M,100
      KT=LL+99
      W=W+1
      WRITE (14,3) A,W,((XC(IB,KB),IB=1,12),KB=LL,KT)
    3 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      WRITE (6,44) A,W
   44 FORMAT (1H ,2I5)
   25 CONTINUE
      DO 22 IH=1,12
      DO 23 LT=501,MI
      MS=LT-500
      XC(IH,MS)=XC(IH,LT)
   23 CONTINUE
   22 CONTINUE
      NS=LM
   19 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE ZERO (XC,NC,MC,NS)
      INTEGER*2 XC(NC,MC)
      DO 4 IZ=1,NC
      DO 4 LZ=NS,MC
    4 XC(IZ,LZ)=0.0
      RETURN
      END
```

PROGRAM: AUTCRO

A. IDENTIFICATION

Title: Auto and cross-correlation of seismic data

Programmer: Z. Hajnal

Date: November 1968

Language: FORTRAN IV

B. PURPOSE

To compute a complete set of auto-correlation and cross-correlation matrix of an n channel seismic record.

C. USAGE

1. Operational Procedure: Subroutine ENT locates the desired seismic record. Subroutine SUPUL locates the required arrival within a record. Subroutine INI computes the average value of a trace. Subroutine STAVD computes the standard deviation per trace. Subroutine INPUT normalizes the data. Subroutine AUTCRO computes the auto and cross-correlation coefficients. Subroutine AUMAX locates the largest coefficient. Subroutine COSTR computes the power spectra of the auto-correlation functions.

2. Parameters: A1 = first record used for computation

L = total number of records used in

the process

N = number of traces

M = maximum size of an array

LL = total number of samples used for correlation

N3 = the number of M arrays used per trace

ST = time in seconds from the beginning of the record before the process starts

LG = number of shifts per correlation

SS = if 5 only auto-correlation is computed, if any other number then both auto and cross-correlation is computed

3. Space Requirement: 150 K

4. Temporary Storage Required: 3 disks

5. Printout: Auto and cross-correlation coefficients

6. Input Tape: 9 track

7. Output Tape: none

8. Time: 36.37 seconds per (2000 x 12) matrix of data

9. Reference: Singleton (1967), Robinson (1967b)

AUTCRO PROGRAM DESCRIPTION

Because of the many uses of the correlation techniques this program was written in a very general form; therefore it is applicable for any requirement. It can compute the multi-channel correlation matrix for as many traces as the programmer wishes. At present it computes the correlation functions for twelve traces. If more than these are required the size of the dimension statements may have to be changed. The seismic data is read from magnetic tape. The output data is stored on disk and printed or punched on cards if it is requested.

From ST the main program computes the number of blocks, which are not used for processing at the beginning of the record. Knowing this data Subroutine ENT and SUPUL are called. The use of these were described in the previous program.

Subroutine INI sums up the samples of the individual traces and computes the average value per trace. At the same time for easier access the data is read on the disk.

Subroutine STAND reads the data from the disk and computes the standard deviation per trace using formula

$$S_x = \left[\frac{1}{n} \sum_{i}^{n} (X_i - \bar{X})^2 \right]^{\frac{1}{2}}$$

where n = total number of samples used per trace

$\bar{X}$ = average value of the trace

Subroutine INPUT reads the data from the disk again and subtracts the average value from them. This new data is also stored on the disk.

Subroutine AUTCRO computes the auto and cross-correlation of twelve seismic traces. The computation is carried out according to the last formula of the correlation theory. The operation is programmed in the right to left sense. This means that always the last member of the array is operated on first. This is required by the nature of the refraction data. The time increments of the arrivals from the first channel to the twelfth are in the left to right sense. Therefore the shifting of the correlating trace must be made to the left to find the best correlation. The maximum dimension of arrays the present program can accomodate is (12 x 2000). The maximum number of correlation coefficients that can be computed is set at one thousand. The correlation coefficients are written on the disk. When the computations are finished subroutine AUMAX is initialled.

Subroutine AUMAX locates the largest correlation coefficient in one correlation function. The location and the actual value of this coefficient is printed out. If the data represent an autocorrelation function then sub-routine COSTR takes over.

Subroutine COSTR computes the cosine transform or more specifically the unbiased estimate of the power spectrum. This subroutine was written by Singleton (1967), but it is also listed in Robinson (1967b). The subprogram in the present form prints out the frequency and the power spectral coefficients.

```
C        COMPUTES AUTO AND CROSS CORRELATION FOR ANY NUMBER OF TRACES
C        A1=NUMBER OF FIRST FILE ON TAPE
C        L= NUMBER OF RECODS ON TAPE
C        N =NUMBER OF TRACES
C        M =NUMBER OF DATAPOINT PER TRACE
C        LL=ARRAY SIZE FOR SUBROUTINE AUTCRO
C        N3=NUMBER OF ARRAYS PROCESSED ON RECORD
C        LG=TOTAL NUMBER OF SHIFTS REQUIRED IN SUBR. AUTCRO
C SUBRT.ENT USED ONLY IF ENTER REQUIRED AT SOME PART OF TAPE OTHER THEN
C THE BEGINNING, A1=THE FIRST USED FILE
C SUBRT.SUPUL USED TO LOCATE ANY PART OF A FILE MB=BLOCK NO.OF START
C SUBRT.STAND COMPUTES THE STANDARD DIV. PER TRACE
C SUBRT.INI COMPUTES THE AVERAGE OF INDIVIDUAL TRACES
C SUBRT.INPUT READ DATA FROM DISK
C        ITS= NUMBER OF BLOCKS READ IN AUTCRO BEFOR PROCESS
C        MB=NO.OF BLOCKS WHERE PROCESS STARTS ON INDIVIDUAL FILE
         INTEGER*2 A,B,A1,MB(15),NST(15)
         INTEGER*2 T(12,2000),LOT(12,100)
         DIMENSION AV(150,12),AVR(12),AVR1(12),E(150,12),E2(12),STD(12)
         DIMENSION DT(12,15),IT(12,15),ST(12),G(1000)
         NFS=60
         N=12
         SS=5
         A1=2
         LL=200
         L=1
         M=100
C        N3= TOTAL NUMBER OF BLOCKS USED PER RECORD N3 MAX=150
         N3=2
         ITS=0
         LG=20
         READ (5,17) (ST(J),J=1,L)
      17 FORMAT (12F6.3)
         DO 18 IS=1,L
         MB(IS)=ST(IS)/.171
         NZ=ST(IS)-(MB(IS)*.171)
         NST(IS)=NZ/.00171
      18 CONTINUE
         READ (5,45) ((DT(I,J),I=1,12),J=1,L)
      45 FORMAT (12F5.2)
         DO 46 IH=1,L
         DO 46 LH=1,12
      46 IT(LH,IH)=DT(LH,IH)/0.00171
         WRITE (6,51) (MB(J),J=1,L)
      51 FORMAT (1H ,12I3)
         DO 50 J2=1,L
         CALL ENT (A,B,LOT,A1)
         CALL SUPUL (A,B,LOT,MB,J2)
      99 WRITE (6,32) A,B
      32 FORMAT (1H ,2I5)
         CALL INI (A,B,T,N,M,AVR1,AV,AVR,N3)
         CALL STAND (T,AVR1,STD,N,M,N3)
         CALL INPUT (A,B,T,N,M,A1,AVR1,STD,N3)
         CALL AUTCRO (T,N,LL,G,LG,ITS,STD,NFS,SS)
         REWIND 10
         REWIND 11
         REWIND 12
         A1=A1+1
```

```
      REWIND 13
   50 CONTINUE
      REWIND 8
      CALL EXIT
      END
```

```
      SUBROUTINE ENT (A,B,LOT,A1)
      INTEGER*2 A,B,A1
      INTEGER*2 LOT (12,100)
      DO 58 MS=1,6000
      READ (8,12) A,B, ((LOT (I,J),I=1,12),J=1,100)
   12 FORMAT (2A2, 250A2,250A2,250A2,250A2,200A2)
      IF (A.EQ.A1) GO TO 65
   58 CONTINUE
   65 BACKSPACE 8
      RETURN
      END
```

```
      SUBROUTINE SUPUL (A,B,LOT,MB,J2)
      INTEGER*2 A,B
      INTEGER*2 LOT(12,100),MB(15)
      II=0
      DO 42 K=1,100
      IF (MB(J2)) 45,45,46
   46 READ (8,5) A,B,((LOT(I,J),I=1,12),J=1,100)
    5 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      II=II+1
   41 IF (II.EQ.MB(J2)) GO TO 45
   42 CONTINUE
   45 RETURN
      END
```

```
      SUBROUTINE INI (A,B,T,N,M,AVR1,AV,AVR,N3)
      INTEGER*2 A,B
      INTEGER*2 T(N,M)
      DIMENSION AV(150,12),AVR(12),AVR1(12)
      DO 99 LS=1,N3
      DO 18 K=1,M,100
      L=K+99
      READ (8,2) A,B,((T(I,J),I=1,12),J=K,L)
    2 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      WRITE (13) ((T(I,J),I=1,12),J=K,L)
   18 CONTINUE
      DO 76 I1=1,N
      AV(LS,I1)=0.
      DO 77 J1=1,M
   77 AV(LS,I1)=AV(LS,I1)+T(I1,J1)
   76 CONTINUE
   99 CONTINUE
      DO 78 NS=1,12
      AVR(NS)=0.
      DO 79 MS=1,N3
   79 AVR(NS)=AVR(NS)+AV(MS,NS)
      AVR1(NS)=AVR(NS)/(M*N3)
      WRITE (6,80) AVR1(NS)
   80 FORMAT (1H ,F11.4)
   78 REWIND 13
      RETURN
      END
```

```
      SUBROUTINE STAND (T,AVR1,STD,N,M,N3)
      DIMENSION E(150,12),STD(12),AVR1(12),E2(12)
      INTEGER*2 T(N,M)
      DO 29 I3=1,N3
      DO 17 K=1,M,100
      L=K+99
        READ (13) ((T(I,J),I=1,12),J=K,L)
   17 CONTINUE
      DO 30 L3=1,N
      E(I3,L3)=0.
      DO 31 KT=1,M
   31 E(I3,L3)=E(I3,L3)+(T(L3,KT)-AVR1(L3))*(T(L3,KT)-AVR1(L3))
   30 CONTINUE
   29 CONTINUE
      DO 32 IS=1,N
      E2(IS)=0.
      DO 33 LS=1,N3
   33 E2(IS)=E2(IS)+E(LS,IS)
      WRITE (6,35) E2(IS)
   35 FORMAT (1H ,E15.5)
      STD(IS)=SQRT(E2(IS)/(M*N3))
      WRITE (6,34) STD (IS)
   34 FORMAT (1H ,E15.5)
   32 REWIND 13
      RETURN
      END
```

```
      SUBROUTINE INPUT (A,B,T,N,M,A1,AVR1,STD,N3)
      INTEGER*2 A,B,A1
      INTEGER*2 T(N,M)
      DIMENSION AVR1(12),STD(12)
      DO 61 L=1,N3
      DO 18 K=1,M,100
      LC=K+99
      READ (13) ((T(I,J),I=1,12),J=K,LC)
   18 CONTINUE
      DO 36 LL=1,N
      DO 37 KK=1,M
   37 T(LL,KK)=(T(LL,KK)-AVR1(LL))
   36 CONTINUE
      DO 25 KS=1,M,100
      LV=KS+99
   25 WRITE (10) ((T(LZ,JZ),LZ=1,12),JZ=KS,LV)
   61 CONTINUE
      REWIND 10
   60 RETURN
      END
```

```
      SUBROUTINE AUTCRO (T,JJ,LL,G,LG,ITS,STD,NFS,SS)
      INTEGER*2 T(JJ,LL),TT(12,100)
      DIMENSION G(LG),STD(12)
      II=0
      IF (ITS.LT.1) GO TO 65
      DO 66 K=1,ITS
   66 READ (10) ((TT(I,J),I=1,12),J=1,100)
   65 DO 67 K=1,LL,100
      L=K+99
      READ (10) ((T(I,J),I=1,12),J=K,L)
   67 CONTINUE
      DO 1 M=1,JJ
      DO 1 N=1,JJ
   25 DO 4 L=1,LG
      G(L)=0.0
      LDOT=LL
      DO 3 J=1,LDOT
      K=J+L-1
C SUBROUTINE AUTCRO COMPUTES AUTO AND CROSS CORRELATION FROM RIGHT TO
C LEFT
C THIS IS NECCESARY BECAUSE OF THE LEFT TO RIGHT INCREMENT IN THE DATA
      JS=LDOT-K+1
      IF (JS.LT.1) GO TO 5
      KK=LDOT-J+1
      G(L)=G(L)+(T(M,JS)*1.0)*(T(N,KK)*1.0)
    3 CONTINUE
    5 G(L)=G(L)/(LL*STD(M)*STD(N))
    4 CONTINUE
      II=II+1
      WRITE (11) M,N,(G(LH),LH=1,LG)
      WRITE (6,26) II
   26 FORMAT (1H ,'RUN NO.=',I5)
      WRITE (6,23) (G(LT),LT=1,LG)
   23 FORMAT (1H ,'G2=',F14.4)
    1 CONTINUE
   10 REWIND 11
      CALL AUMAX (G,LG,NFS,II,SS)
      REWIND 10
      RETURN
      END
```

```
      SUBROUTINE AUMAX (G,LG,NFS,II,SS)
      DIMENSION G(LG),S(100)
      DO 21 K=1,II
      READ (11) M,N,(G(L),L=1,LG)
      IF (SS.NE.5) GO TO 25
      IF (M.NE.N) GO TO 21
   25 INDEX=1
      DO 1 I=1,LG
      IF (G(INDEX).LT.G(I)) INDEX=I
    1 CONTINUE
      YMAX=G(INDEX)
      WRITE (6,20) YMAX,INDEX
   20 FORMAT(1H ,'GMAX=',F14.4,I5)
      DO 2 J=1,LG
      G(J)=G(J)/YMAX
      WRITE (6,18) M,N,J,G(J)
   18 FORMAT (' ','G(M=',I3,'N=',I3,'L=',I3,')',E17.8)
    2 CONTINUE
      IF (M.EQ.N) GO TO 19
   19 CALL COSTR(LG,G,S,NFS,INDEX)
   21 CONTINUE
      REWIND 11
      RETURN
      END
```

```
      SUBROUTINE COSTR(LG,G,S,NFS,INDEX)
      DIMENSION G(LG),S(NFS),GP(300)
      IF(INDEX.LT.100) GO TO 58
      LU=INDEX
      DO 51 KB=1,LU
      KZ=LU-KB+1
   51 GP(KB)=G(KZ)
      DO 53 KT=1,LU
   53 G(KT)=GP(KT)
      GO TO 59
   58 LU=LG+1-INDEX
      DO 52 KB=1,LU
      KLZ=INDEX+KB-1
   52 G(KB)=G(KLZ)
   59 FNQ=1./(2*0.00171)
      DF=FNQ/LG
      DO 50 K=1,NFS
      KK=K-1
      W=KK*3.14159265*2*DF
      F=KK*DF
      CD=SIN(0.5*W)
      CD=2*CD*CD
      CR=-(CD+CD)
      COSW=1.0
      S(K)=0.0
      DO 1 I=2,LU
      CD=CR*COSW+CD
      COSW=COSW+CD
    1 S(K)=G(I)*COSW+S(K)
      S(K)=G(1)+S(K)+S(K)
      WRITE (6,2) F,S(K)
    2 FORMAT (1H ,'F=',F8.3,'PED=',E11.4)
   50 CONTINUE
      RETURN
      END
```

PROGRAM: STACK

A. IDENTIFICATION

Title: Velocity filtering

Programmer: Z. Hajnal

Date: November 1968

Language: FORTRAN IV

B. PURPOSE

To sum up seismic traces to improve the signal to noise ratio.

C. USAGE

1. Operational Procedure: Subroutine ENT moves the tape to the required record. Subroutine SUPUL locates the necessary section of data within a record. Subroutine INI computes the average value per trace. Subroutine STAND computes the standard deviation per trace. Subroutine INPUT and NORMEN normalize the trace. Subroutine SUMI carries out the summing process. Subroutine DAVE prepares the data in a format which is required for plotting.

2. Parameters: A1 = number of the first record processed

   L = total number of records processed

   N4 = number of output traces after process

N = total number of traces processed

C = amplification constant

M = maximum number of samples per trace normalized per loop

Mz = maximum number of samples summed per trace per loop

ST = time in seconds from the first part of the record which is not processed.

DT = amount of shift in seconds required per trace before summation

3. Space Requirement: 170 K

4. Temporary Storage Required: 3 disks

5. Printout: average value per trace, standard deviation per trace, record and trace number, maximum number per trace

6. Input Tape: 9 track unprocessed data

7. Output Tape: 9 track processed data

8. Time: 2.35 minutes per 80 block record

9. Reference: none

STACK PROGRAM DESCRIPTION

This program was weritten to provide velocity filtering for N number of traces. Because of the non-uniform gain setting and the effects of the different ground to geophone coupling, the data must be normalized before velocity filtering. This program follows the same normalization process as was described by the section on correlation techniques.

First the main program converts ST and DT to sample interval and stores this data as MB, NST, IT variables. The second step involves the location of the data for normalization. Subroutine ENT and SUPUL are called. Their description can be found in the previous programs. The third operational process is the normalization. Subroutine INI reads the data from the tape and sums them up trace by trace. From these the average value per trace is found. The data at the same time is written on temporary disk storage.

Subroutine STAND reads the data from the disk and computes the standard deviation per trace. The formula for this was given in the correlation program. Subroutine INPUT subtracts the average value from trace to trace.

Subroutine NORMEN divides the data with the standard deviation. Subroutine SUMI is the part of the program package where the velocity filtering takes place. First the traces are shifted and then summed up. With the present arrangement N number of traces can be summed up into one to three output traces. The output data is written on the disk.

Subroutine DAVE is a service routine. It reads the output data from the temporary disk storage and finds the maximum number in every trace. Knowing this number, a scaling factor is computed. This will adjust the data according to the scaling requirement of the plotting system.

As a final step Subroutine TPPLT is called. This outputs the data on a nine track tape in a format, which makes the data ready for plotting on the Calcomp 750/563 plotting system. The detailed description of this last subroutine will be found in the section related to program PLOTMOD.

```
C      A1=NUMBER OF FIRST FILE ON TAPE
C      L= NUMBER OF RECODS ON TAPE
C      N =NUMBER OF TRACES
C      M =NUMBER OF DATAPOINT PER TRACE
C      N3=NUMBER OFARRAYS PROCESSED ON RECORD
C SUBRT.ENT USED ONLY IF ENTER REQUIRED AT SOME PART OF TAPE OTHER THEN
C THE BEGINNING, A1=THE FIRST USED FILE
C SUBRT.SUPUL USED TO LOCATE ANY PART OF A FILE MB=BLOCK NO.OF START
C SUBRT.STAND COMPUTES THE STANDARD DIV. PER TRACE
C SUBRT.INI COMPUTES THE AVERAGE OF INDIVIDUAL TRACES
C SUBRT.INPUT READ DATA FROM DISK
C      MB=NO.OF BLOCKS WHERE PROCESS STARTS ON INDIVIDUAL FILE
C      C= CONSTANT FACTOR TO INCREASE ALL AMPLITUDES
C      N4= NO. OF CHANNELS RESULTED FROM STAKING
       INTEGER*2 A,B,A1,MB(15),NST(15)
       INTEGER*2 T(12,1500),LOT(12,100)
       INTEGER*2 S(3,1500)
       DIMENSION AV(12,12),AVR(12),AVR1(12),E(12,12),E2(12),STD(12)
       DIMENSION DT(12,15),IT(12,15),ST(15)
       CALL TPST
       MZ=1400
       N=12
       N4=2
       A1=579
       L=9
       C=1
       M=1500
C  N3 MAX. IS 8 .THIS IS EQUIVALENT OF 18,76 SEC. SEISMIC DATA PLOTTED
C N3 HERE MUST BE N3/3 OF CONVOLV
       N3=4
       READ (5,17) (ST(J),J=1,L)
    17 FORMAT (12F6.3)
       DO 18 IS=1,L
       MB(IS)=ST(IS)/.171
       DZ=ST(IS)-(MB(IS)*.171)
       NST(IS)=DZ/.00171
    18 CONTINUE
       READ (5,45) ((DT(I,J),I=1,12),J=1,L)
    45 FORMAT (12F5.2)
       DO 46 IH=1,L
       DO 46 LH=1,12
    46 IT(LH,IH)=DT(LH,IH)/0.00171
       WRITE (6,51) (MB(J),J=1,L)
    51 FORMAT (1H ,12I3)
       WRITE (6,52) (NST(JS),JS=1,L)
    52 FORMAT (1H ,12I4)
       DO 50 J2=1,L
       CALL ENT (A,B,LOT,A1)
       CALL SUPUL (A,B,LOT,MB,J2)
    99 WRITE (6,32) A,B
    32 FORMAT (1H ,2I5)
       CALL INI (A,B,T,N,M,AVR1,AV,AVR,N3)
       CALL STAND (T,AVR1,STD,N,M,N3)
       NS=1
       DO 55 I=1,N3
       CALL INPUT (A,B,T,N,M,A1,AVR1,NS)
       CALL NORMEN (M,T,N,STD,NS)
       CALL SUM1 (IT,T,M,MZ,S,N,J2)
```

```
      NS=101
      N=12
   55 CONTINUE
      REWIND 10
      REWIND 11
      REWIND 12
      CALL DAVE (S,MZ,N3,N4,C,NST,J2)
      A1=A1+1
      REWIND 13
   50 CONTINUE
      REWIND 8
      CALL TPFIN
      CALL EXIT
      END
```

```
      SUBROUTINE ENT (A,B,LOT,A1)
      INTEGER*2 A,B,A1
      INTEGER*2 LOT (12,100)
      DO 58 MS=1,6000
      READ (8,12) A,B, ((LOT (I,J),I=1,12),J=1,100)
   12 FORMAT (2A2, 250A2,250A2,250A2,250A2,200A2)
      IF (A.EQ.A1) GO TO 65
   58 CONTINUE
   65 BACKSPACE 8
      RETURN
      END
```

```
      SUBROUTINE SUPUL (A,B,LOT,MB,J2)
      INTEGER*2 A,B
      INTEGER*2 LOT(12,100),MB(15)
      II=0
      DO 42 K=1,100
      IF (MB(J2)) 45,45,46
   46 READ (8,5) A,B,((LOT(I,J),I=1,12),J=1,100)
    5 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      II=II+1
   41 IF (II.EQ.MB(J2)) GO TO 45
   42 CONTINUE
   45 RETURN
      END
```

```
      SUBROUTINE INI (A,B,T,N,M,AVR1,AV,AVR,N3)
      INTEGER*2 A,B
      INTEGER*2 T(N,M)
      DIMENSION AV(12,12),AVR(12),AVR1(12)
      DO 99 LS=1,N3
      DO 18 K=1,M,100
      L=K+99
      READ (8,2) A,B,((T(I,J),I=1,12),J=K,L)
    2 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      WRITE (13) ((T(I,J),I=1,12),J=K,L)
   18 CONTINUE
      DO 76 I1=1,N
      AV(LS,I1)=0.
      DO 77 J1=1,M
   77 AV(LS,I1)=AV(LS,I1)+T(I1,J1)
   76 CONTINUE
   99 CONTINUE
      DO 78 NS=1,12
      AVR(NS)=0.
      DO 79 MS=1,N3
   79 AVR(NS)=AVR(NS)+AV(MS,NS)
      AVR1(NS)=AVR(NS)/(M*N3)
      WRITE (6,80) AVR1(NS)
   80 FORMAT (1H ,F11.4)
   78 REWIND 13
      RETURN
      END
```

```
      SUBROUTINE STAND (T,AVR1,STD,N,M,N3)
      DIMENSION E(12,12),STD(12),AVR1(12),E2(12)
      INTEGER*2 T(N,M)
      DO 29 I3=1,N3
      DO 17 K=1,M,100
      L=K+99
        READ (13) ((T(I,J),I=1,12),J=K,L)
   17 CONTINUE
      DO 30 L3=1,N
      E(I3,L3)=0.
      DO 31 KT=1,M
   31 E(I3,L3)=E(I3,L3)+(T(L3,KT)-AVR1(L3))*(T(L3,KT)-AVR1(L3))
   30 CONTINUE
   29 CONTINUE
      DO 32 IS=1,N
      E2(IS)=0.
      DO 33 LS=1,N3
   33 E2(IS)=E2(IS)+E(LS,IS)
      WRITE (6,35) E2(IS)
   35 FORMAT (1H ,E15.5)
      STD(IS)=SQRT(E2(IS)/(M*N3))*.01
      WRITE (6,34) STD (IS)
   34 FORMAT (1H ,E15.5)
   32 REWIND 13
      RETURN
      END
```

```
      SUBROUTINE INPUT (A,B,T,N,M,A1,AVR1,NS)
      INTEGER*2 A,B,A1
      INTEGER*2 T(N,M)
      DIMENSION AVR1(12)
      DO 18 K=NS,M,100
      L=K+99
      READ (13) ((T(I,J),I=1,12),J=K,L)
   18 CONTINUE
      DO 36 LL=1,N
      DO 37 KK=NS,M
   37 T(LL,KK)=T(LL,KK)-AVR1(LL)
   36 CONTINUE
   60 RETURN
      END
```

```
      SUBROUTINE NORMEN (M,T,N,STD,NS)
      INTEGER*2 T(N,M)
      DIMENSION STD (N)
      DO 30 I=1,N
      DO 40 J=NS,M
   40 T(I,J)=T(I,J)/STD(I)
   30 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SUM1 (IT,T,M,MZ,S,N,J2)
      INTEGER*2 T(N,M),IT(12,15),S(3,1500)
      N=1
      ITN=IT(N,J2)
      ITN1=IT(N+1,J2)
      ITN2=IT(N+2,J2)
      ITN3=IT(N+3,J2)
      ITN4=IT(N+4,J2)
      ITN5=IT(N+5,J2)
      ITN6=IT(N+6,J2)
      ITN7=IT(N+7,J2)
      ITN8=IT(N+8,J2)
      ITN9=IT(N+9,J2)
      ITN10=IT(N+10,J2)
      ITN11=IT(N+11,J2)
      DO 71 J=1,MZ
      S(1,J)=T(N,J+ITN)+T(N+1,J+ITN1)+T(N+2,J+ITN2)+T(N+3,J+ITN3)+T(N+4,
     1J+ITN4)+T(N+5,J+ITN5)
      S(2,J)=T(N+6,J+ITN6)+T(N+7,J+ITN7)+T(N+8,J+ITN8)+T(N+9,J+ITN9)+T(N
     1+10,J+ITN10)+T(N+11,J+ITN11)
   71 CONTINUE
      WRITE (10) (S(1,J),J=1,MZ)
      WRITE (11) (S(2,J),J=1,MZ)
      WRITE (12) (S(3,J),J=1,MZ)
      DO 22 IZ=1,12
      DO 22 LZ=1401,M
      MS=LZ-1400
   22 T(IZ,MS)=T(IZ,LZ)
      NS=101
      RETURN
      END
```

```
      SUBROUTINE DAVE (S,MZ,N3,N4,C,NST,J2)
      INTEGER*2 S(3,MZ),NST(15),YMAX
      INTEGER*2 Y(12000)
      LOGICAL PRNT
      JJ=9
      DO 9 IB=1,N4
      II=0
      LL=JJ+IB
      M1=NST(J2)
      IF (M1) 8,8,13
    8 M1=1
   13 DO 10 KB=1,N3
      READ (LL) (S(IB,J),J=1,MZ)
      DO 11 K=M1,MZ
      II=II+1
   11 Y(II)=S(IB,K)*(-1)*C
      M1=1
   10 CONTINUE
      INDEX=1
      DO 1 I=1,II
      IY=Y(INDEX)
      IZ=Y(I)
      IF (IABS(IY).LT.IABS(IZ)) INDEX=I
    1 CONTINUE
      IY=Y(INDEX)
      YMAX=IABS(IY)
      C=4000./YMAX
      WRITE (6,15) YMAX
   15 FORMAT (' ','YMAX=',I5)
      DO 2 J=1,II
      Y(J)=Y(J)*C
    2 CONTINUE
      PRNT=.FALSE.
      CALL TPPLT (Y,1,II,3*0.00170,1./4000.,1.0,PRNT)
    9 REWIND LL
      RETURN
      END
```

PROGRAM: HZINTEG

A. IDENTIFICATION

Title: Multiple correlation

Programmer: Z. Hajnal

Date: December 1968

Language: FORTRAN IV

B. PURPOSE

To integrate the result of multiple correlation for identification of weaker events.

C. USAGE

1. Operational Procedure: Subroutine ENT moves the tape to the required record. Subroutine SUPUL locates the section of interest within a record of data. Subroutine INI computes the average value per trace. Subroutine STAND computes the standard deviation per trace. Subroutine INPUT and NORMEN normalize the trace. Subroutine SUM2 carries out the multiple correlation process.

2. Parameters: A1 = number of the first record processed

   L = total number of records processed

   N4 = number of output traces after

process

N = total number of traces processed

C = amplification constant

M = maximum number of samples per traces, normalized per loop.

Mz = maximum number of samples summed per trace per loop

ST = time in seconds from the first part of the record which is not processed

DT = amount of shift in seconds required per trace before summation

SECIN = the integration interval in seconds

C = constant factor to control the integration output

C1 = amplification constant

3. Space Requirement: 180 K
4. Temporary Storage Required: 3 disks
5. Printout: average value per trace, standard deviation per trace, record and trace number, maximum number per trace.
6. Input Tape: 9 trace unprocessed data
7. Output Tape: 9 track processed data
8. Time: 2.5 minutes per 80 block record
9. Reference: none

HZINTEG PROGRAM DESCRIPTION

This is a modified version of the program STACK. This can sum traces and integrate at the same time. It moves the tape to the required data as well as normalizes the traces before they are processed.

Subroutine SUM2 is the part of the program where both the summation and integration takes place. The traces are shifted according to the input requirements and then they are summed up to two resultant traces. These data are stored temporarilly on a disk storage. When the summation is finished for the entire record, the summed data is read back from the disk, multiplied together, and integrated on a predetermined interval. With the present dimension settings the integration interval can vary from 0 to 2.39 seconds. Because the original data is dimensioned as integer variable an integration control factor C had to be applied to eliminate the possibility that the output would reach a larger value than the maximum allowed ± 32,000. The final output is stored on the disk or tape. If plotting follows the processing, subroutine DAVE, which prepares the data for the requested plotting format, is called.

```
C      STACKING PROGRAM 3 TRACES FROM 12
C   A1=NUMBER OF FIRST FILE ON TAPE USED FOR PROCESSING      234
C      L= NUMBER OF RECODS ON TAPE
C      N =NUMBER OF TRACES
C      M =NUMBER OF DATAPOINT PER TRACE
C      N3=NUMBER OFARRAYS PROCESSED ON RECORD
C SUBRT.ENT USED ONLY IF ENTER REQUIRED AT SOME PART OF TAPE OTHER THEN
C THE BEGINNING, A1=THE FIRST USED FILE
C SUBRT.SUPUL USED TO LOCATE ANY PART OF A FILE MB=BLOCK NO.OF START
C SUBRT.STAND COMPUTES THE STANDARD DIV. PER TRACE
C SUBRT.INI COMPUTES THE AVERAGE OF INDIVIDUAL TRACES
C SUBRT.INPUT READ DATA FROM DISK
C      MB=NO.OF BLOCKS WHERE PROCESS STARTS ON INDIVIDUAL FILE
C      C= CONSTANT FACTOR TO INCREASE ALL AMPLITUDES
C      N4= NO. OF CHANNELS RESULTED FROM STACKING
       INTEGER*2 A,B,A1,MB(15),NST(15)
       INTEGER*2 T(12,500),LOT(12,100)
       INTEGER*2 S(2,500),SUM3(500)
       DIMENSION AV(100,12),AVR(12),AVR1(12),E(100,12),E2(12),STD(12)
       DIMENSION DT(12,15),IT(12,15),ST(15)
       CALL TPST
       N=12
       N4=1
       C1=1
C   C=CONSTANT FACTOR TO CONTROL INTEGRATION OUTPUT
       C=.01
       A1=579
       L=9
       NTOB=80
       M=500
C   N3= THIS FIGURE IS COMPUTED FROM NTOB,NTOB=TOTAL NO. OF BLOCKS PER
C   FILE OR DIGITIZED SEISMIC RECORD
C   MZ IS REQUIRED BECAUSE OF STATIC CORR. MZ=M-ITMAX HERE ITMAX=.171 SEC
       M=500
       MZ=400
       SECIN=.200
       READ (5,17) (ST(J),J=1,L)
    17 FORMAT (12F6.3)
       DO 18 IS=1,L
       MB(IS)=ST(IS)/.171
       DZ=ST(IS)-(MB(IS)*.171)
       NST(IS)=DZ/.00171
    18 CONTINUE
       READ (5,45) ((DT(I,J),I=1,12),J=1,L)
    45 FORMAT (12F5.2)
       DO 46 IH=1,L
       DO 46 LH=1,12
    46 IT(LH,IH)=DT(LH,IH)/0.00171
       WRITE (6,51) (MB(J),J=1,L)
    51 FORMAT (1H ,12I3)
       WRITE (6,52) (NST(JS),JS=1,L)
    52 FORMAT (1H ,12I4)
       DO 50 J2=1,L
       N3P=NTOB-MB(J2)
       N3=N3P/(M/100)
       CALL ENT (A,B,LOT,A1)
       CALL SUPUL (A,B,LOT,MB,J2)
    99 WRITE (6,32) A,B
```

```
   32 FORMAT (1H ,2I5)
      CALL INI (A,B,T,N,M,AVR1,AV,AVR,N3)
      CALL STAND (T,AVR1,STD,N,M,N3)
      NS=1
C  SECIN= INTEGRATIOM INTERVAL
      INT=SECIN/0.00171
      MM=MZ
      LV=1
      LGZ=0
      IDD1=MM-INT
      ITM=IDD1/100
      IDD=ITM*100
      NCT=N3*M
      KCB=M-IDD
      NCB=NCT-KCB
      N3=NCB/IDD
      DO 55 I=1,N3
      CALL INPUT (A,B,T,N,M,A1,AVR1,NS)
      CALL NORMEN (M,T,N,STD,NS)
      CALL SUM2 (T,N,M,MZ,S,IT,INT,SUM3,J2,LV,MM,I,C,LGZ,IDD)
      NS=(M+1)-IDD
   55 CONTINUE
      REWIND 10
      REWIND 11
      REWIND 12
      CALL DAVE (SUM3,N3,N4,C1,NST,J2)
      A1=A1+1
      REWIND 13
   50 CONTINUE
      REWIND 8
      CALL TPFIN
      CALL EXIT
      END
```

```
      SUBROUTINE ENT (A,B,LOT,A1)
      INTEGER*2 A,B,A1
      INTEGER*2 LOT (12,100)
      DO 58 MS=1,6000
      READ (8,12) A,B, ((LOT (I,J),I=1,12),J=1,100)
   12 FORMAT (2A2, 250A2,250A2,250A2,250A2,200A2)
      IF (A.EQ.A1) GO TO 65
   58 CONTINUE
   65 BACKSPACE 8
      RETURN
      END
```

```
      SUBROUTINE SUPUL (A,B,LOT,MB,J2)
      INTEGER*2 A,B
      INTEGER*2 LOT(12,100),MB(15)
      II=0
      DO 42 K=1,100
      IF (MB(J2)) 45,45,46
   46 READ (8,5) A,B,((LOT(I,J),I=1,12),J=1,100)
    5 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      II=II+1
   41 IF (II.EQ.MB(J2)) GO TO 45
   42 CONTINUE
   45 RETURN
      END
```

```
      SUBROUTINE INI (A,B,T,N,M,AVR1,AV,AVR,N3)
      INTEGER*2 A,B
      INTEGER*2 T(N,M)
      DIMENSION AV(100,12),AVR(12),AVR1(12)
      DO 99 LS=1,N3
      DO 18 K=1,M,100
      L=K+99
      READ (8,2) A,B,((T(I,J),I=1,12),J=K,L)
    2 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      WRITE (13) ((T(I,J),I=1,12),J=K,L)
   18 CONTINUE
      DO 76 I1=1,N
      AV(LS,I1)=0.
      DO 77 J1=1,M
   77 AV(LS,I1)=AV(LS,I1)+T(I1,J1)
   76 CONTINUE
   99 CONTINUE
      DO 78 NS=1,12
      AVR(NS)=0.
      DO 79 MS=1,N3
   79 AVR(NS)=AVR(NS)+AV(MS,NS)
      AVR1(NS)=AVR(NS)/(M*N3)
      WRITE (6,80) AVR1(NS)
   80 FORMAT (1H ,F11.4)
   78 REWIND 13
      RETURN
      END
```

```
      SUBROUTINE STAND (T,AVR1,STD,N,M,N3)
      DIMENSION E(100,12),STD(12),AVR1(12),E2(12)
      INTEGER*2 T(N,M)
      DO 29 I3=1,N3
      DO 17 K=1,M,100
      L=K+99
        READ (13) ((T(I,J),I=1,12),J=K,L)
   17 CONTINUE
      DO 30 L3=1,N
      E(I3,L3)=0.
      DO 31 KT=1,M
   31 E(I3,L3)=E(I3,L3)+(T(L3,KT)-AVR1(L3))*(T(L3,KT)-AVR1(L3))
   30 CONTINUE
   29 CONTINUE
      DO 32 IS=1,N
      E2(IS)=0.
      DO 33 LS=1,N3
   33 E2(IS)=E2(IS)+E(LS,IS)
      WRITE (6,35) E2(IS)
   35 FORMAT (1H ,E15.5)
      STD(IS)=SQRT(E2(IS)/(M*N3))*.1
      WRITE (6,34) STD (IS)
   34 FORMAT (1H ,E15.5)
   32 REWIND 13
      RETURN
      END
```

```
      SUBROUTINE INPUT (A,B,T,N,M,A1,AVR1,NS)
      INTEGER*2 A,B,A1
      INTEGER*2 T(N,M)
      DIMENSION AVR1(12)
      DO 18 K=NS,M,100
      L=K+99
      READ (13) ((T(I,J),I=1,12),J=K,L)
   18 CONTINUE
      DO 36 LL=1,N
      DO 37 KK=NS,M
   37 T(LL,KK)=T(LL,KK)-AVR1(LL)
   36 CONTINUE
   60 RETURN
      END
```

```
      SUBROUTINE NORMEN (M,T,N,STD,NS)
      INTEGER*2 T(N,M)
      DIMENSION STD (N)
      DO 30 I=1,N
      DO 40 J=NS,M
   40 T(I,J)=T(I,J)/STD(I)
   30 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SUM2 (T,N,M,MZ,S,IT,INT,SUM3,J2,LV,MM,I,C,LGZ,IDD)
      INTEGER*2 T(N,M),S(2,M),SUM3(M),SUM1(500)
      DIMENSION IT(12,15)
    1 N=1
      ITN=IT(N,J2)
      ITN1=IT(N+1,J2)
      ITN2=IT(N+2,J2)
      ITN3=IT(N+3,J2)
      ITN4=IT(N+4,J2)
      ITN5=IT(N+5,J2)
      ITN6=IT(N+6,J2)
      ITN7=IT(N+7,J2)
      ITN8=IT(N+8,J2)
      ITN9=IT(N+9,J2)
      ITN10=IT(N+10,J2)
      ITN11=IT(N+11,J2)
      DO 71 J=1,MZ
      S(1,J)=T(N,J+ITN)+T(N+1,J+ITN1)+T(N+2,J+ITN2)+T(N+3,J+ITN3)+T(N+4,
     1J+ITN4)+T(N+5,J+ITN5)
      S(2,J)=T(N+6,J+ITN6)+T(N+7,J+ITN7)+T(N+8,J+ITN8)+T(N+9,J+ITN9)+T(N
     1+10,J+ITN10)+T(N+11,J+ITN11)
   71 CONTINUE
      DO 75 LG=LV,MM
      LGG=LG-LGZ
   75 SUM1(LG)=S(1,LGG)*S(2,LGG)*C
      WRITE (10) (SUM1(J),J=LV,MM)
      N=12
      REWIND 10
      DO 74 LL=1,M
   74 SUM3(LL)=0
      READ(10) (SUM1(J),J=LV,MM)
      NI=1
      DO 72 II=1,IDD
      SUM3(II)=0
      DO 73 KK=NI,INT
   73 SUM3(II)=SUM3(II)+SUM1(KK)
      NI=NI+1
      INT=INT+1
   72 CONTINUE
      INT=INT-IDD
      WRITE (11) IDD
      WRITE (11) (SUM3(JJ),JJ=1,IDD)
      WRITE (6,17) IDD
   17 FORMAT (' ','IDD=',I5)
      DO 22 IZ=1,12
      KP=IDD+1
      DO 22 LZ=KP,M
      MS=LZ-IDD
   22 T(IZ,MS)=T(IZ,LZ)
      REWIND 10
      RETURN
      END
```

```
      SUBROUTINE DAVE (SUM3,N3,N4,C1,NST,J2)
      INTEGER*2 SUM3(1500),NST(15),YMAX
      INTEGER*2 Y(12000)
      LOGICAL PRNT
      JJ=10
      DO 9 IB=1,N4
      II=0
      LL=JJ+IB
      M1=NST(J2)
      IF (M1) 8,8,13
    8 M1=1
   13 DO 10 KB=1,N3
      READ (LL) IDD
      READ (LL) (SUM3(J),J=1,IDD)
      WRITE (6,19)  N3
   19 FORMAT (' ','N3=',I5)
      DO 11 K=M1,IDD
      II=II+1
   11 Y(II)=SUM3 (K)*(-1)*C1
      WRITE (6,20) M1
   20 FORMAT (' ','M1=',I5)
      M1=1
   10 CONTINUE
      INDEX=1
      DO 1 I=1,II
      IY=Y(INDEX)
      IZ=Y(I)
      IF (IABS(IY).LT.IABS(IZ)) INDEX=I
    1 CONTINUE
      IY=Y(INDEX)
      YMAX=IABS(IY)
      C=8000./(2*YMAX)
      WRITE (6,15) YMAX
   15 FORMAT (' ','YMAX=',I6)
      DO 2 J=1,II
      Y(J)=Y(J)*C
    2 CONTINUE
      PRNT=.FALSE.
      CALL TPPLT (Y,1,II,3*0.00170,1./4000.,1.0,PRNT)
    9 REWIND LL
      RETURN
      END
```

PROGRAM: PLOTMOD

A. IDENTIFICATION

Title: Plotting of seismic data

Programmer: Z. Hajnal

Date: October 1968

Language: FORTRAN IV

B. PURPOSE

To prepare data for plotting according to a given format.

C. USAGE

1. Operational Procedure: Subroutine ENT locates the first required record. Subroutine SUPUL removes the unwanted data from the record. The main program puts the required amount of useful data on a disk. Subroutine DAVE applies the scale factor. Subroutine TPPLT prepares the data for plotting according to a given format.

2. Parameters: A1 = number of the first record processed

   L = total number of records processed

   M = maximum length of the array read at one time

   DRS = start of digital seismic record

in seconds

STP = time in seconds where the plotting is started on the individual records

EDTP = end of plot in seconds per record

DTT = line increments from trace to trace

3. Space Requirement: 120 K
4. Temporary Storage Required: 1 disk
5. Printout: number of blocks and samples discarded before plot, record number, block number, maximum number per trace.
6. Input Tape: 9 track seismic data
7. Output Tape: 9 track data for plot
8. Time: 2.45 seconds per digital block
9. Reference: none

PLOTMOD PROGRAM DESCRIPTION

In most cases processing of the digital seismic records requires considerable computer time. This can cause operational problems if a general purpose computer, which serves many types of programs, is used for the process. Usually the input and output processes are the slowest part of the program. An attempt was made to improve this situation. This was done by writing the output data on tape or disk at the time of the processing and using the above program when plotting became possible at minimal operational periods.

The PLOTMOD is a general purpose program which prepares L number of seismic records for any given plotting format. The output is stored on a magnetic tape which must be compatable with Calcomp 750/563 plotting system. All DRS, STP, EDTP, DTT must be provided for the program as input data on individual computer cards.

The main program computes the following times ST = STP - DRS, N3 = EDTP - STP. These are converted to equivalent digital interval units. The first difference represent the length of the record which is discarded before plotting. The second difference is the total length of the plotted record. DTT is used only if a shift of traces is required or it is necessary that the plotting of traces is not terminated at the same time on the individual records. When these data are available subroutine ENT and SUPUL are called. These programs were described previously. At the end of the subroutine SUPUL the control is returned to the main program. The main program reads N3 blocks of data from the input tape and writes these on the disk. After this operation, subroutine DAVE is called. Subroutine DAVE reads the data, trace by trace, from the disk. When one complete trace is read the absolute value of the largest element in the trace is determined. Using this number a scale factor for the Y coordinate of the plotter is determined. When the scale factor is known all the members of the one dimensional array is multiplied with it. The sample program shows the case where the scale factor adjusts the largest number of the array to 2000. After the above multiplication subroutine TPPLT is called.

Subroutine TPPLT is a subprogram which calls all the software provided by Calcomp to convert the data to a language which is compatible to the plotting system. This subroutine requires the following input parameters.

Y = array of one seismic trace.

I = the first element of the trace to be plotted.

II = last element of the array to be plotted. It is set at 12,000 in the present case. This is equal to 20.52 seconds of seismic signal.

XSL = the scale in X direction. It is in inches per unit. The present scale is 3 inches per second.

YSL = scale in Y direction. It is in inches per interval. The present scale is one inch per 4000.

S = the separation in inches between traces. It is one half of an inch at the present time.

PRNT = either PRNT or ·FALSE·. If PRNT = PRNT the data is also printed by the printer. If PRNT = ·FALSE· the data is only written on the magnetic tape.

Subroutine DAVE follows the same procedure for N number of traces. When the N th number of trace is written on the tape the control returns to the main program. A new record is read from the input tape and the entire process is continued until all the L number of records are processed. Subroutine TPPLT was provided by the Department of Earth Sciences.

```
C   THE PROGRAM PREPARES DATA FOR PLOT ON CALCOMP 750/563 SYSTEM
C   SEISMIC DATA READ FROM MAG. TAPE OUTPUT ON MAG.TAPE
C      A1= NO OF SEISMIC RECORD TO TAKE DATA FROM
C   L= NO OF RECORDS TAKEN FROM THE MAGNETICK TAPE
C      N3= NO OF (12,100) BLOCKS REQUIRED FROM ONE RECRD
C   DRS=START OF DIGITAL RECORD IN SECONDS
C   STP=START OF PLOT IN SECONDS
C   EDTP=END OF PLOT IN SECONDS
C   DTT=TIME INCREMENTS FROM TRACE TO TRACE
      INTEGER*2 T(12,100)
      INTEGER*2 LOT(12,100)
      INTEGER*2 A,B,A1,MB(15),GAR(12,100),NST(15)
      DIMENSION ST(15),DRS(15),STP(15),EDTP(15),DTT(15)
      M=100
      N=12
      L=2
      A1=586
      CALL TPST
      READ (5,13) (DRS(I),I=1,L)
   13 FORMAT (12F7.3)
      READ (5,15) (STP(IL),IL=1,L)
   15 FORMAT (12F7.3)
      READ (5,17) (EDTP(IT),IT=1,L)
   17 FORMAT (12F7.3)
      READ (5,21) (DTT(J),J=1,L)
   21 FORMAT (12F6.3)
      DO 18 IS=1,L
      ST(IS)=STP(IS)-DRS(IS)
      MB(IS)=ST(IS)/.171
      DZ=ST(IS)-(MB(IS)*.171)
      NST(IS)=DZ/.00171
   18 CONTINUE
      WRITE (6,22) (MB(IG),IG=1,L)
   22 FORMAT(1H ,'MB=NO.OF BLOCKS=',12I4)
      WRITE (6,23) (NST(IGG),IGG=1,L)
   23 FORMAT (1H ,'NST=NO.OF INTERVALS=',12I3)
      DO 11 J2=1,L
      CALL ENT (A,A1,GAR)
      CALL SUPUL (A,B,GAR,MB,J2)
      ZHT=(EDTP(J2)+(DTT(J2)*N))-STP(J2)
      N3=ZHT/.171
      SGT=.171*N3
      ENG=ZHT-SGT
      IF (ENG.EQ.0.) GO TO 100
      N3=N3+1
  100 DO 19 LL=1,N3
      READ (8,2) A,B,((T(I,J),I=1,12),J=1,100)
    2 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      WRITE (6,99) A,B
   99 FORMAT (1H ,2I5)
      WRITE (13) ((T(I,J),I=1,12),J=1,100)
   19 CONTINUE
      REWIND 13
      CALL DAVE (T,N,M,NST,J2,L,DTT,EDTP,STP)
      A1=A1+1
   11 CONTINUE
      REWIND 8
      CALL TPFIN
```

```
      SUBROUTINE ENT (A,A1,GAR)
      INTEGER*2 A,B,A1
      INTEGER*2 GAR(12,100)
      DO 58 MS=1,6000
      READ(8,2) A,B,((GAR(I,J),I=1,12),J=1,100)
    2 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      IF(A.EQ.A1) GO TO 65
   58 CONTINUE
   65 BACKSPACE 8
      RETURN
      END
```

251

```
      SUBROUTINE SUPUL (A,B,GAR,MB,J2)
      INTEGER*2 A,B,GAR(12,100),MB(15)
      II=0
      DO 42 K=1,100
      IF (MB(J2)) 43,43,46
   46 READ (8,5) A,B,((GAR(I,J),I=1,12),J=1,100)
    5 FORMAT (2A2,250A2,250A2,250A2,250A2,200A2)
      II=II+1
      IF (II.EQ.MB(J2)) GO TO 43
   42 CONTINUE
   43 RETURN
      END
```

```
      SUBROUTINE DAVE (T,N,M,NST,J2,L,DTT,EDTP,STP)
      INTEGER*2 T(N,M)
      INTEGER*2 Y(12000),NST(15),YMAX
      DIMENSION DTT(15),EDTP(15),STP(15)
      LOGICAL PRNT
      DO 9 IB=1,N
      KZ=IB-1
      II=0
      ZCH=(EDTP(J2)+(DTT(J2)*KZ))-STP(J2)
      N33=ZCH/.171
      EKD=.171*N33
      EFT=ZCH-EKD
      IF (EFT.EQ.0.) GO TO 21
      N33=N33+1
   21 M1=NST(J2)
      IF (M1) 8,8,14
    8 M1=1
   14 DO 10 KB=1,N33
      READ (13) ((T(I,J),I=1,12),J=1,100)
      KT=100
      IF (KB.NE.N33) GO TO 18
      KT=EFT/0.00171
   18 DO 11 K=M1,KT
      II=II+1
   11 Y(II)=T(IB,K)
      M1=1
   10 CONTINUE
      INDEX=1
      DO 1 I=1,II
      IY=Y(INDEX)
      IZ=Y(I)
      IF (IABS(IY).LT.IABS(IZ)) INDEX=I
    1 CONTINUE
      IY=Y(INDEX)
      YMAX=IABS(IY)
      C=2000./YMAX
      WRITE (6,15) YMAX
   15 FORMAT (' ','YMAX=',I5)
      DO 2 J=1,II
      Y(J)=Y(J)*C
    2 CONTINUE
      Y(II)=0
      PRNT=.FALSE.
      CALL TPPLT (Y,1,II,3*0.00170,1./4000.,.5,PRNT)
    9 REWIND 13
      RETURN
      END
```

PROGRAM: SRLFIT

A. IDENTIFICATION

Title: Least square best fit

Programmer: Z. Hajnal

Date: June 1969

Language: FORTRAN IV

B. PURPOSE

To fit points to straight line segments.

C. USAGE

1. Operation Procedure: Main program controls input data. Subroutine LEAST computes least square best fit.

2. Parameters: NC = total number of groups in input data

   N = number of points in a data group

3. Space Requirement: 120 K

4. Temporary Storage Required: none

5. Printout: velocity, slope, standard deviation, confidence limit

6. Input Tape: none

7. Output Tape: none

8. Time: 2.40 seconds per 130 points

9. Reference: Bowker and Lieberman (1959, p. 266), Steinhart and Meyer (1961, p. 135)

SRLFIT PROGRAM DESCRIPTION

The program consists of the main program and a subroutine. The present program setting is at NC = 10 if the number of data points is not higher than 150 in the individual groups.

Input data is read from computer cards. It consists of the number of points within one group and the actual time and distance data.

The main program reads the total number of input information. After this the first group of data is selected. Subroutine LEAST takes the selected group of data and computes the linear least-square fit to the data. The mathematical equations were taken from Bowker and Lieberman (1959, p. 266) and Steinhart and Meyer (1961, p. 135). The output comprises the slope of the best fit line, the velocity, the standard error and the confidence limit of the slope.

When the computation is finished the control returns to the main program. If it is required the same set of time and distance data is squared and the subroutine is called again. The output is then the results of the best $X^2 - T^2$ fit.

The previous procedures are repeated as many times as it is indicated by the input parameter NC.

```
C LEAST SQUARE FIT FOR FIRST BREAK DATA  GEOPHYSICS  DEPT< OF GEO< HAJNAL
      DIMENSION X(1500),T(1500),XX(1500),TT(1500),N(20)
C       NC=THE TOTAL NUMBER OF DATA GROUPS                         255
      NC=3
      LS=1
      READ (5,13) (N(J),J=1,NC)
   13 FORMAT (20I4)
      NN=0
      DO 30 L=1,NC
   30 NN=NN+N(L)
      READ (5,10) (T(J),X(J),J=LS,NN)
   10 FORMAT (F5.2,F7.3)
      NT=N(1)
      DO 31 M=1,NC
      CALL LEAST (X,T,NT,LS)
      DO 50 KP=LS,NT
      TT(KP)=T(KP)*T(KP)
   50 XX(KP)=X(KP)*X(KP)
      CALL LEAST (XX,TT,NT,LS)
      LS=NT+1
      NS=M+1
      IF (NS.GT.NC) GO TO 16
      NT=NT+N(NS)
   31 CONTINUE
   16 CALL EXIT
      END
```

```
      SUBROUTINE LEAST (X,T,N,LS)
      DIMENSION X(N),T(N)
      II=LS
      S=N-LS
   25 SUMX=0.0
      TIME=0.0
      DO 11 I=II,N
      SUMX=SUMX+X(I)
      TIME=TIME+T(I)
   11 CONTINUE
      XF=SUMX/S
      TF=TIME/S
      HX=0.00
      BX=0.00
      DO 12 K=II,N
      HX=HX+(X(K)-XF)*(T(K)-TF)
      BX=BX+(X(K)-XF)**2
   12 CONTINUE
      B=HX/BX
      V=1./B
      C=TF-B*XF
      TH=0.00
      XZ=0.00
      XG=0.00
      DO 13 M=II,N
      TH=TH+(T(M)-TF)**2
      XG=XG+((X(M)-XF)*(T(M)-TF))
      XZ=XZ+(X(M)-XF)**2
   13 CONTINUE
      XS=XG*XG
      SDD=(TH-(XS/XZ))/S
      ST=SQRT(SDD)
      XGG=XG/S
      DXX=XGG/B
      SXT=(SUMX*TIME)/S
      TSUSQ=(TIME*TIME)/S
      TSQ=0.00
      XT=0.00
      DO 30 M=II,N
      TSQ=TSQ+(T(M)*T(M))
   30 XT=XT+(X(M)*T(M))
      SB=SQRT(SDD/DXX)
      DXP=ST*(SQRT((1./N)+((XF*XF)/DXX)))
      WRITE (6,20) B,C,ST,V
   20 FORMAT (1H ,'SLPE=',F9.5,'INTCEPT=',F9.5,'ST.DIV=',F9.5,'V=',F5.2)
      WRITE (6,31) SB,DXX,DXP
   31 FORMAT (1H ,'SB=',E15.5,'DXX=',E15.5,'DXP=',E15.5)
      WRITE (6,21) (X(I),T(I),I=II,N)
   21 FORMAT (1H ,F10.3,F8.3)
      RETURN
      END
```

PROGRAM: STATS

A. IDENTIFICATION

Title: Polynomial regression analysis

Programmer: F. Chebib

Date: June 1966

Language: FORTRAN IV

B. PURPOSE

To compute nth order polynomial fit to a given set of data.

C. USAGE

1. Operational Procedure: Order of program operation is main program, subroutine GDATA, subroutine CORRE, subroutine ORDER, subroutine MINV, subroutine MULTR.

2. Parameters:
   1. title of the data set
   2. number of samples
   3. largest power of the independent variable (max. 98)
   4. a T will cause input data to be listed. An F or blank will suppress this listing.

3. Space Requirement: 150 K

4. Temporary Storage Required: none

5. Printout: list of input data (optional), mean and standard deviation, a matrix of all possible correlations of the dependent variable and all the independent powers variables, the partial and standardized regression coefficients, the value of intercept and the multiple correlation coefficient, a list of the observed, expected and adjusted values of the independent variable for each value of the dependent variable (optional).
6. Input Tape: none
7. Output Tape: none
8. Time: 1.55 seconds per 130 points
9. Reference: University of Manitoba Computer Centre 1969 Statistical Package, p. 19, International Business Machines Systems 360 Scientific Subroutine Package, File H20-0205-3, (360A-CM-03X), Version III.

STATS PROGRAM DESCRIPTION

This program was designed to perform a complete polynomial regression analysis on any number of sets of data with options to select any combinations of the powers of the independent variable for the analysis. It consists of one main program and five subroutines, four of which are in the IBM Scientific Subroutine Package. The dimensions are set up so that the program can handle a power of not larger than 98.

No listing of this program was available.

PROGRAM: LEASTMO

A. IDENTIFICATION

Title: Velocity determination from wide angle reflections.

Programmer: Z. Hajnal

Date: June 1969

Language: FORTRAN IV

B. PURPOSE

To compute interval velocity by iteration process.

C. USAGE

1. Operational Procedure: Main program only.

2. Parameters: NUMB1 = total number of points used in the computation

   ZS = depth of the first interface

   VEL = vertical velocity in the first layer

   W1 = slope of the first interface

   VAM = approximate velocity of propogation in the second layer

   W2 = approximate slope of the second interface

3. Space Requirement: 120 K

4. Temporary Storage Required: none

5. Printout: corrected velocity of the second layer,
   corrected slope of the second interface
6. Input Tape: none
7. Output Tape: none
8. Time: 120 seconds per 50 points
9. Reference: none

LEASTMO PROGRAM DESCRIPTION

The main program is a set of applied formulae. The mathematical description was presented at the velocity determination in the section of wide angle reflection for the two-layer case. A set of IF statements control the directional changes of the estimated angle P_2.

```
      DIMENSION TM(60),TMSQ(60),XM(60),ANG(60),ANG2(60),ZMR(60),ZD2(60
     2),W2(60),ALF1(60),ALF2(60),HA1(60),HA2(60),XA1(60),XA2(60),XP2(6
     30),XP1(60),TAA(60),TBB(60),TACB(60),CON2(60),TAB(60),ZM(60),DM(11,
     412),X(60),XSQ(60),TCMSQ(60),W(60),TPCMQ(60),XPQ(60),XAB(60),TQ(60)
      DIMENSION T2(60),TTSQ(60),XFM(60),P2(60),VP(60)
      NUMB1=50
      READ (5,601) (W(I),I=1,NUMB1)
  601 FORMAT (10F7.4)
      READ (5,201) (X(I),TM(I),I=1,NUMB1)
  201 FORMAT (2F8.4)
      DO 760 I=1,NUMB1
      TMSQ(I)=TM(I)*TM(I)
  760 XSQ(I)=X(I)*X(I)
      DO 66 K=1,NUMB1
   66 W2(K)=0.03490
      ZS=17.45
      VEL=6.05
      DM(1,M4)=122.356
      II=0.0
      VAM=6.90
      WRITE (6,541) DM(1,M4)
  541 FORMAT(' ','DM=',F8.3)
      PB=SQRT(DM(1,M4))-(2*ZS/VEL)
  915 HH2=.5*(VAM*PB)
      ZIS=HH2+ZS
      WRITE (6,810) II,VAM,HH2
  810 FORMAT (' ','ITERATION=',I3,'VAM=',F5.2,'HH2=',F6.2)
      LL=0
      DO 910 LM=1,NUMB1
      CC=VEL/VAM
      CU=VAM/VEL
      CBB=CC
      CM=6.90/7.90
      ANG2(LM)=ATAN(CM/SQRT(1.-CM**2))
  895 CFP=SIN(ANG2(LM))*CBB
      ANG(LM)=ATAN(CFP/SQRT(1.-CFP**2))
      ALF2(LM)=ANG2(LM)-W(LM)
      CP=SIN(ALF2(LM)+W(LM))
  813 ALF1(LM)=ATAN((CC*CP)/SQRT(1.-(CC*CP)**2))-W(LM)
      HA1(LM)=ZS/COS(W(LM))
      HA2(LM)=HH2/COS(W2(LM))
      XA1(LM)=HA1(LM)/((1./TAN(ALF1(LM)))-TAN(W(LM)))
      XA2(LM)=(HA2(LM)+(XA1(LM)*(TAN(W2(LM)-TAN(W(LM))))))/(1./TAN(ALF
     12(LM))+TAN(W2(LM)))
      XP2(LM)=(HA2(LM)+(XA1(LM)+XA2(LM))*(TAN(W(LM))+TAN(W2(LM))))/(1.
     2/(TAN(ANG2(LM)))+TAN(W(LM)))
      XP1(LM)=(HA1(LM)+(XA1(LM)+XA2(LM)+XP2(LM))*TAN(W(LM)))/(1./TAN(ANG
     1(LM)))
      XFM(LM)=XA1(LM)+XA2(LM)+XP1(LM)+XP2(LM)
      XTT=XFM(LM)-X(LM)
      IF (XTT) 890,891,892
  890 IF (ABS(XTT).LE..5) GO TO 891
      ANG2(LM)=ANG2(LM)+0.001745
      GO TO 895
  892 IF (XTT.LE..5) GO TO 891
      ANG2(LM)=ANG2(LM)-0.0017545
      GO TO 895
  891 TAA(LM)=(HA1(LM)+XA1(LM)*TAN(W(LM)))/(VEL*COS(ALF1(LM)))
```

```
      TBB(LM)=(HA1(LM)+(TAN(W(LM))*(XA1(LM)+XA2(LM)+XP2(LM))))/(VEL*COS(
     1ANG(LM)))
      TACB(LM)=TM(LM)-TAA(LM)-TBB(LM)
      TTSQ(LM)=TACB(LM)*TACB(LM)
      TAH=2*HH2/VAM
      XAB(LM)=XA2(LM)+XP2(LM)
      TAB(LM)=XAB(LM)/VAM
      CON2(LM)=(TAH*TAH)-(2*TAH*SIN(W2(LM))*TAB(LM))
      TCMSQ(LM)=TTSQ(LM)-CON2(LM)
      IF (TCMSQ(LM)) 910,567,567
  567 LL=LL+1
      TPCMQ(LL)=SQRT(TCMSQ(LM))
      P2(LL)=XAB(LM)
  910 CONTINUE
      TSM=0.0
      XPM2=0.0
      DO 911 LN=1,LL
      TSM=TSM+(TPCMQ(LN)*P2(LN))
      XPM2=XPM2+(P2(LN)*P2(LN))
      VP(LN)=XPM2/TSM
  911 CONTINUE
      DO 846 L=1,NUMB1
      WRITE (6,888) ANG(L),ANG2(L),ALF1(L),ALF2(L),XA1(L),XA2(L),XP1(L),
     1XP2(L),TM(L),TAA(L),TBB(L),X(L),XAB(L),TPCMQ(L),VP(L)
  888 FORMAT (4F7.4,10F9.4,F8.4)
  846 CONTINUE
      LL=0
      VAM2=XPM2/TSM
      DO 912 NN=1,NUMB1
  912 W2(NN)=ATAN(TAN(W2(NN))*(VAM2/VAM))
      IF (VAM2.LT.6.35) GO TO 913
      IF (VAM2.GT.7.00) GO TO 913
  930 DO 931 KZ=1,NUMB1
      XPQ(KZ)=XAB(KZ)*XAB(KZ)
      ZK=0.5*SQRT((TTSQ(KZ)*VAM2*VAM2)-XPQ(KZ))
      ZM(KZ)=ZK/COS(W2(KZ))
      ZM(KZ)=ZM(KZ)+HA1(KZ)
      XM(KZ)=XA2(KZ)+XA1(KZ)
      MM=KZ+1
      IF (MM.GE.21) GO TO 951
      IF (MM.NE.20) GO TO 949
  951 MM=MM+1
  949 WRITE (6,950) MM,ZM(KZ),XM(KZ),W2(KZ)
  950 FORMAT (1H ,'RSTE=',I3,'MODE=',F7.3,'DIST=',F8.3,'W2=',E13.5)
  931 CONTINUE
  913 VAM=VAM2
      II=II+1
      IF (II.GT.50) GO TO 920
      GO TO 915
  920 CALL EXIT
      END
```

PROGRAM: DISTAN

A. IDENTIFICATION

Title: Distance determination from latitude and longitude.

Programmer: Z. Hajnal (M. J. Keen)

Date: April 1966

Language: FORTRAN II

B. PURPOSE

To determine distance between shotpoint and recording site by the latitude and longitude of these locations.

C. USAGE

1. Operational Procedure: one main program
2. Parameters: N = number of shotpoints
   M = number of recording sites
3. Space Requirement: 104 K
4. Temporary Storage Required: none
5. Printout: distance in km. between the shotpoint and recording site, list of the input data
6. Input Tape: none
7. Output Tape: none
8. Time: 30.0 seconds per 50 locations
9. Reference: Bullen (1963, p. 154)

DISTAN PROGRAM DESCRIPTION

The program was originated by Dr. M. J. Keen of the Institute of Oceanography, Dalhousie University, Halifax, Nova Scotia. This program was modified by the writer from moving shotpoint to moving recording sites. The computation formulae were taken from Bullen (1963, p. 154). The input data consists of the latitude and the longitude of the surveying locations. The data is read from computer cards.

```
C MODIFIED ARC7 DISTANCE PROGRAM U. OF MAN. GEOLOGY NOV 15 1966
C FINDS DISTANCE FROM GIVEN LATITUDE AND LONGITUDE
      DIMENSION SLD(60), SLM(60), SOD(60), SOM(60), RLD(60), RLM(60),
     1ROD(60), ROM(60), SP(60), R(60)
    1 READ (1, 70) (SLD(J), SLM(J), SOD(J), SOM(J), SP(J), J=1,3)
   70 FORMAT (F4.0, F6.2, F4.0, F6.2, I3)
    2 READ (1, 71) (RLD(K), RLM(K), ROD(K), ROM(K), R(K), K=1,56)
   71 FORMAT (F4.0, F6.2, F4.0, F6.2, I5)
      DO 96 J=1,3
      WRITE (3, 87)
      AO=(SLD(J)+SLM(J)/60.)*0.01745329
      BO=(SOD(J)+SOM(J)/60.)*0.01745329
      TANAO=(SIN(AO)/COS(AO))*.993277
      COSAO=COS(ATAN(TANAO))
      SINAO=SIN(ATAN(TANAO))
      DO 4 K=1,56
      A1=(RLD(K)+RLM(K)/60.)*0.01745329
      B1=(ROD(K)+ROM(K)/60.)*0.01745329
      TANA1= (SIN(A1)/COS(A1))*.993277
      SINA1=SIN(ATAN(TANA1))
      COSA1=COS(ATAN(TANA1))
      A=(COSAO*COS(BO)-COSA1*COS(B1))**2
      B=(COSAO*SIN(BO)-COSA1*SIN(B1))**2
      C=(SINAO-SINA1)**2
      SUM=A+B+C
      AOBOM=(AO+A1)/2.
      SINX=SIN(AOBOM)
      SINX2=SINX**2
      F=.003367*SINX2
      F1=1.-F
      D=6378.388*F1
      COSD=1.-0.5*SUM
      SIND=SQRT(1.-COSD*COSD)
      DELT=ATAN(SIND/COSD)
      S=D*DELT
      WRITE (3, 92) SP(J), R(K), S
   92 FORMAT (8X,I3,11X,I5,7X,F7.2)
    4 CONTINUE
   87 FORMAT (1H ,3X,8HSHOTP.NO,2X,10HRECORS.NO,2X,11HDISTANCE.KM)
   96 CONTINUE
      WRITE (6,21) (SLD(J),SLM(J),SOD(J),SOM(J),SP(J),J=1,3)
   21 FORMAT (1H ,'SHOT P.,LAT.AND LONG.',F4.0,F6.2,F4.0,F6.2,I3)
      WRITE (6,22) (RLD(K),RLM(K),ROD(K),ROM(K),R(K),K=1,56)
   22 FORMAT (1H ,'REC.S. LAT.,AND LONG.',F4.0,F6.2,F4.0,F6.2,I3)
      CALL EXIT
      END
```

PROGRAM: DEPTH

A. IDENTIFICATION

Title: Two-layer depth calculation from seismic data.

Programmer: Z. Hajnal

Date: January 1969

Language: FORTRAN IV

B. PURPOSE

To compute depth of the first interface from reflection and refraction data.

C. USAGE

1. Operational Procedure: Main program controls input data. Subroutine RFRL1 computes the depth at recording site from the refraction arrival. Subroutine REFL1 computes depth from reflection arrival data.

2. Parameters: NRR = total number of refraction data
   NRE = total number of reflection data

3. Space Requirement: 104 K

4. Temporary Storage Required: none

5. Printout: number of the recording site, depth in km., offset distance

6. Input Tape; none

7. Output Tape: none
8. Time: 1.75 sec. per 50 data points
9. Reference: none
10. Remark: Because of the simplicity of this program no detailed program description is given.

```
C     DEPTH CALCULATIONS FROM REFRACTION AND REFLECTION DATA
C     SUBROUTINE RFLI1 COMPUTES DEPTH FROM ONE REFRACTOR
C     SUBROUTINE REFL1 COMPUTES DEPTH FROM FIRST REFRECTOR
C     PROGRAM WAS WRITTEN BY Z HAJNAL DEPT. OF EARTH SCI. NOV 1969
      DIMENSION T(150),X(150),TREF(150),XREF(150),ZZ(150),ZRE(150)
      DIMENSION XR(150)
      NRR=84
      NRE=52
      READ (5,1) (T(J),X(J),J=1,NRR)
    1 FORMAT (F5.2,F7.3)
      READ (5,2) (XREF(L),TREF(L),L=1,NRE)
    2 FORMAT (F8.4,F6.2)
      READ (5,3) V0,V1
    3 FORMAT (2F5.2)
      CALL RFRL1 (T,X,V0,V1,NRR,ZZ)
      CALL REFL1 (TREF,XREF,NRE,ZRE,V0,XR)
      CALL EXIT
      END
```

```
      SUBROUTINE RFRL1 (T,X,VO,V1,NRR,ZZ)
      DIMENSION T(NRR),X(NRR),ZZ(NRR)
      CNS=SQRT((V1*V1)-(VO*VO))
      CON=(V1*VO)/CNS
      P=VO/V1
      PP=CNS/V1
      TAD=P/PP
      DO 10 K=1,NRR
      ZZ(K)=(T(K)-(X(K)/V1))*CON
   10 CONTINUE
      ZS=ZZ(1)/2
      DO 11 L=1,NRR
      ZZ(L)=ZZ(L)-ZS
      OFFST=ZZ(L)*TAD
      WRITE (6,2) L,ZZ(L),T(L),X(L),OFFST
    2 FORMAT (1H ,I4,'RSTDEPTH=',F8.3,'T=',F5.2,'X=',F7.3,'OFST=',F6.2)
   11 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE REFL1 (TREF,XREF,NRE,ZRE,VO,XR)
      DIMENSION TREF(NRE),ZRE(NRE),XR(NRE),XREF(NRE)
      VV=VO*VO
      DO 20 L=1,NRE
      ZRE(L)=0.5*SQRT(((TREF(L)*TREF(L))*VV)-(XREF(L)*XREF(L)))
      XR(L)=XREF(L)/2
      WRITE (6,2) L,ZRE(L),XR(L)
    2 FORMAT (1H ,I4,'DEPTH=',F7.3,'DISTDE=',F7.3)
   20 CONTINUE
      END
```

PROGRAM: THEORE

A. IDENTIFICATION

Title: Theoretical arrival times for reflection rays from multi-layer crust.

Programmer: Z. Hajnal

Date: August 1969

Language: FORTRAN IV

B. PURPOSE

To compute theoretical reflection arrival times from an estimated crustal section.

C. USAGE

1. Operational Procedure: Subroutine REL1 computes arrival times for the first interface. Subroutine REL2 derives the same data from the second interface. Subroutine REL3 determines the arrival times from the third interface.

2. Parameters: H_1, H_2, H_3 = thickness of the first, second and third layer

   W_1, W_2, W_3 = slope of the first, second and third interface

   V_1, V_2, V_3 = longitudinal velocity in the first, second and third layer

LL = total number of computations required

3. Space Requirement: 120 K
4. Temporary Storage Required: none
5. Printout: depth to the interface, angle of imergence, arrival time, distance between shotpoint and recording site.
6. Input Tape: none
7. Output Tape: none
8. Time:
9. Reference: none

THEORE PROGRAM DESCRIPTION

The program formulae are equivalent to the equations derived for wide angle reflection in the section of velocity determination. In the present program the angle of emergence at the surface is varied from 0° to 90°.

All subroutines have the following optional features. First the angle of emergence is changed approximately half a degree from one loop to the other. When the distance reached a given zone of interest, if required the angle of emergence will change only 5 or 10 seconds from one computation to the other. It is also possible to make a gradual variation in the input parameters of a given subroutine.

```
C   COMPUTATION OF THEORETICAL REFLECTION TIMES
C   PROGRAM WAS WRITTEN BY Z HAJNAL NOV/69
C   DEPT. OF EARTH SCIENCES.
C   OUTPUT GIVEN FOR  ONE TO THREE LAYER CASES
C      INPUT DATA
       H1=18.30
       H2=18.47
       H3=6.50
       W1=0.0
       W2=0.0
       W3=0.0
       V1=6.05
       V2=6.90
       V3=7.90
       V4=8.45
       LL=140
       CALL REL1 (H1,W1,V1,V2,LL)
       CALL REL2 (H1,H2,W1,W2,V1,V2,V3,LL)
       LL=350
       CALL  REL3 (H1,H2,H3,W1,W2,W3,V1,V2,V3,V4,LL)
       CALL EXIT
       END
```

```
      SUBROUTINE REL1 (H1,W1,V1,V2,LL)
      T=0.0174533/2.
      WRITE (6,21)
   21 FORMAT (T35,'DEPTH',T10,'TIME',T24,'DISTANCE',T54,'ANGLE OF EMERG.
     1')
      KK=LL-1
      TT=T
      DO 1 K=1,KK
      SEN=SIN(TT)
      P=SEN/V1
      HOS=SQRT(1.-SEN*SEN)
      VAN=SEN/HOS
      EMER1 = ATAN (VAN)
      P1=EMER1+W1
      ALF1= P1-W1
      HA1=H1
      PA1= HA1
      XA1= PA1/((1./TAN(ALF1))+TAN(W1))
      PP1=HA1-(XA1*TAN(W1))
      XP1=PP1 * TAN(EMER1)
      TA1= PP1/(V1*COS(ALF1))
      TP1=PP1/(V1*COS(EMER1))
      XR1=XA1+XP1
      TR1= TA1+TP1
      VR=V1/V2
      DE=TT/0.0174533
      IF(SEN.NE.VR) GO TO 10
      WRITE(6,20) XA1,P,XR1
   20 FORMAT (1H  ,'CRITICAL P=',F9.3,'RAYP=',F9.6,'CRI.D=',F9.3)
   10 WRITE (6,22) K,TR1,XR1,HA1,DE
   22 FORMAT (T3,I4,T10,F9.3,T25,F9.3,T35,F9.3,T55,F9.5)
      TT=TT+T
    1 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE  REL2   (H1, H2, W1, W2, V1,V2,V3,LL)
      T=0.0174533/2.
      WRITE (6,22)
   22 FORMAT (T1,'SEC.LAYER',T55,'ANGLE OF EMERG.',T12,'TIME',T24,'DISTA
     1NCE',T35,'DEPTH')
      KK=LL-1
      TT=T
      DO 2 K=1,KK
      SEN=SIN(TT)
      P=SEN/V1
      HOS=SQRT(1.-SEN*SEN)
      VAN=SEN/HOS
      EMER1 = ATAN (VAN)
      SEN2 =(V2/V1)*SIN( EMER1+W1)
      SS=1.-(SEN2*SEN2)
      IF(SS.LE.0.) GO TO 50
      HOS2=SQRT(1.-SEN2*SEN2)
      P2=ATAN(SEN2/HOS2)
      EMER2=P2-W1
       ALF2 = P2+ W1
      PAL = (V1/V2) * SIN(ALF2- W1)
      HPAL=SQRT(1.-PAL*PAL)
      PAP=ATAN(PAL/HPAL)
      ALF1 = PAP + W1
      HA1=H1
      HA2=H2
      PA1=HA1
      XA1=PA1/((1./TAN(ALF1)) + TAN(W1))
      PA2=HA2 + XA1*(TAN(W1)- TAN(W2))
      XA2 = PA2/((1./TAN(ALF2)) + TAN(W2))
      PP2 = HA2 +(( XA1 + XA2)*(TAN(W1) - TAN(W2)))
      XP2= PP2 /(( 1./ TAN(EMER2)) - TAN(W1))
      PP1=HA1-((XA1 + XA2 +XP2) * TAN(W1))
      XP1 = PP1 * TAN(EMER1)
      TA1 = (PA1-XA1*TAN(W1))/(V1 * COS(ALF1))
      TA2 =(PA2- XA2 * TAN(W2))/(V2 * COS(ALF2))
      TP2 = (PP2 + XP2 * TAN(W1))/(COS(EMER2)*V2)
      TP1 = PP1/(COS(EMER1)*V1)
      DE=TT/0.0174533
      HH2=HA1+HA2
      XR2= XA1+XA2 + XP1 + XP2
      TR2= TA1 + TA2+ TP1 + TP2
      VR2 = V2/V3
      IF(SEN2.NE.VR2) GO TO 5
       XCP= XA1 +XA2
      WRITE(6,21) XCP,P XR2
   21 FORMAT (1H ,'CRIP.L2=',F9.3,'RAYP=',F9.6,'CRI.D=',F9.3)
    5 WRITE (6,25) K,TR2,XR2,HH2,DE
   25 FORMAT (T3,I4,T10,F9.3,T25,F9.3,T35,F9.3,T55,F9.5)
      TT=TT+T
    2 CONTINUE
   50 RETURN
      END
```

```
      SUBROUTINE REL3(H1,H2,H3,W1,W2,W3,V1,V2,V3,V4,LL)
      T=0.0174533/2.
      DO 50 L=1,2
      WRITE (6,22)
   22 FORMAT (T1,'THIRD LAYER',T55,'ANGLE OF EMERG.',T13,'TIME',T24,'DIS
     1TANCE',T35,'DEPTH')
      TT=T
      IF (L.LT.2) GO TO 23
      T=0.00008
      W3=-0.0350000
   23 KK=LL-1
      DO 3 K=1,KK
      SEN=SIN(TT)
      P=SEN/V1
      HOS=SQRT(1.-SEN*SEN)
      VAN=SEN/HOS
      EMER1=ATAN(VAN)
      SEN2=(V2/V1)*SIN(EMER1+W1)
      HOS2=SQRT(1.-SEN2*SEN2)
      P2=ATAN(SEN2/HOS2)
      EMER2=P2-W1
      SEN3=(V3/V2)*(EMER2+W2)
      HOS3=SQRT(1.-SEN3*SEN3)
      P3 = ATAN(SEN3/HOS3)
      EMER3=P3-W2
      ALF3=P3+W3
      PAL=(V2/V3)*SIN(ALF3-W2)
      HPAL=SQRT(1.-PAL*PAL)
      PAP=ATAN(PAL/HPAL)
      ALF2=PAP+W2
      PAC=(V1/V2)*SIN(ALF2-W1)
      HPAC=SQRT(1.-PAC*PAC)
      PA3=ATAN(PAC/HPAC)
      ALF1=PA3+W1
      HA1=H1
      HA2=H2
      HA3=H3
      HH3=HA1+HA2+HA3
      PA1=HA1
      XA1=PA1/((1./TAN(ALF1)) + TAN(W1))
      PA2=HA2+XA1*(TAN(W1)-TAN(W2))
      XA2=PA2/((1./TAN(ALF2))+TAN(W2))
      PA3=HA3+((XA1+XA2)*(TAN(W2)-TAN(W3)))
      XA3=PA3/((1./TAN(ALF3))+TAN(W3))
      PP3=HA3+((TAN(W2)-TAN(W3))*(XA1+XA2+XA3))
      XP3=PP3/((1./TAN(EMER3))- TAN(W2))
      PP2=HA2+((TAN(W1)-TAN(W2))*(XA1+XA2+XA3+XP3))
      XP2=PP2/((1./TAN(EMER2)) - TAN(W1))
      PP1=HA1-(TAN(W1)*(XA1+XA2+XA3+XP3+XP2))
      XP1 = PP1*TAN(EMER1)
      TA1=(PA1- XA1*TAN(W1))/(V1*COS(ALF1))
      TA2=(PA2 - XA2*TAN(W2))/(V2* COS(ALF2))
      TA3=(PA3- XA3*TAN(W3))/(V3*COS(ALF3))
      TP3=(PP3+XP3*TAN(W2))/(V3*COS(EMER3))
      TP2=(PP2+ XP2*TAN(W1))/(V2*COS(EMER2))
      TP1=PP1/(V1*COS(EMER1))
      XR3=XA1+XA2+XA3+XP3+XP2+XP1
      XA=XA1+XA2+XA3
```

```
      IF (L.GT.1) GO TO 28
      IF (XR3.LT.110.) GO TO 28
      T=TT
      GO TO 50
   28 TR3=TA1+TA2+TA3+TP3+TP2+TP1
      DE=TT/0.0174533
      VR3=V3/V4
      IF(SEN3.NE.VR3) GO TO 10
      XCP=XA1+XA2+XA3
      WRITE(6,21) XCP,P,XR3
   21 FORMAT(1H ,'CRIP.L3=',F9.3,'RAYP=',F9.6,'CRID=',F9.3)
   10 WRITE (6,31) K,TR3,XR3,HH3,DE,XA
   31 FORMAT (T3,I4,T10,F9.3,T25,F9.3,T35,F9.3,T55,F9.5,T70,F8.3)
      TT=TT+T
    3 CONTINUE
   50 CONTINUE
      RETURN
      END
```