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

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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.

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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

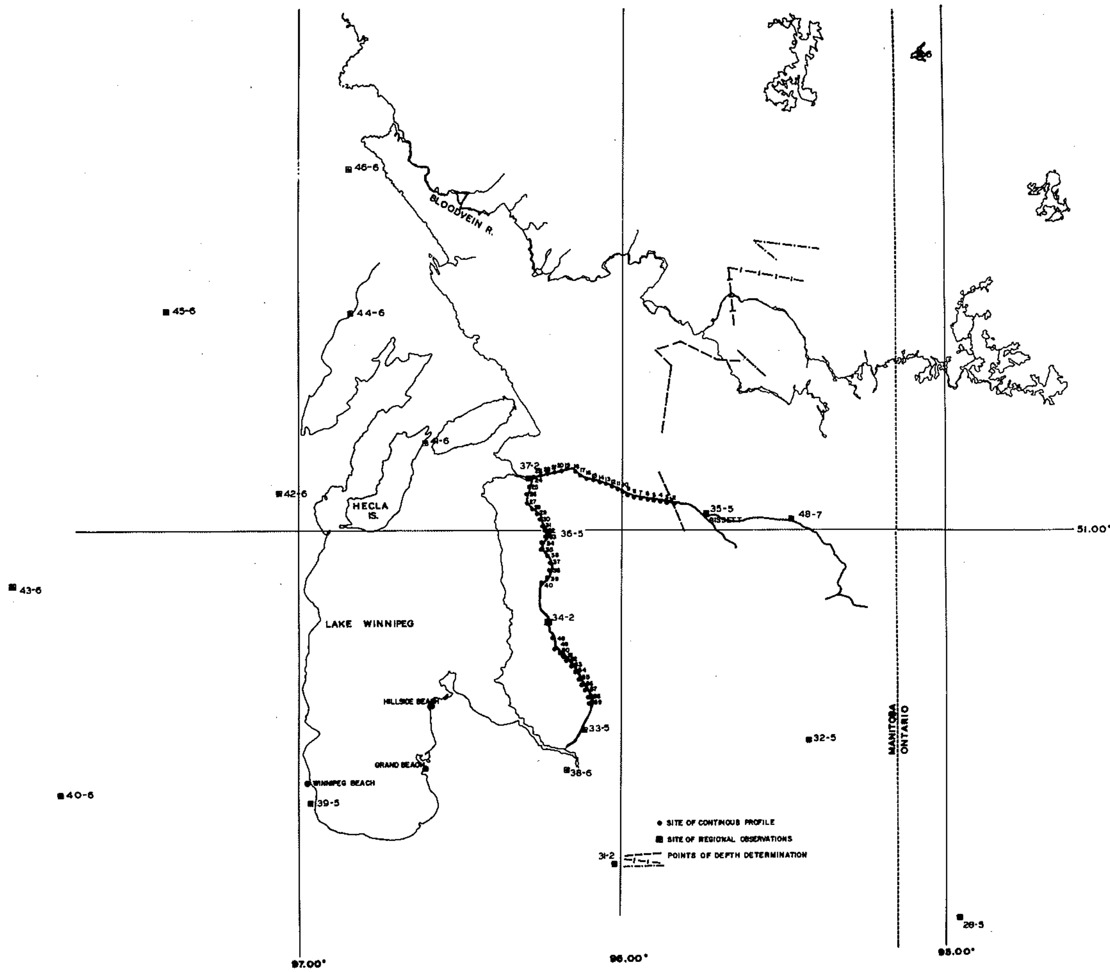

FIGURE 1. Location map of the regional and detailed refraction survey sites.

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 shot-point 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

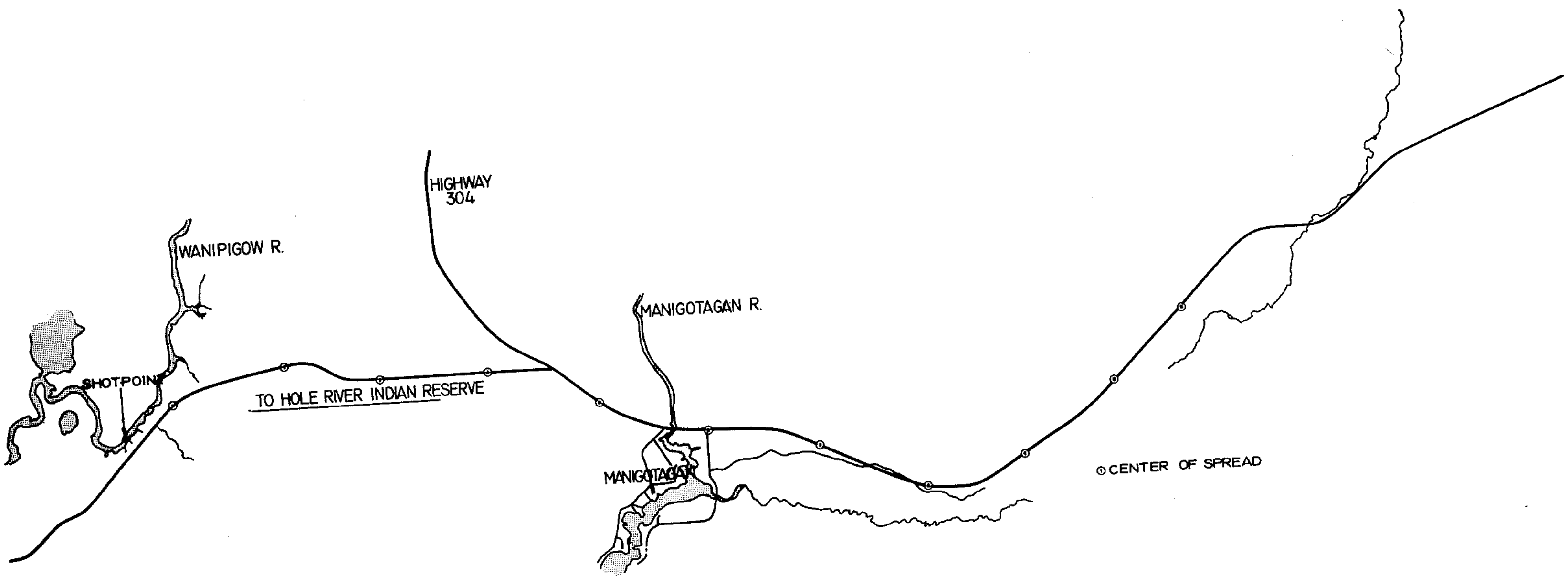

FIGURE 2. Location map of the vertical reflection survey sites.

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

$$A = X\ W^n$$