

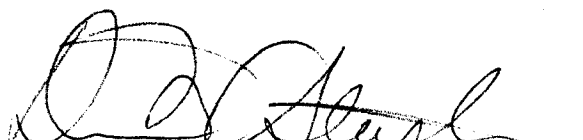
1165
OF
86-16

CAVITY DETECTION USING HIGH-RESOLUTION
SEISMIC REFLECTION METHODS

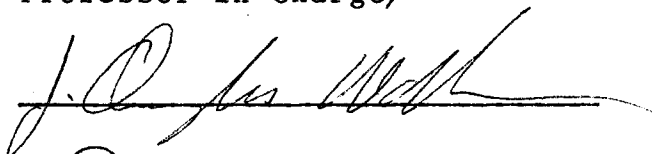
by

Keith L. Branham
B.S., Southwest Missouri State University, 1984

Submitted to the Department of
Geology and the Faculty of the
Graduate School of the University
of Kansas in partial fulfillment
of the requirements for the degree
of Master of Science.



Professor in Charge






Committee Members



For the Department



Date thesis Accepted

ABSTRACT

Surface collapses due to abandoned coal mines are a problem of great concern in southeastern Kansas. A reliable, cost-efficient method for detecting these mined cavities is needed to evaluate prospective construction sites.

High-resolution reflection seismology was used successfully to detect mined cavities in a 1 meter (3 feet) thick coal seam at depths of 9 and 13 meters (29 and 43 feet). A dominant frequency of 275 Hz was attained and reflections from both the top and bottom of the coal seam were resolved. The reflected event from the top of the coal seam exhibited reduced amplitudes over water and coal ash slurry-filled cavities. The reflected event from the bottom of the coal seam exhibited a velocity pull-up beneath water and slurry-filled cavities.

ACKNOWLEDGEMENTS

I wish to thank my committee members, Don Steeples, Don Sprowl, and Doug Walker for their helpful input and expeditious review of this study. Thanks to Rick Miller, Ralph Knapp, and Carl McElwee for their scientific input and constructive criticisms. Thanks to all of my fellow graduate students who helped collect the seismic data in the field. Thanks to Janice Sorensen for her endless assistance in researching this study, and to all members of the Kansas Geological Survey staff for their friendship and support. Thanks to Larry Brady for sharing his knowledge of the southeastern Kansas coal field. Thanks to my sister Rhonda for providing the word processing equipment used to prepare this study. Most of all, I thank my wife Cynthia for her never-ending support and for the countless nights she sat alone while I studied or gazed into a CRT for hours on end.

This project was funded by the Office of Surface Mining through Assistance Agreement # J5150055.

TABLE OF CONTENTS

	page
Abstract.....	i
Acknowledgements.....	ii
List of Illustrations.....	v
List of Tables.....	vii
Introduction.....	1
Purpose of Study.....	1
Previous Work.....	2
Study Area.....	4
Geological Background.....	10
Depositional Environment.....	10
Local Structural Features.....	12
Local Stratigraphy.....	14
Seismic Theory.....	19
Common Depth Point Method.....	20
Resolution.....	24
Pittsburg Industrial Park Seismic Data.....	25
Processing.....	30
Line 1 Interpretation.....	32
Line 2 Interpretation.....	35
Line 3 Interpretation.....	37
Pittsburg Mobile Home Park Seismic Data.....	42
Frontenac Seismic Data.....	44
50 Caliber Seismic Data.....	44
Processing.....	47

TABLE OF CONTENTS (cont'd)

Interpretation.....	50
30.06 Seismic Data.....	63
Conclusions.....	66
References Cited.....	68
Appendices.....	71
A - Justification of Field Parameters.....	71
B - Seismic Data Processing Steps.....	74

LIST OF FIGURES

	page
Figure 1: Map of the southeastern Kansas coal field.....	5
Figure 2: Map of mined areas of the Weir-Pittsburg coal bed around the study area.....	7
Figure 3: Map showing the locations of the work sites for the study.....	8
Figure 4: Subsurface mine map of the Frontenac site.....	9
Figure 5: Map showing the regional structural features surrounding the study area.....	11
Figure 6: Structural contour map of the study area.....	13
Figure 7: Composite stratigraphic section of the Cherokee Group in southeastern Kansas....	16
Figure 8: Stratigraphic section from the Weir-Pittsburg coal bed to the surface.....	17
Figure 9: Diagram illustrating the Common Depth Point (CDP) method.....	23
Figure 10: Map of the Pittsburg Industrial Park study site.....	26
Figure 11: A 24-channel field file with part of the geophones located over coal and others over cavity.....	29
Figure 12: Frequency spectrum plot of the Pittsburg data indicating a predominant frequency of 275 Hz.....	31
Figure 13: CDP seismic section of Pittsburg line 1 with interpreted geological cross-section.....	34
Figure 14: CDP seismic section of Pittsburg line 2 with interpreted geological cross-section. Residual statics applied.....	36

LIST OF FIGURES (cont'd)

Figure 15: CDP seismic section of Pittsburg line 2 with no residual statics applied..... 38

Figure 16: CDP seismic section, interpreted geological cross-section, and surface topography of Pittsburg line 3..... 40

Figure 17: Enlarged portion of the seismic section in figure 16..... 41

Figure 18: Mine map of the Pittsburg mobile home park study site..... 43

Figure 19: CDP seismic section of the Pittsburg mobile home park line..... 45

Figure 20: Walkaway noise test of the Frontenac site using the 50 caliber source..... 46

Figure 21: Map showing the location of the Frontenac 50 caliber seismic line over the known cavity..... 48

Figure 22: 50 caliber seismic section of the line shot west to east..... 52

Figure 23: CDP's 145 to 335 of the 50 caliber line shot west to east..... 53

Figure 24: Interpreted version of the seismic section in figure 23..... 54

Figure 25: CDP's 335 to 525 of the 50 caliber line shot west to east..... 55

Figure 26: Interpreted version of the seismic section in figure 25..... 56

Figure 27: CDP seismic section of the 50 caliber line shot east to west with an interpreted version..... 59

Figure 28: Diagram of a model which produces a shadow zone and causes a shift of the effects of the cavity 61

Figure 29: Diagram illustrating how the location and size of the cavity may be deduced... 62

LIST OF FIGURES (cont'd)

Figure 30: CDP seismic section of the Frontenac 30.06 line superposed over the previous 50 caliber lines.....	64
Figure 31: CDP seismic section of the Frontenac 30.06 line located 15 meters north of the previous 50 caliber lines.....	65

LIST OF TABLES

	page
Table 1: Compressional acoustic velocities for coal as cited from various sources.....	21
Table 2: Recording parameters for the Pittsburg Industrial Park and mobile home park sites.....	28
Table 3: Processing steps and parameters used for the Pittsburg Industrial Park and mobile home park data.....	33
Table 4: Recording parameters for the Frontenac 50 caliber lines.....	49
Table 5: Processing steps and parameters for the Frontenac 50 caliber data.....	51

INTRODUCTION

Subsurface cavities of various origins pose many problems for engineers and hydrologists and it is often necessary to obtain some knowledge of the subsurface prior to excavation or construction. High-resolution reflection seismology has shown great promise for being the reliable, cost-efficient method of cavity detection needed to evaluate prospective construction sites.

High-resolution seismic reflection profiles were recorded at three different sites within mined areas of the southeastern Kansas coal field. Mined cavities within the Weir-Pittsburg coal bed were the target of the study.

PURPOSE OF STUDY

In some areas, abandoned coal mines cause serious problems such as water pollution and surface collapse. Surface and ground waters percolate through the mines, react with sulfide minerals, and eventually make their way to nearby streams (Fisher, 1971). In areas such as southeast Kansas, some of these mines are so near to the surface that catastrophic collapse is common place, causing surface depressions.

Locating subsurface mines has long been a problem. Inaccuracies in mine maps, be it due to plotting errors, north arrow mislocation or differential

shrinkage of map paper, further complicate the location of these cavities (Fisher, 1971). At present, the only reliable method for defining these voids is drilling, which is very costly.

This study examines the application of the high-resolution reflection seismology method for locating abandoned subsurface coal mines in a one meter (3 ft) thick coal bed at depths ranging from 10 to 20 meters (30 to 60 ft).

PREVIOUS WORK

Seismic research has been conducted to detect cavities due to salt solution mining (Cook, 1965), lava flow tunnels (Watkins et al., 1967), and abandoned subsurface coal mines (Fisher, 1971; Hasbrouck and Padgett, 1982) with limited success. Most of the research done on coal mine detection has involved refraction seismology or S-wave reflection seismology. This study is the first to locate water-filled coal mine cavities at depths of less than 30 meters (100 feet) by high-resolution P-wave reflection seismology techniques.

Most researchers using seismic techniques for cavity detection cite three phenomena for evidence of a cavity: free oscillations or resonance of the cavity walls, anomalous amplitude attenuations, and delay of arrival times (Cook, 1965; Watkins et al., 1967; Fisher,

1971). Biot (1952) found that the resonant frequency (f) of a cylindrical borehole in an infinite solid is related to the borehole diameter (D) and shear wave velocity (Vs) of the medium by the relation $D=V_s/1.55f$. This relationship is true for a homogeneous medium, such as a basalt layer, but does not appear to be applicable in the coal mine case since the cavity is bounded by three different materials (Fisher, 1971); the bottom of the cavity being composed of underclay, the sides of coal, and the roof of the overlying strata, all of which possess different elastic properties.

Cook (1965) found that seismic energy transmitted through a cavity and reflected from a deeper horizon was attenuated correspondingly more than reflected energy missing the cavity, giving rise to a seismic amplitude "shadow". Anomalous reflection amplitudes over lava tunnels have also been observed (Watkins et al., 1967).

Due to the elastic properties of fluids, seismic shear waves will not be propagated by voids or water-filled cavities, and may therefore be utilized for cavity detection. Strong SH waves have been generated and good reflections received from the tops of brine cavities 150 meters deep (Cook, 1965). Shear wave reflections have also been used to evaluate the

resources of a shallow coal seam (Hasbrouck and Padget, 1982).

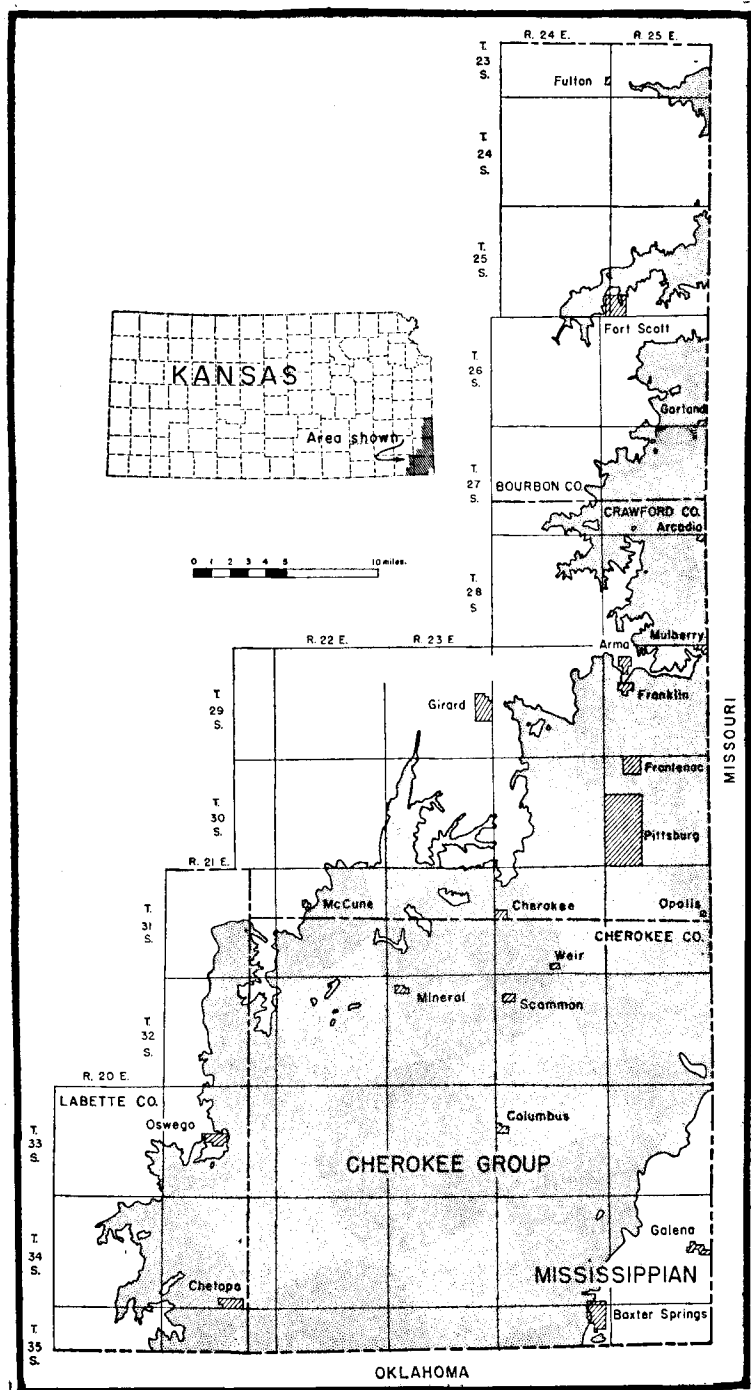
Seismic refraction has been used for cavity detection with limited success (Fisher, 1971). In dealing with the cyclothem coals of southeast Kansas, however, the alternating shales yield various low velocity layers which make refraction seismology unfeasible in this area.

High-resolution reflection seismology has been used to evaluate detailed structural and stratigraphic features of a coal seam in Wyoming which is about 30 meters (100 ft) thick and buried at a depth of 180 meters (600 ft) (Greaves, 1985). A similar study was conducted over two coal seams approximately 15 to 30 meters (50 to 100 ft) thick buried at a depth of 670 meters (2200 ft) in central Utah (Fry and Orange, 1982). Neither of these studies, however, involved cavity detection of previously mined areas.

STUDY AREA

The area chosen for this study is in the southeastern Kansas coal field (see figure 1). The Weir-Pittsburg coal bed has been extensively mined in this area by both subsurface and strip-mining methods. The subsurface mines leave behind a maze of interconnecting cavities. Figure 2 is a portion of a

Figure 1: Map showing the extent of the Cherokee Group in southeast Kansas which makes up the southeast Kansas coal field. (from Schoewe, 1959)



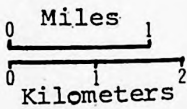
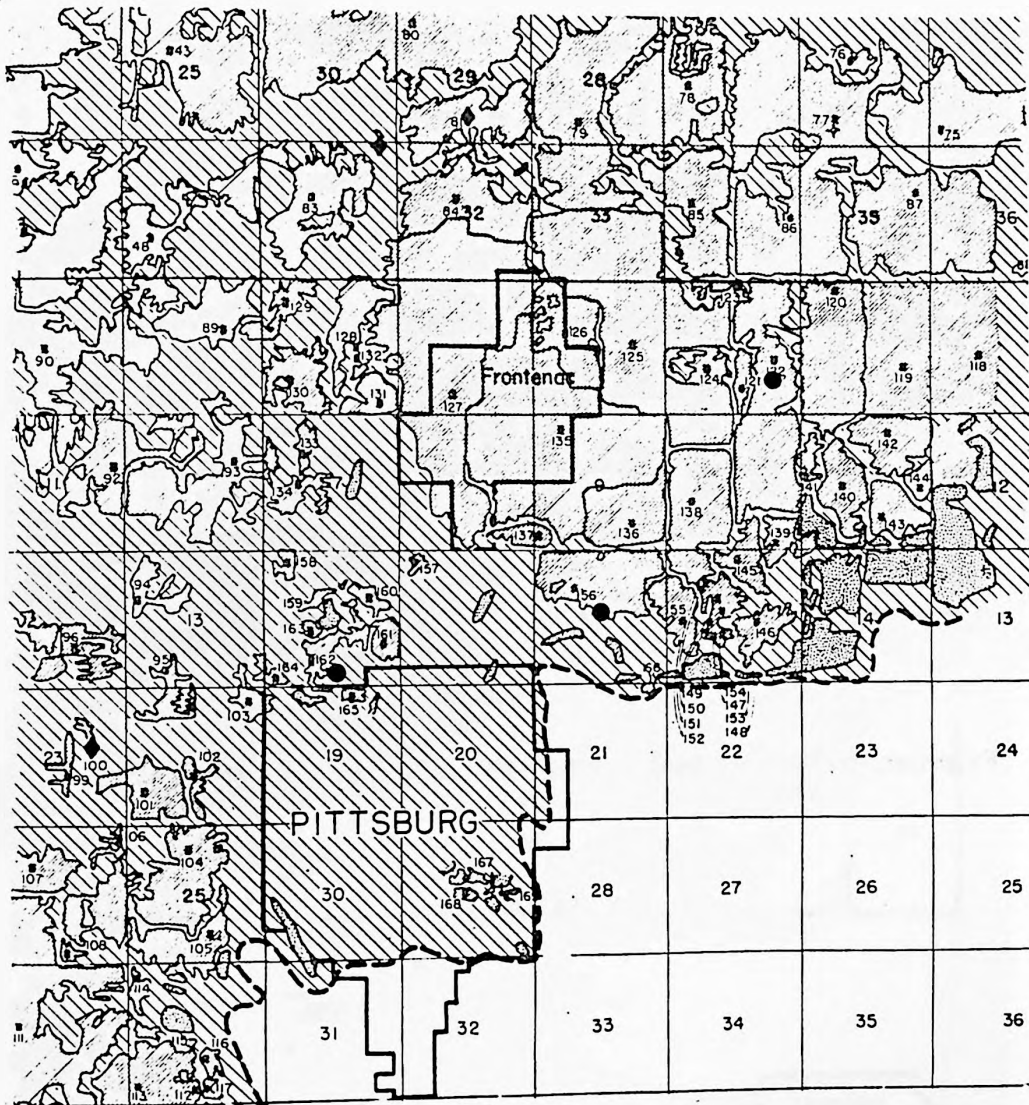
map showing mined areas of the Weir-Pittsburg coal bed in and around the study area as of 1944. Most of the region around the study area has been undermined and many cases of surface collapse have occurred.

The three work sites chosen for this study are located in T.30S., R.25E. (figure 3). The first site is located in the Pittsburg Industrial Park on the northeast edge of the city of Pittsburg, Kansas. This location was selected because of drill-hole data and numerous surface collapses that indicate subsurface cavities at depths of 6-15 meters (20-49 feet).

The second site is located within a mobile home park on the west edge of Pittsburg. This location was chosen because a mine map and surface collapse indicate subsurface cavities. The depth of the coal bed mined at this site is estimated to be about 10 meters.

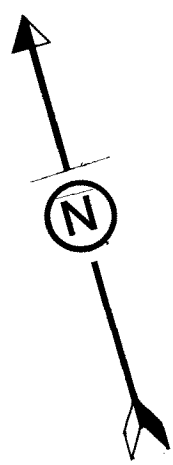
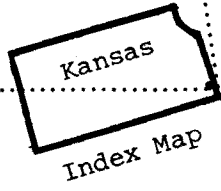
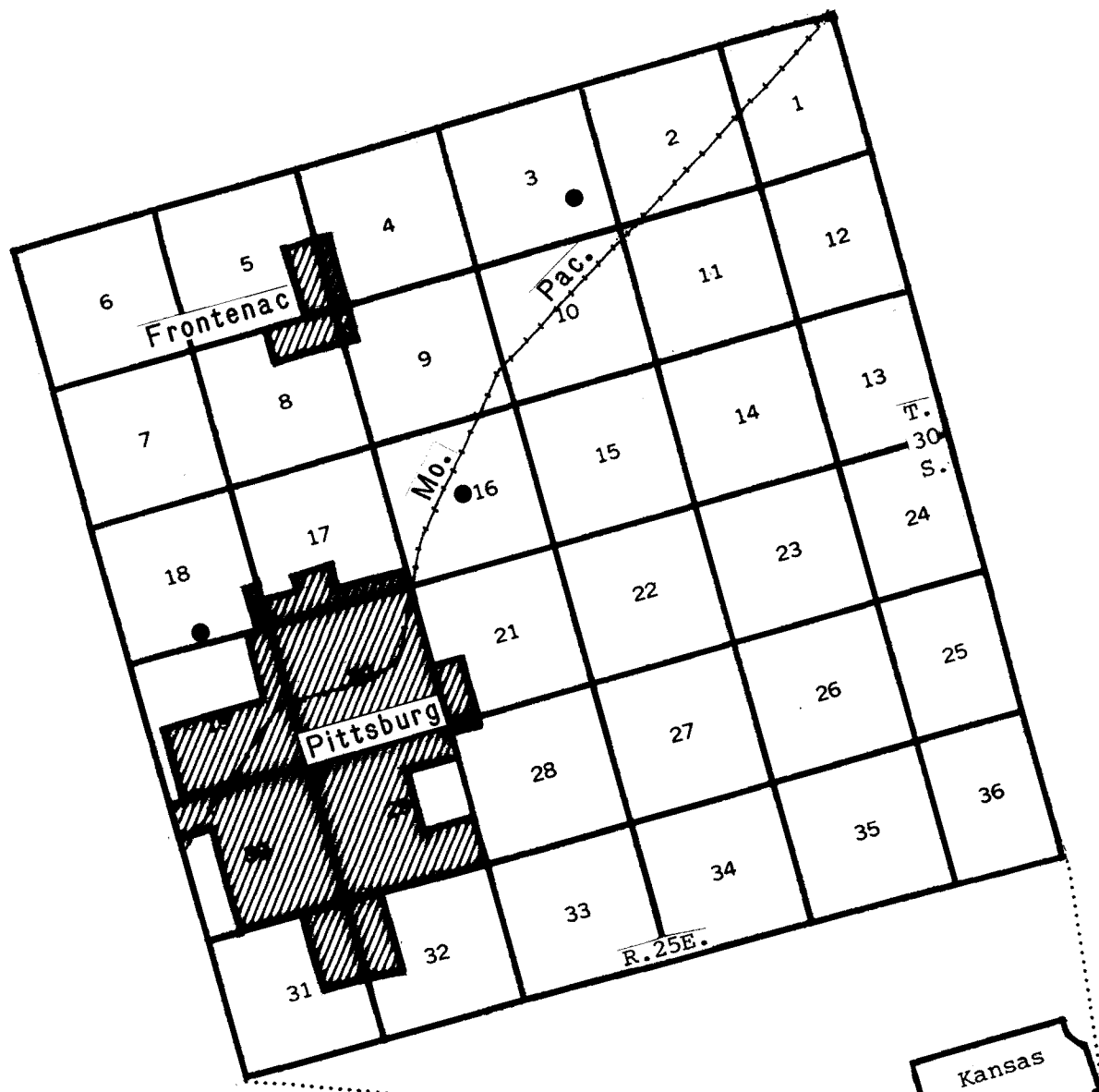
The third site is located approximately two miles east of Frontenac, Kansas. This location was chosen because a subsurface mine map of the area indicates a long, single cavity at a depth of about 20 meters (60 feet) with undisturbed coal on either side. A portion of this mine map is displayed in figure 4. This situation should give rise to a continuous seismic character everywhere on the line except directly over the single cavity, thus aiding in the identification and location of the cavity.

Figure 2: Map of mined areas of the Weir-Pittsburg coal bed around the study area. (from Abernathy, 1944)



- Study sites
- Mined area
- Unmined area
- Mine index number
- Stripped area
- Approximate outcrop of Weir-Pittsburg coal

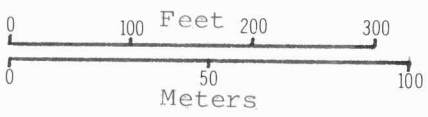
Figure 3:Map showing the location of the work sites for the study.



● Study Sites



Figure 4: Detailed subsurface mine map of the Frontenac work site showing long single cavity with unmined coal on either side. (from Brown, 1933)



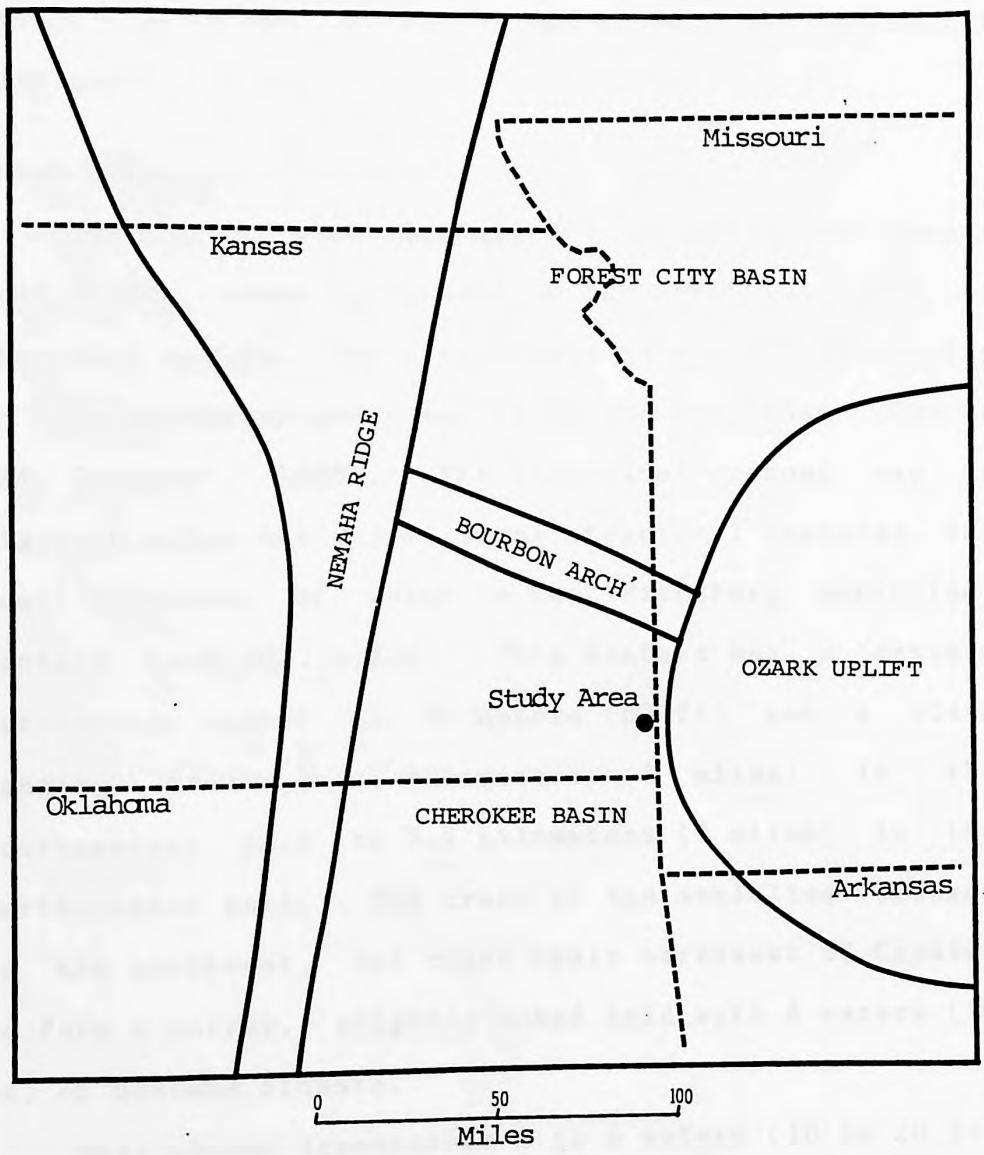
GEOLOGICAL BACKGROUND

The study area is located in the Cherokee basin which is bounded on the east by the Ozark uplift, on the west by the Nemaha Ridge, and is separated from the Forest City basin on the north by the Bourbon arch (figure 5). Pennsylvanian age sedimentary rocks in the Cherokee basin gradually thicken to the south into the thick Pennsylvanian sequence of the Arkoma basin (Harris, 1984). The convergent Ouachita system had a direct influence on the structural and depositional framework for the Pennsylvanian strata in the Cherokee basin. Terrigenous sediments were supplied to this basin from the Appalachian, Ouachita and Arbuckle-Wichita mountains, as well as the Canadian Shield.

Depositional Environment

The various phases of the Cherokee cyclothems are best interpreted as facies of alluvial-deltaic complexes (Heckel et al., 1979). The repetitive nature of the various lithologies is due to delta shifting and distributary abandonment with slow subsidence but no significant change in eustatic sea level. The Cherokee coals are the culmination of aggrading sedimentation on delta plains. The idealized sequence of lithologies in the Cherokee type cyclothems reflects progradation of a clastic wedge: dark marine shale with rare limestone,

Figure 5: Map showing the regional structural features surrounding the study area.



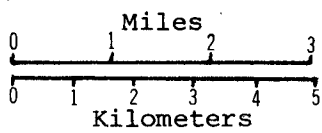
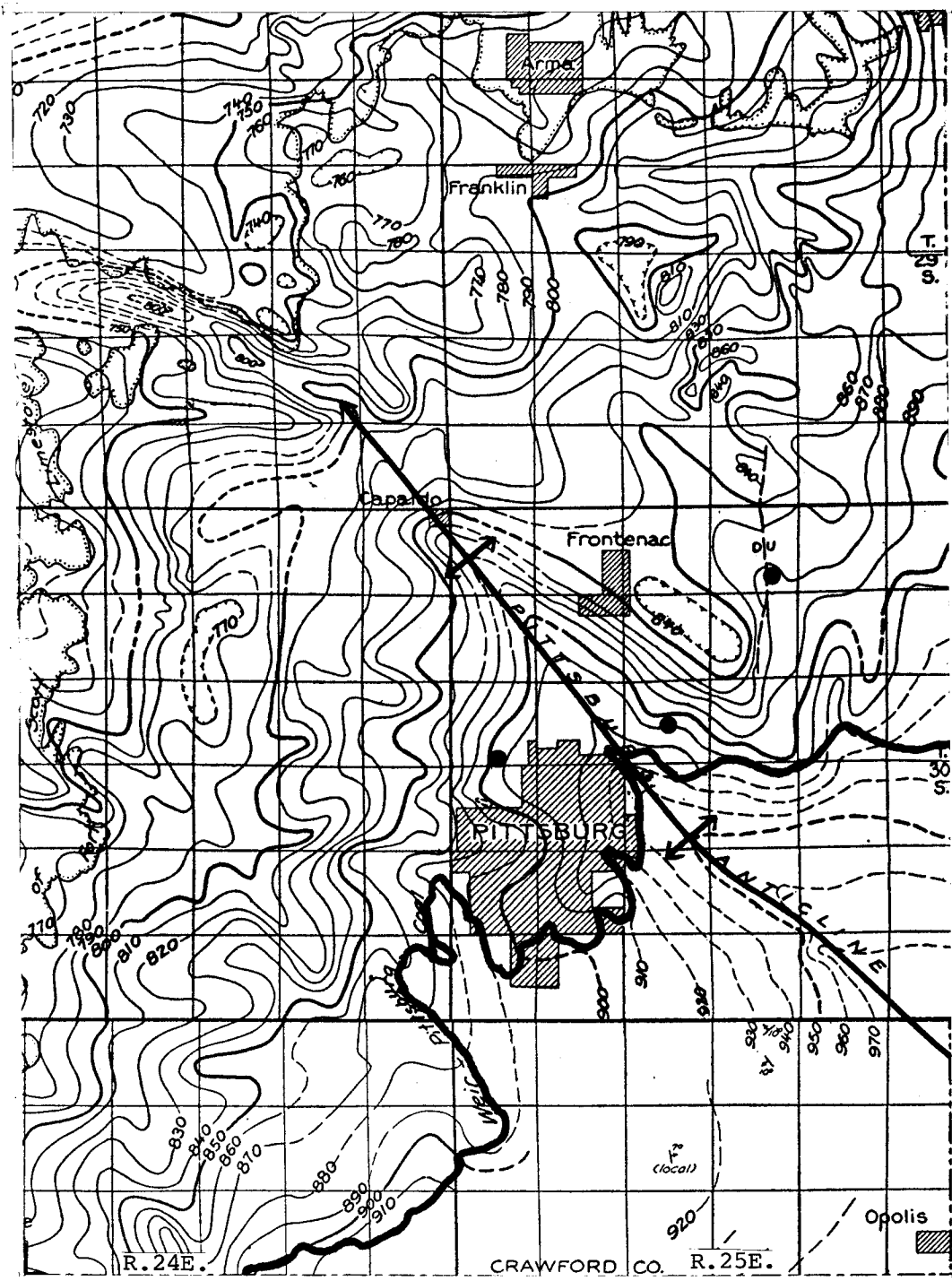
gray sideritic shale, gray silty shale with thin sandstone interbeds, rare cross-bedded sandstone, thin-bedded sandstone, siltstone and shale, and underclay with coal.

Local Structural Features

The study took place in the southeastern Kansas coal field, which is located on the northwest flank of the Ozark uplift. The strata here have a prevailing dip to the northwest and a strike to the northeast (Pierce and Courtier, 1938). The structural contour map in figure 6 shows the major local structural features, the most prominent of which is the Pittsburg anticline, located in T.30S.,R,25E. This feature has a maximum structural relief of 21 meters (69 ft) and a width ranging from 6.4 kilometers (4 miles) in the southeastern part to 3.2 kilometers (2 miles) in the northwestern part. The crest of the anticline plunges to the northwest, but rises again northwest of Capaldo to form a narrow, slightly domed fold with 6 meters (20 ft) of maximum closure.

Many closed depressions 3 to 6 meters (10 to 20 ft) in depth are found in the study area (Pierce and Courtier, 1938). These features are thought to be due in part to differential compaction. Other larger and deeper depressions are attributed to solution of

Figure 6: Structural contour map of the study area showing local structural features. The contours are drawn on the top of the Weir-Pittsburg coal bed using a contour interval of 10 feet. The dark outline is the approximate outcrop of the coal bed. (from Pierce and Courtier, 1938)



● Study Sites

Mississippian limestones and subsequent sinking of the overlying Cherokee shales.

Four faults have been identified in the southeastern Kansas coal field (Pierce and Courtier, 1938). The largest of these is a north-striking fault located within the study area east of Frontenac. The horizontal extent of this fault is about 4 kilometers (2.5 miles), and the throw is 4 to 5 meters (12 to 15 ft). This fault is not observed on the surface and had been interpreted in the past, from mine and drill-hole data, as a normal fault. One of the seismic lines shot at the Frontenac site traverses the fault perpendicular to it's strike. The seismic data suggest that this feature is a reverse fault rather than a normal fault. The fact that this fault occurs on the flank of the Pittsburg anticline, a compressional feature, lends support to the interpretation of this feature as a reverse fault. This seismic data will be presented later in the section on interpretation of the Frontenac data.

Local Stratigraphy

The Cherokee Group includes both marine and nonmarine strata (Zeller, 1968). This group is composed mostly of sandstone and sandy shale and also contains the most important coal beds in the state. Very little

limestone is present. Thickness of the Cherokee Group ranges from 110 to 150 meters (360 to 500 ft). The Cherokee Group has been divided into two formations; the Krebs and the Cabaniss. A composite stratigraphic section is presented in figure 7. The Cabaniss Formation contains the coal interval which is the subject of this study. Therefore, that section of the Cabaniss above and including the Weir-Pittsburg coal bed will be emphasized. A detailed stratigraphic section was constructed from data collected from drill cuttings (figure 8).

The Cabaniss Formation is primarily shale but contains some sandstone, limestone and coal (Zeller, 1968). Thickness of the Cabaniss Formation ranges from 106 meters (350 ft) in northern Craig County, Oklahoma, to 67 meters (220 ft) in southern Bourbon County, Kansas (Harris, 1984).

The Weir-Pittsburg coal bed is the thickest of the southeastern Kansas coals with an average thickness of 1 meter (3 to 3.5 ft) (Pierce and Courtier, 1938; Howe, 1956; and Zeller, 1968) and a maximum thickness of about 1.5 meters (5 ft) in Labette County, Kansas (Howe, 1956). This coal bed has been extensively mined and has been the most commercially important of all of the southeast Kansas coals. It is often used as a marker horizon for the middle Cherokee. The extensive

Figure 7: Composite stratigraphic section of the Cherokee Group in southeast Kansas. (from Harris, 1985)

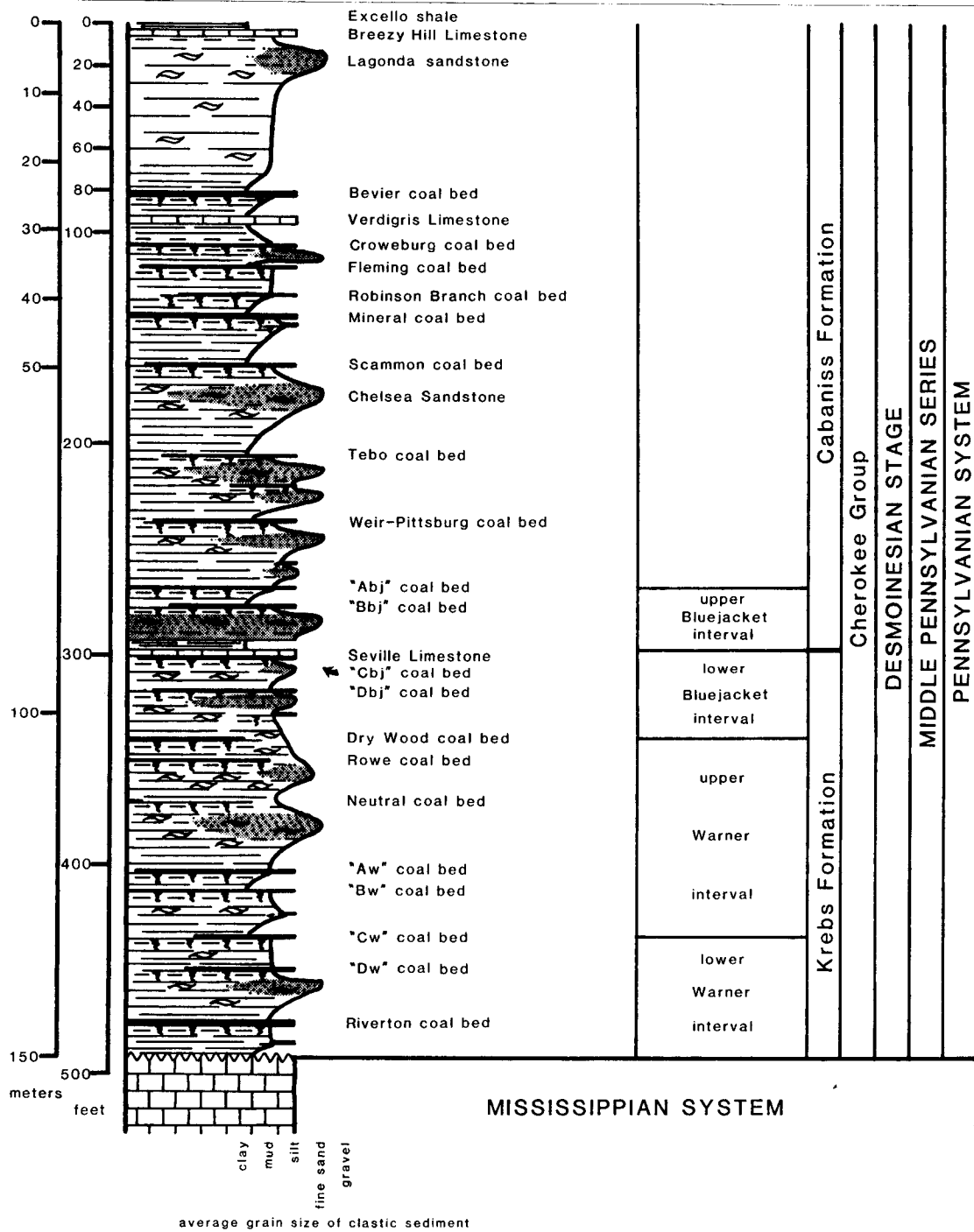
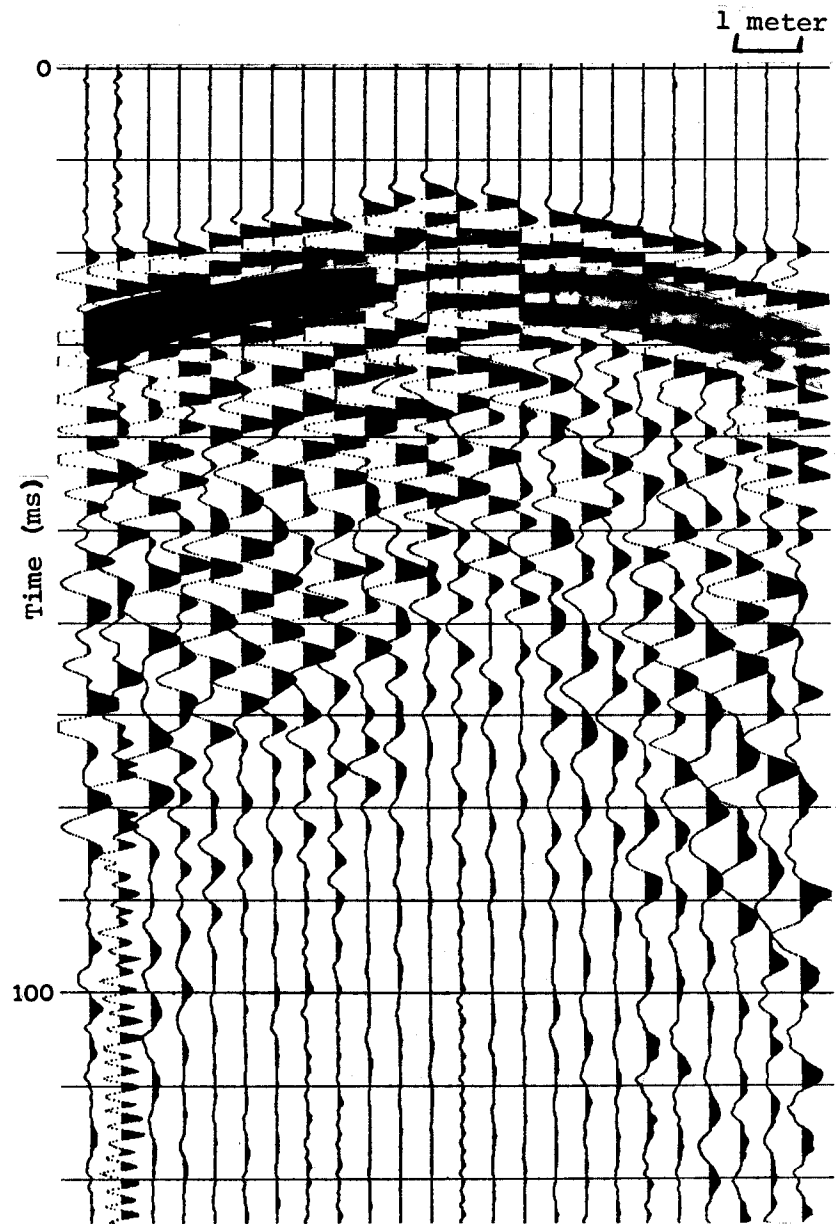
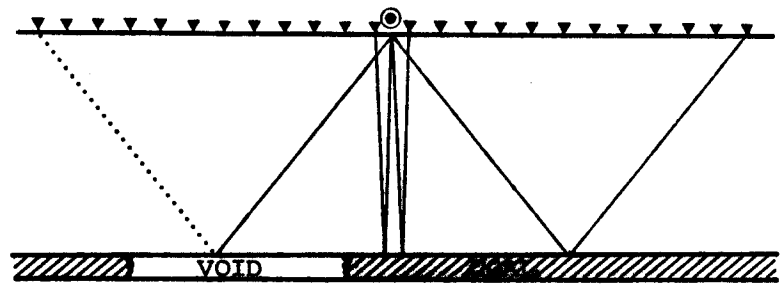


Figure 8: Stratigraphic section from the Weir-Pittsburg coal bed to the surface, based on drill cuttings. The resistant layers shown are based on drilling resistance.



mining of the Weir-Pittsburg coal prompted the study of this area.

The interval above the Weir-Pittsburg coal consists of shale, sandy shale, some sandstone and other thinner coals (Pierce and Courtier, 1938). These include dark gray, micaceous sandy or silty shales, with some interbedded fine-grained sandstones. Small isolated clay-ironstone concretions are also common (Howe, 1956). Above these shales is the Tebo underclay, a silty, gray clay averaging 1 meter (3 ft), which is overlain by the Tebo coal bed. The Tebo coal is generally only about 15 cm (0.5 ft) thick and is usually not mined commercially. In some areas of eastern Crawford County, Kansas, and western Barton County, Missouri, an impure nodular to massive limestone up to 25 cm (10 in) thick is found locally beneath the Tebo underclay (Howe, 1956), but was not found at the project sites. The interval between the Weir-Pittsburg and Tebo coal beds is generally 4.5 to 7.5 meters (15 to 25 ft) thick (Zeller, 1968) but decreases to zero, so that the two are in contact, in northwestern Cherokee County, Kansas (Howe, 1956). At the Frontenac site this interval was found to be about 10 meters (30 ft) thick.

Above the Tebo coal is another interval of shales (Howe, 1956). Directly above the Tebo coal bed is 30 to 60 cm (1 to 2 ft) of black, fissile shale, overlain by

an impure pyritic limestone averaging 10 cm (4 in) in thickness, which is in turn overlain by 1.5 to 2 meters (5 to 7 ft) of dark gray to black fissile shale containing clay-ironstone beds. The presence of the limestone bed was not obvious from the drill cuttings at the Frontenac site. Above the dark shale and limestone is more sandstone and sandy shale.

SEISMIC THEORY

Reflection seismology involves introducing an acoustic wave into the ground by means of an artificial source, typically some form of explosion or weight drop, and the subsequent monitoring at the surface of the energy reflected from subsurface geological structure. This monitoring is done by means of a geophone, a velocity sensitive device which converts the ground motion from the reflected energy into electronic pulses whose time varying amplitudes are recorded onto digital tape.

The amount of energy reflected at a given boundary is dependent upon the contrast in the acoustic impedance of the two layers, where acoustic impedance (Z) is defined as the product of the acoustic velocity (V) and the density (ρ) of each layer: $Z=(V\rho)$. The amount of energy reflected at normal incidence is determined by the reflection coefficient (R) which is defined as:

$$R = (Z2 - Z1) / (Z2 + Z1)$$

where: Z1 = Acoustic impedance of
upper layer

Z2 = Acoustic impedance of
lower layer .

Therefore, if two consecutive layers have a contrast in acoustic impedance, reflections can result.

It is possible for a water-filled cavity and a coal seam to have essentially the same acoustic impedance. The acoustic velocity of water is approximately 1600 m/s and the density of water is 1 g/cc, yielding an acoustic impedance of 1600. The coals of southeastern Kansas have a density of about 1.4 g/cc, therefore, an acoustic velocity of 1150 m/s would also give rise to an acoustic impedance of 1600. Under these conditions, the transition from the coal seam to the water-filled cavity could be undetectable by seismic P-wave reflection methods, unless a velocity pull-up occurs from a deeper reflection. Examination of table 1, which cites values for acoustic velocity in coal from various references, reveals that a value of 1150 m/s is reasonable for the velocity of coal.

Common Depth Point Method

The Common Depth Point (CDP) method is a very powerful technique for enhancing seismic reflection data. This method involves summing or stacking together

TABLE 1

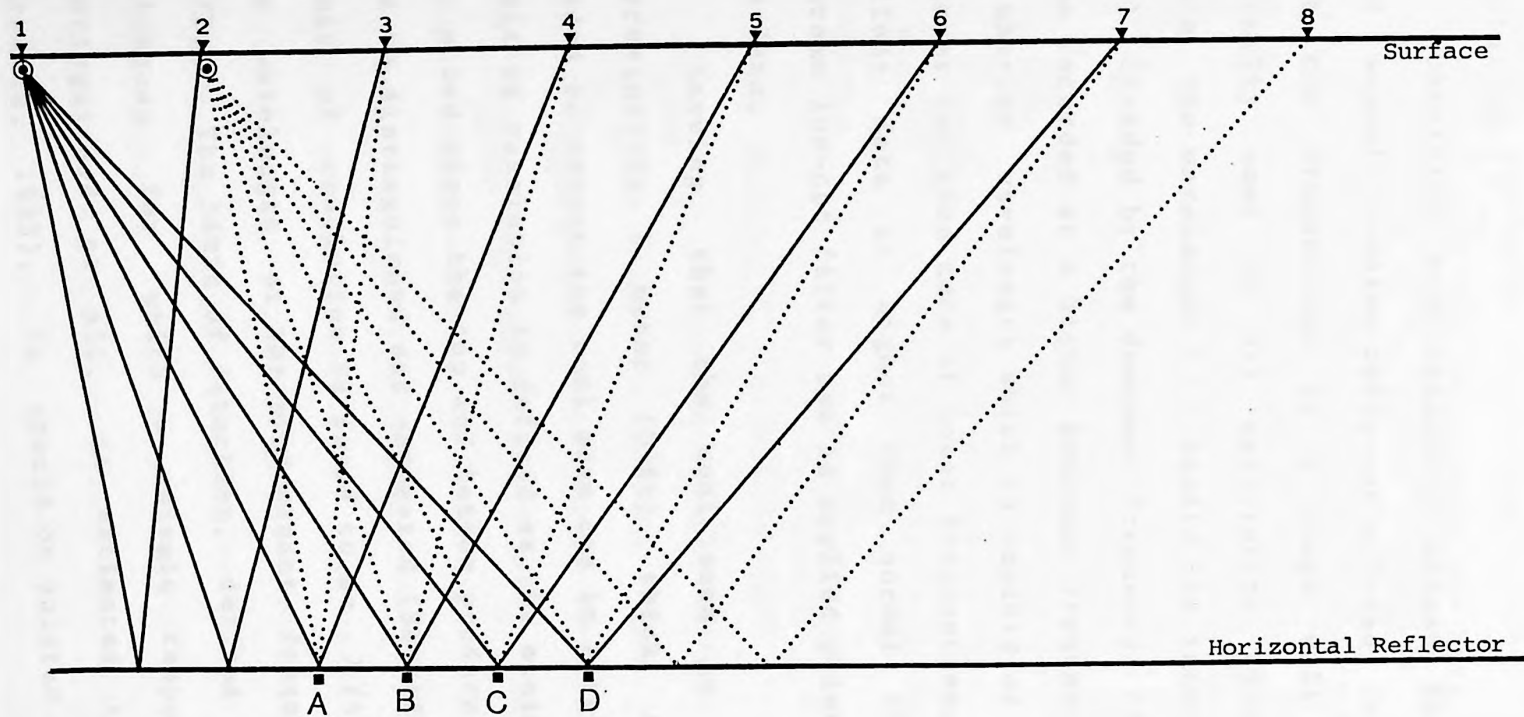
Compressional acoustic velocities for coal as cited from various sources.

VELOCITY (m/s)	STUDY AREA	REFERENCE
2400	Eastern Australia	Hawkins et al., 1982
640-2000	Kentucky	Rodriguez, 1986
1700	Wyoming	Greaves, 1985
650-1400	West Germany	Asten et al., 1982
510	Pennsylvania	Wolfe, 1983

signals from different shot and geophone locations which are reflected from a common point in the subsurface.

Figure 9 illustrates the CDP method. This figure shows how two consecutive shotpoints, at locations 1 and 2, are recorded at six adjacent locations. For example, energy from shot 1 travels along the solid line raypaths, is reflected at the subsurface reflector, and received at locations 2 through 7. Likewise, energy from shot 2 travels along the dotted line raypaths, is reflected, and received at locations 3 through 8. Note that the interval between the reflection points is exactly half that of the receiver spacing, yielding two reflection points for every surface location. The points on the reflector labelled A,B,C and D reflect energy from both shots and are therefore referred to as common reflection points or common depth points (CDP). Since the signals recorded along paths 1-A-4 and 2-A-3 possess a common reflection point, A, they will be summed together after correcting for the difference in path length (normal moveout), as will the signals reflected at B,C and D. Stacking multiple traces in this fashion increases the signal-to-noise ratio, where signal is defined as any event on the seismic record from which we wish to obtain information and noise is anything which interferes with this signal (Telford et al., 1976).

Figure 9:Diagram illustrating the Common Depth Point (CDP) method. Signals from different sources which reflect at a common reflection point, such as those travelling along paths 1-A-4 and 2-A-3, are summed together during processing.



⊙ Shot location

▼ Geophone location

■ Common reflection point

Resolution

Obtaining high resolution seismic data requires a good signal-to-noise ratio and a broad frequency band with the frequencies in a range well above those typically used in oil exploration (Greaves, 1985). Since the wavelength (λ) equals the interval velocity (V_i) divided by the dominant frequency (f), $\lambda = V_i/f$, data recorded at a higher dominant frequency will yield a shorter wavelength which is capable of resolving a thinner bed than data of lower frequencies. In order to collect data at higher than normal frequencies, an extreme low-cut filter can be applied prior to recording the data.

Knowing that the coal seam in question is approximately 1 meter (3 ft) thick, the frequency needed to detect the coal seam can be established. The limit of resolution is defined as the minimum thickness of a bed where the top and bottom produce effects that can be distinguished and separated (Sheriff, 1980). The limit of resolution is found to be $\lambda/4$ where λ is the wavelength of the predominant frequency (Widess, 1973). The limit of detection, defined as the minimum thickness for which a seismic response can be distinguished at all, is estimated to be $\lambda/30$ (Greaves, 1985). It should be pointed out that the

practical limits for any data set depend on signal-to-noise ratio and the experience and judgement of the interpreter.

Assuming an average velocity for coal of 1000 m/s and knowing the coal thickness to be about 1 meter, the frequency necessary for resolution can be calculated as follows:

$$\lambda / 4 = V_i / 4f = (1000\text{m/s}) / 4f = 1\text{m}$$

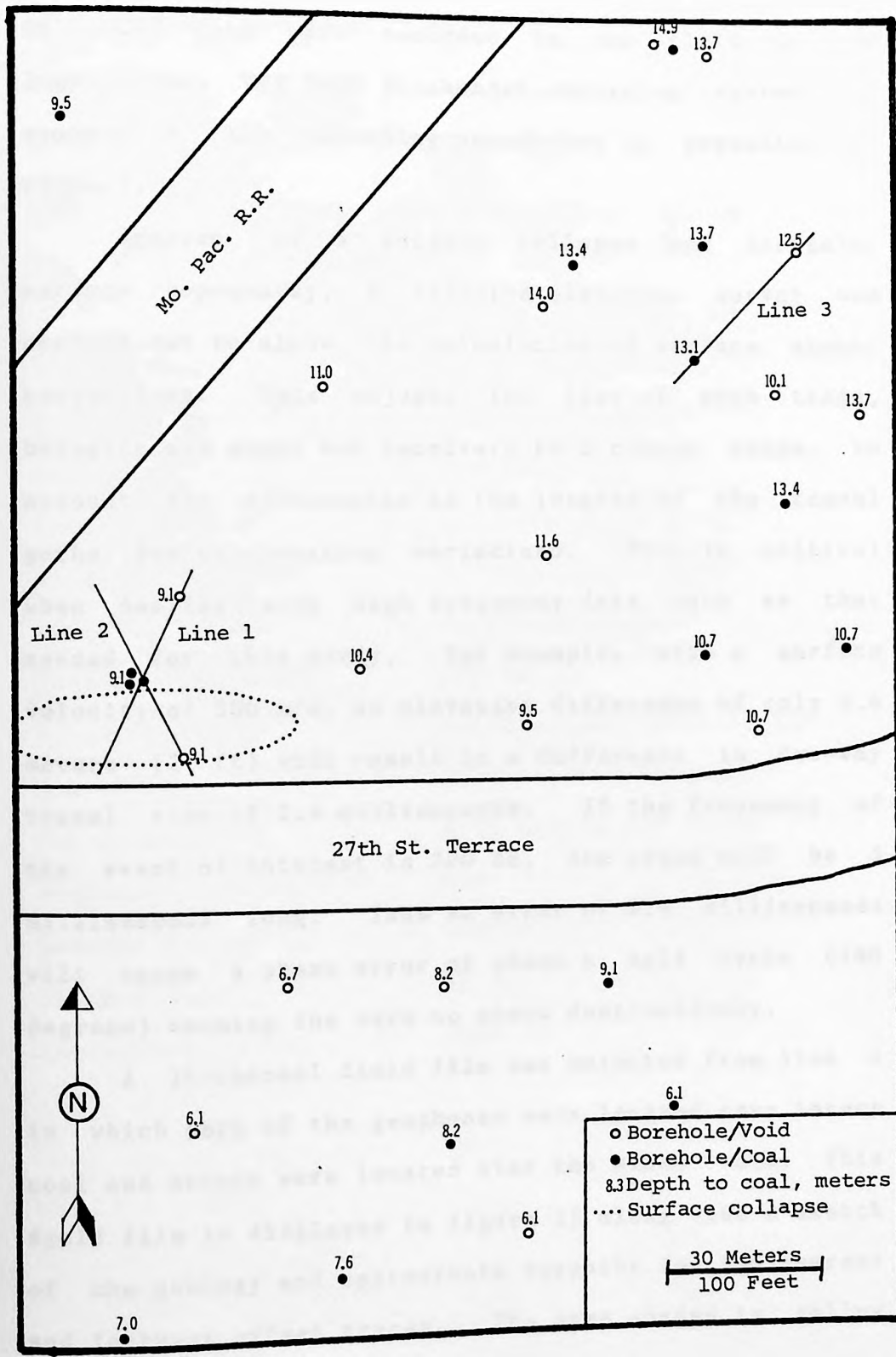
therefore, $f = (1000\text{m/s}) / 4(1\text{m}) = 250 \text{ Hz}$

This frequency has been attained in this thesis by use of a 340 Hz low-cut filter prior to analog to digital conversion.

PITTSBURG INDUSTRIAL PARK SEISMIC DATA

Data were collected at the Pittsburgh Industrial Park site in July of 1985 and June of 1986. Two intersecting lines were shot tying together information from three drill holes, and a third line was shot 125 meters to the northeast (figure 10). The three lines were shot using a split-spread array of single 100 Hz geophones spaced at half meter intervals. This geometry produced quarter meter intervals between CDP locations. Assuming that the mine cavities are at least 2 to 3 meters across, this array should provide adequate horizontal resolution to detect the void. A modified 30.06 rifle was used as an energy source and the twelve-

Figure 10:Map of the Pittsburgh Industrial Park study site showing locations of the seismic lines, drill-holes and surface collapse.



fold CDP data were recorded in the field by an Input/Output DHR 2400 24-channel recording system. A summary of the recording parameters is presented in table 2.

Because of a surface collapse and irregular surface topography, a relative elevation survey was carried out to allow the calculation of surface static corrections. This adjusts the time of each trace, bringing all shots and receivers to a common datum, to account for differences in the lengths of the travel paths due to elevation variations. This is critical when dealing with high frequency data such as that needed for this study. For example, with a surface velocity of 500 m/s, an elevation difference of only 0.6 meters (2 ft) will result in a difference in two-way travel time of 2.4 milliseconds. If the frequency of the event of interest is 200 Hz, one cycle will be 5 milliseconds long. Thus an error of 2.4 milliseconds will cause a phase error of about a half cycle (180 degrees) causing the data to stack destructively.

A 24-channel field file was selected from line 1 in which part of the geophones were located over intact coal and others were located over the mined void. This field file is displayed in figure 11 along with a sketch of the geology and approximate raypaths for the nearest and furthest offset traces. The area shaded in yellow

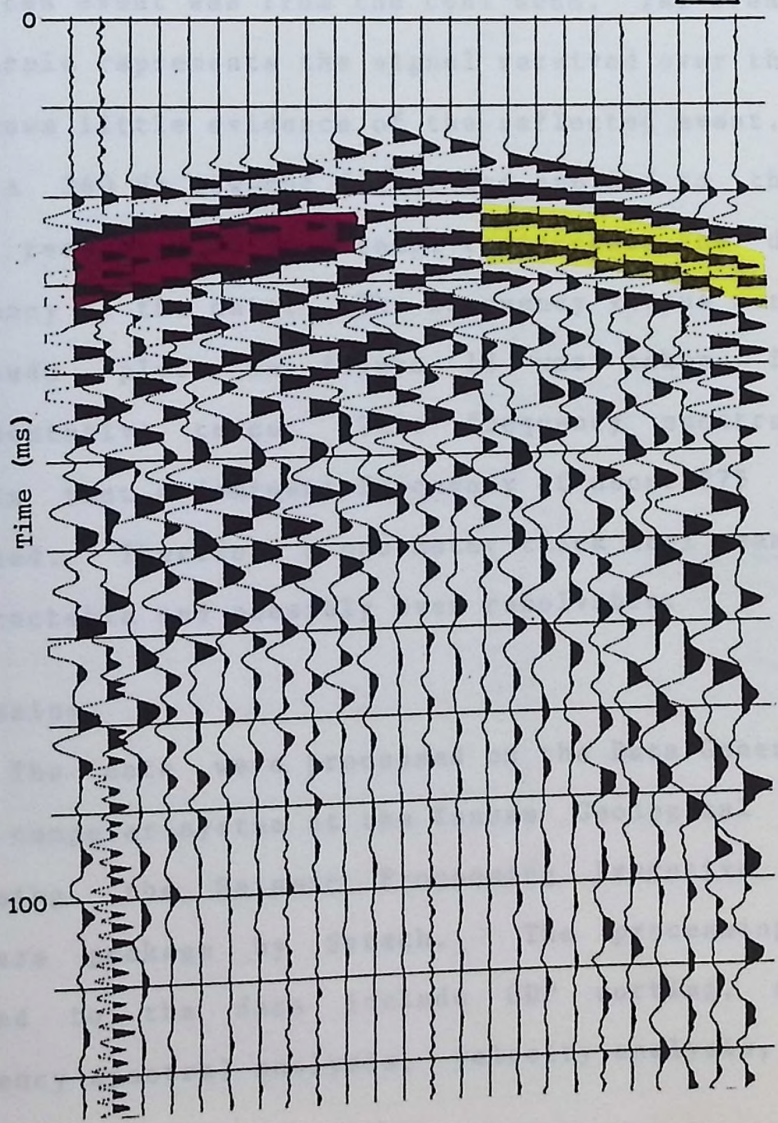
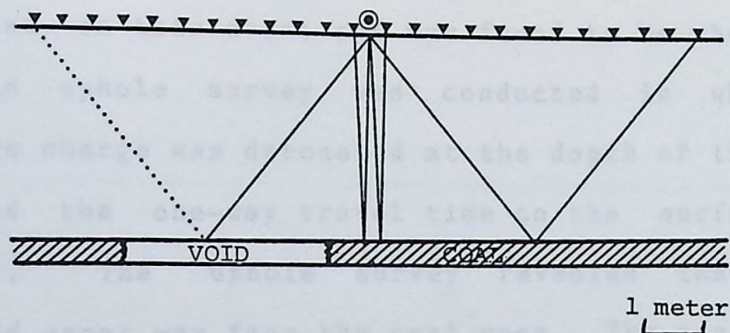
TABLE 2

Recording parameters for the Pittsburg Industrial Park
and mobile home park sites.

Record Length	125 milliseconds
Sampling Interval	250 microseconds
Source	30.06 Rifle
Source Interval	1/2 meter (1.6 feet)
Receiver Interval	1/2 meter (1.6 feet)
Receiver Array	Single geophones
Geophone Frequency	100 Hz
Field Geometry	Split-spread, 12-fold CDP
Near Offsets	3.25 meters (11 feet)
Far Offsets	8.75 meters (29 feet)
High-cut Filter	Out
Low-cut Filter	340 Hz
Notch Filter	60 Hz
Anti-alias Filter	3000 Hz

Figure 11:A 24-channel field file with part of the geophones located over intact coal and others over cavity. The event shaded in yellow represents the signal received over the coal seam. The area shaded in purple represents the signal received over the void.

represents a reflected event received over the intact coal seam. A normal wavelet (NWO) velocity was calculated. An angle survey was conducted which an explosive charge was placed at the top of the coal seam and the time for the wavelet to surface was measured.



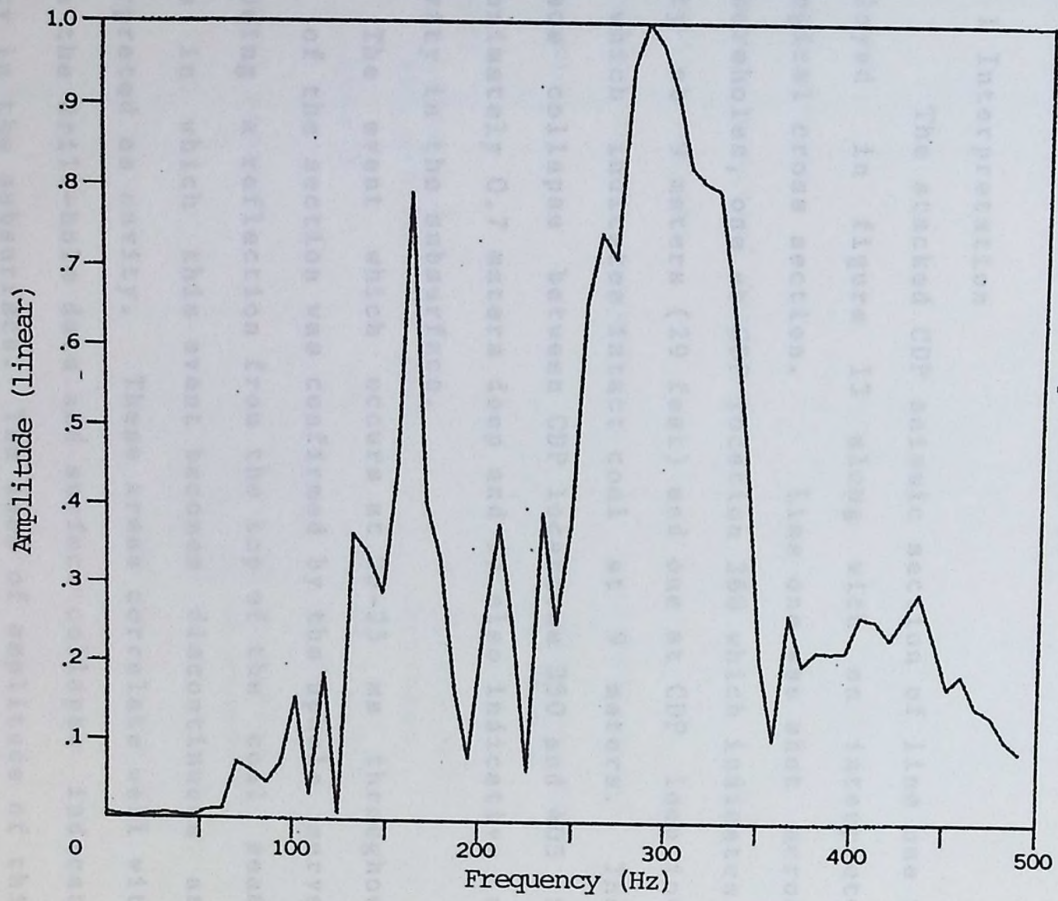
represents a reflected event received over the intact coal seam. A normal moveout (NMO) velocity was calculated on this event and was found to be about 500 m/s. An uphole survey was conducted in which an explosive charge was detonated at the depth of the coal seam and the one-way travel time to the surface was measured. The uphole survey revealed that this reflected event was from the coal seam. The area shaded in purple represents the signal received over the void and shows little evidence of the reflected event.

A 340 Hz low-cut filter was applied to the data while recording in an attempt to increase the dominant frequency of the data. The frequency versus normalized amplitude plot in figure 12 was taken from a representative trace. This frequency spectrum plot reveals that a dominant frequency of about 275 Hz was attained. Therefore a one meter thick coal seam should be detectable and possibly even resolvable.

Processing

The data were processed on the Data General MV-8000 computer system at the Kansas Geological Survey, utilizing the Seismic Processing Executive (SPEX) software package by Sytech. The processing steps applied to the data include CDP sorting, editing, frequency spectral analysis, velocity analysis, static

Figure 12: Frequency spectrum plot of the Pittsburg data
indicating a predominant frequency of 275 Hz.



correction, CDP stacking, filtering and scaling. In addition, a residual statics process was applied to the stacked data to remove minor undulations in the events of interest. A summary of the processing steps and parameters is presented in table 3.

Line 1 Interpretation

The stacked CDP seismic section of line one is displayed in figure 13 along with an interpreted geological cross section. Line one was shot across two boreholes, one at CDP location 260 which indicates a cavity at 9 meters (29 feet) and one at CDP location 346 which indicates intact coal at 9 meters. The surface collapse between CDP locations 350 and 405 is approximately 0.7 meters deep and is also indicative of a cavity in the subsurface.

The event which occurs at 23-25 ms throughout most of the section was confirmed by the uphole survey as being a reflection from the top of the coal seam. Areas in which this event becomes discontinuous are interpreted as cavity. These areas correlate well with where the drill-hole data and surface collapse indicate cavity in the subsurface. The loss of amplitude of this event over the water-filled cavities is attributable to the contrast of the reflection coefficients. The acoustic velocity of the water in the cavities is

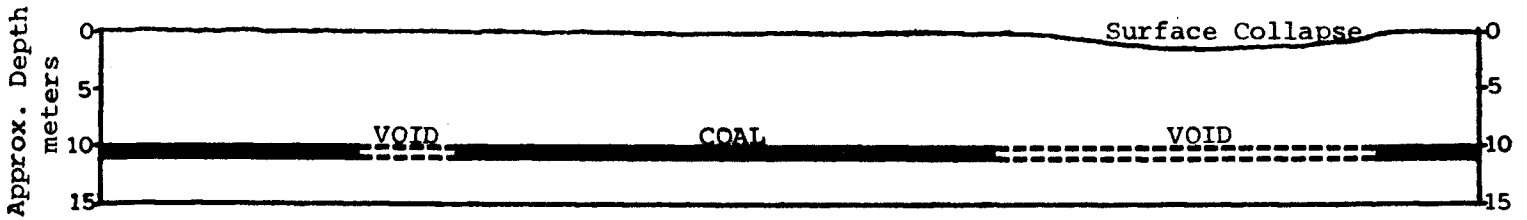
TABLE 3

Processing steps and parameters used for the Pittsburgh Industrial Park and mobile home park data.

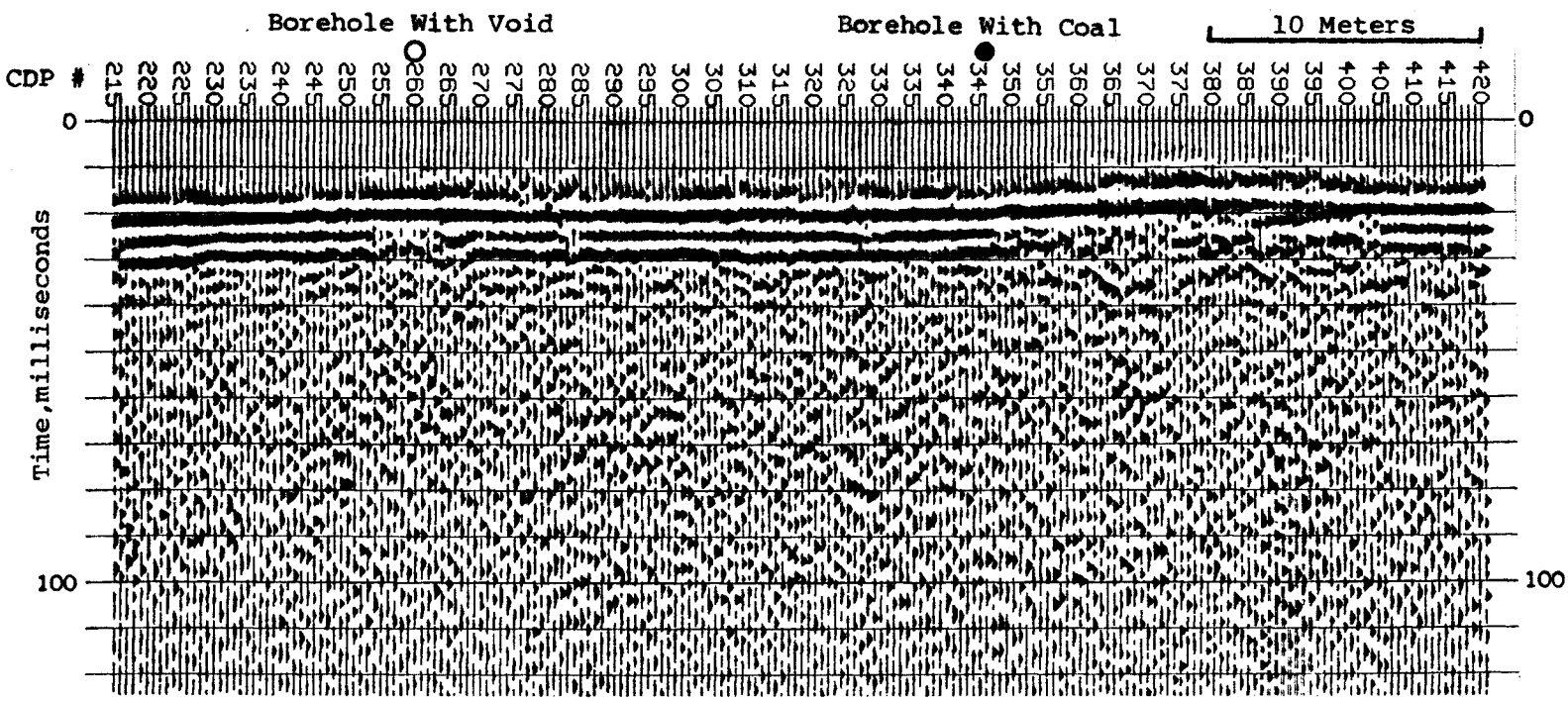
CDP sort	
Bad trace edit	
Frequency spectral analysis	
Velocity analysis	
Elevation static corrections:	hand calculated
CDP stack:	Stacking velocity Vs=475 m/s
Filter:	
Lines 1 & 2 and mobile home park	40-80-270-360 Bandpass
Line 3	30-60-210-315 Bandpass
Residual statics:	20 ms center 30 ms window 23 trace pilot
Scale:	50 ms window, RMS

Figure 13: CDP seismic section of Pittsburg line 1 with interpreted geological cross-section.

GEOLOGICAL CROSS SECTION



SEISMIC SECTION



greater than the acoustic velocity of the coal, and the overlying shales and clays have an even higher velocity. The reflection coefficient for the boundary between the water and shale will therefore be smaller than the reflection coefficient for the boundary between the coal and the shale, yielding a reduced reflection amplitude over the water-filled cavities.

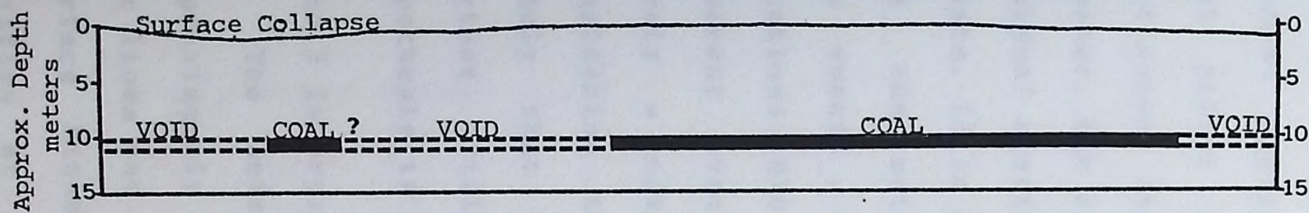
The event at 28-30 ms throughout the section is interpreted as a reflection from the bottom of the coal. A velocity pull-up is observed in this event under the water-filled cavities, due to the higher acoustic velocity of the water relative to the coal.

Line 2 Interpretation

The stacked CDP seismic section and interpreted geological cross section for line two are shown in figure 14. The signal-to-noise ratio and overall data quality were not as high on line two because of radio frequency interference with the seismic amplifiers, but there is still useful information present. Line two was also shot across two boreholes, one at CDP location 834 which indicates void and one at CDP location 894 which indicates coal. The reflected events from the coal seam are still located between 23 and 30 milliseconds, indicating that this procedure is reproducible in this area.

Figure 14: CDP seismic section of Pittsburg line 2 with interpreted geological cross-section. Residual statics applied.

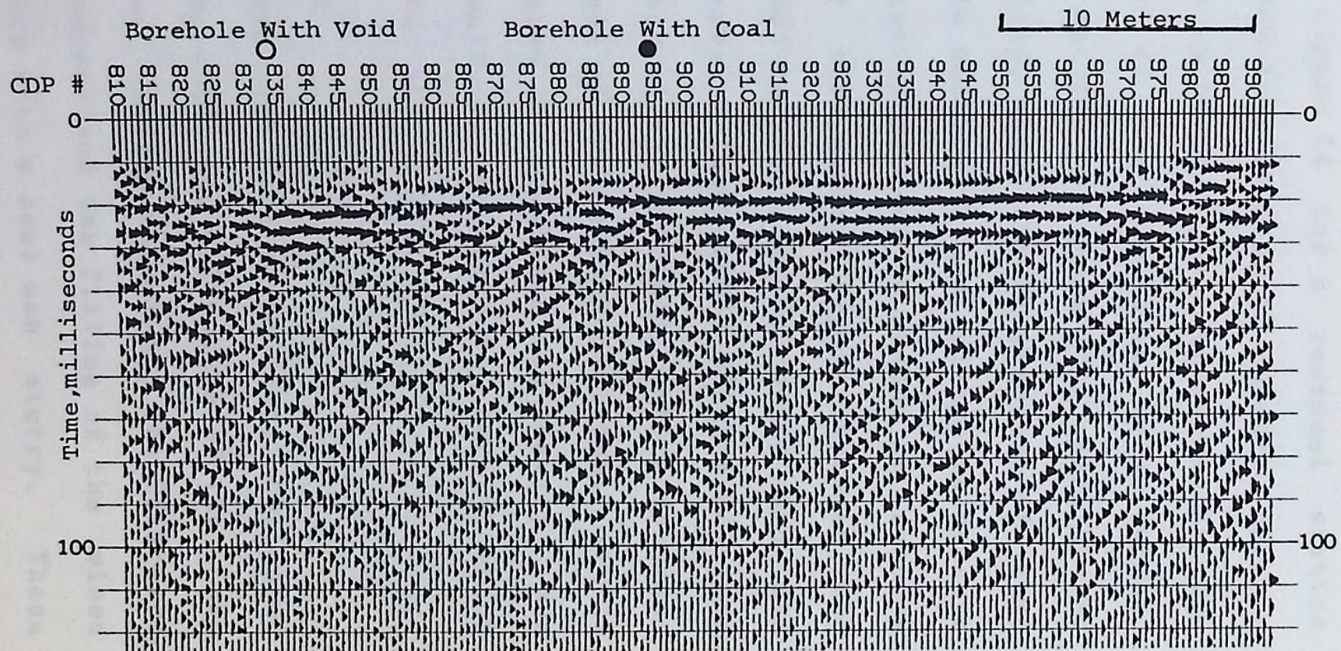
GEOLOGICAL CROSS SECTION



SE

SEISMIC SECTION

NW

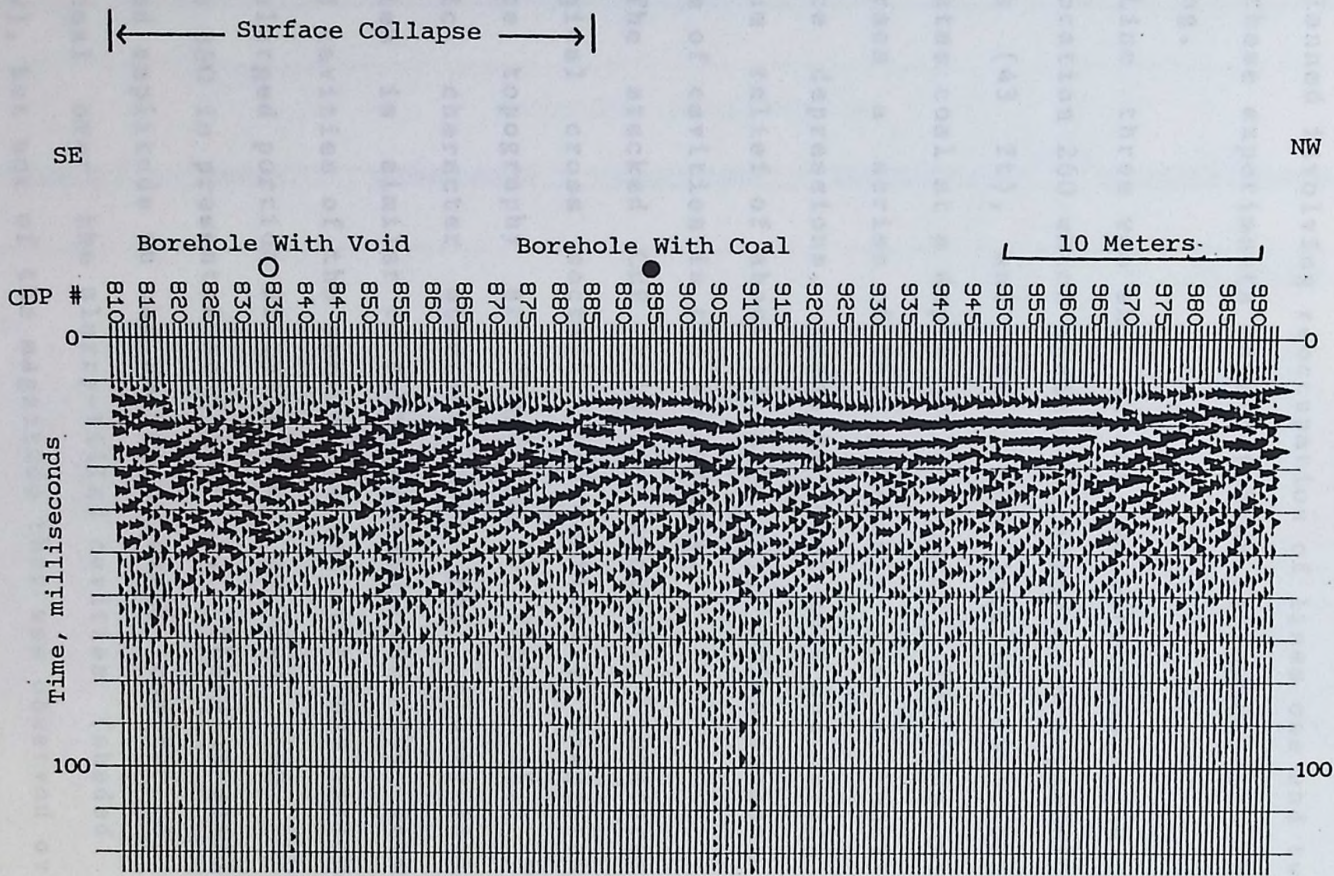


The interpretation of the portion of the section between CDP locations 835 and 847 is unclear. The seismic section in figure 14 has a residual statics process applied. From this section it appears that a coal pillar may be present, as evidenced by the continuous character of the events in this region. However, the seismic section in figure 15, which has no residual statics applied, shows little evidence of these events. It is possible that; 1) a coal pillar is present and the residual statics process is needed to resolve the events, or, 2) the entire region between CDP locations 810 and 885 is underlain by cavity and the coherent events observed between CDP's 835 and 847 are merely a manifestation of the residual statics process. Considering the extent of the surface collapse, it is likely that the region is underlain by cavity, but further drilling would be necessary to verify which hypothesis is correct.

Line 3 Interpretation

The seismic data for line three were collected approximately one year after the collection of the data for lines one and two. During this time, the Office of Surface Mining had supervised the filling of the mined cavities at this site with a coal ash slurry. These slurry-filled cavities should yield a slightly different

Figure 15: CDP seismic section of line 2 with no residual statics applied.



seismic character than that observed over the water-filled cavities of lines one and two. Additional tests are planned involving reoccupation of lines one and two, but these experiments have not been performed at this writing.

Line three was shot across two boreholes, one at CDP location 260 which indicates cavity at a depth of 13 meters (43 ft), and one at CDP location 394 which indicates coal at a depth of 13 meters. The line also traverses a series of fairly evenly spaced, shallow surface depressions, trending east-west and having a maximum relief of about 10 cm (4 in), which suggest a system of cavities in the subsurface.

The stacked CDP seismic section, interpreted geological cross section, and vertically exaggerated surface topography are displayed in figure 16. The seismic character observed over the slurry-filled cavities is similar to that observed over the water-filled cavities of the previous lines, but less extreme. An enlarged portion of the seismic section from CDP's 315 to 360 is presented in figure 17. There is still a reduced amplitude in the reflected event from the top of the coal over the slurry-filled cavities (shaded in yellow), but not of the magnitude that was observed over the water-filled cavities. The velocity pull-up of the lower event is more obvious with the slurry-filled

Figure 16: CDP seismic section, interpreted geological cross section, and vertically exaggerated surface topography of Pittsburg line 3. The areas shaded in yellow are interpreted as cavity.

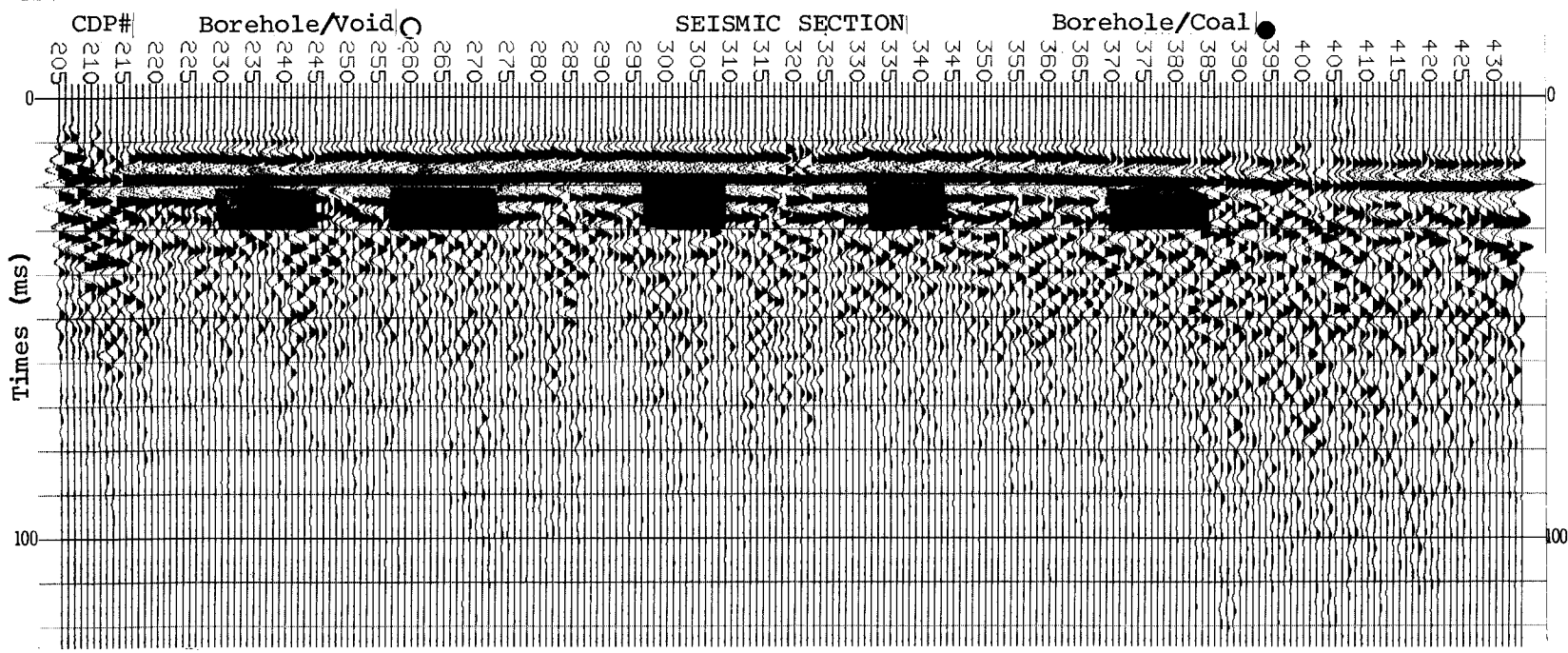
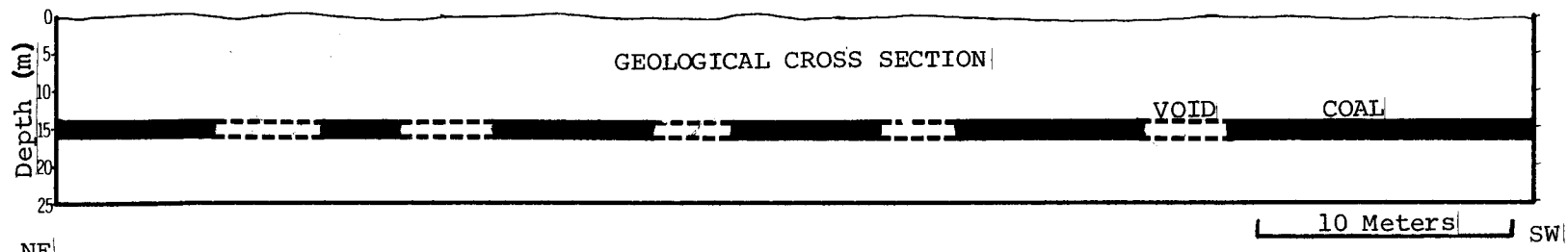
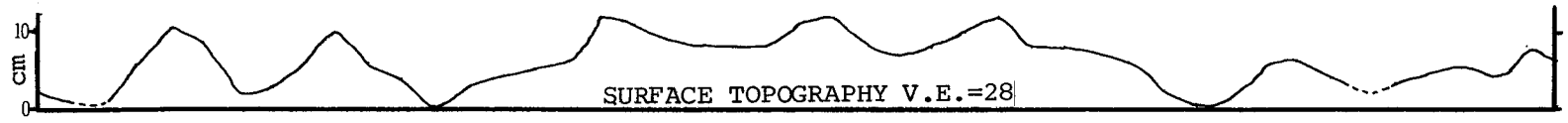
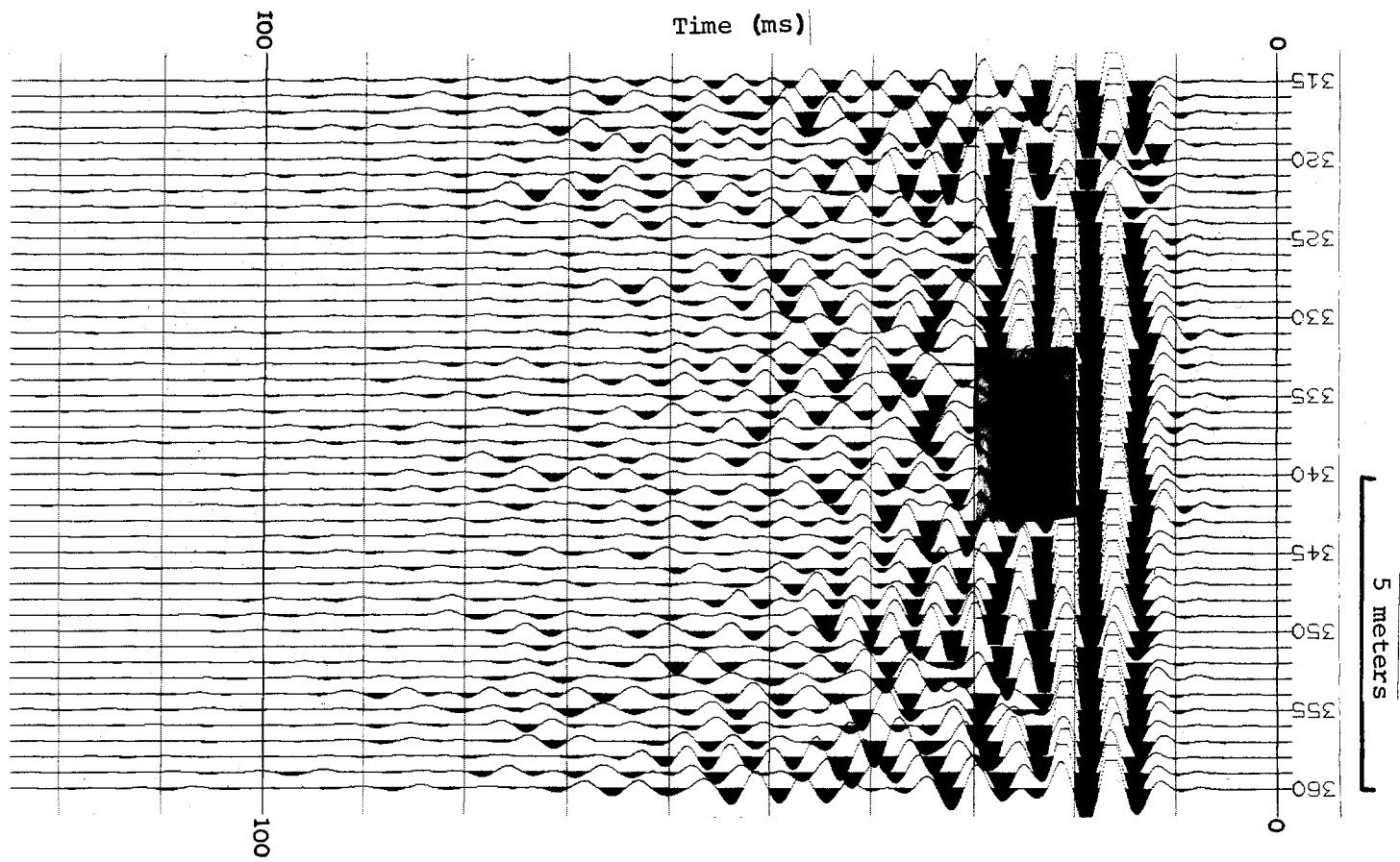


Figure 17: Enlarged portion of the seismic section in figure 16. The area shaded in yellow is interpreted as cavity.



cavities. The ash slurry is overall more "coal like" than the water, thus the change in the seismic character is more subtle. The locations interpreted as cavity correlate well with the shallow surface depressions and drill data, confirming that these depressions are due to slumping over a system of subsurface cavities.

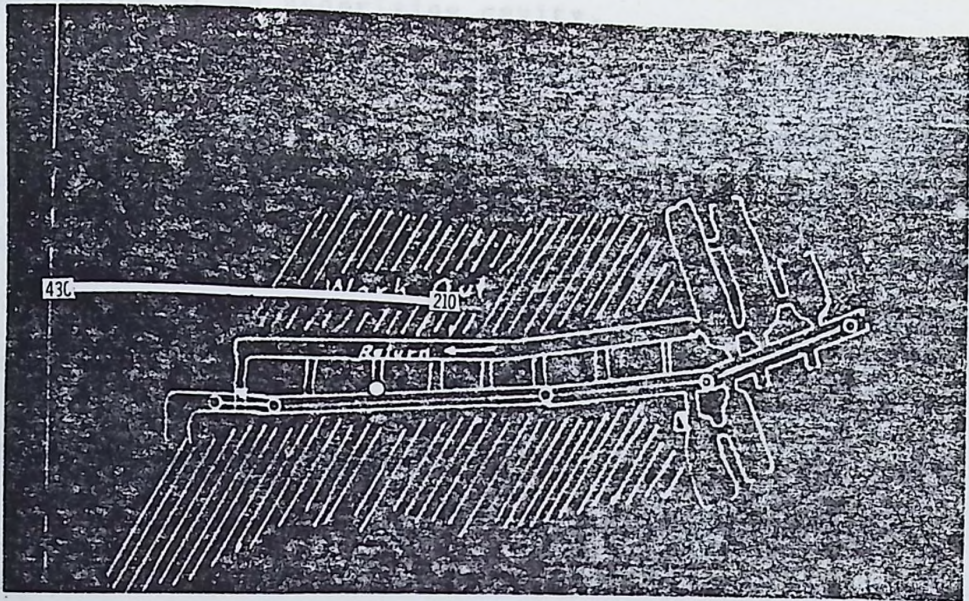
The region between CDP's 385 and 405 on the seismic section is of poor data quality. This is probably due to poor source and receiver coupling, caused by disturbed surface conditions associated with the drilling of the borehole.

PITTSBURG MOBILE HOME PARK SEISMIC DATA

Data were collected at the Pittsburg mobile home park site in July of 1985. These data were also shot with the 30.06 rifle using the same recording parameters as were used for the industrial park data (Table 2). The processing steps were also the same as for the industrial park data (Table 3).

The seismic line was shot over a known mined area (figure 18). A recent surface collapse, with a depth of approximately 0.7 meters, was located 15 meters south of the line. Buildings and other cultural obstructions prevented orienting the line north-south, so as to transect the mined area shown on the mine map. Therefore, the line was shot east to west with no

Figure 18: Mine map of the Pittsburg mobile home park study site showing the locations of the seismic line and the surface collapse. The west end of the line is located 475 ft north and 5 ft east of the southwest corner of the SE 1/4 of sec. 18. (from Brown, 1915)



100 feet
30 meters



○ Surface Collapse

assurance of an underlying cavity.

The seismic section presented in figure 19 confirms that the seismic line did not pass over a mined cavity, as evidenced by the continuous character of the events present. The data does, however, exhibit the same type of events as seen over the coal seam at the industrial park site.

FRONTENAC SEISMIC DATA

Data were first collected at the Frontenac site in January of 1986. Since the coal seam is at roughly twice the depth (20 meters) as at the previous sites in Pittsburg, it was believed that a more powerful source than the 30.06 rifle was needed. A 50 caliber single shot rifle was chosen as a source.

50 Caliber Seismic Data

A walk-away noise test was conducted to determine the optimum offsets to use for recording the CDP line. A plot of this test is displayed in figure 20. Single geophones were placed in a line at half meter intervals with the source located 5 meters from the nearest phone. From the seismogram records in the field, the event underlined at about 50 ms. on the figure appeared to be a possible reflection event. Therefore the 24 channels with offsets of 20 to 32 meters (shaded in yellow) were

Figure 19: CDP seismic section of the Pittsburgh mobile home park line.

W

E

10 meters

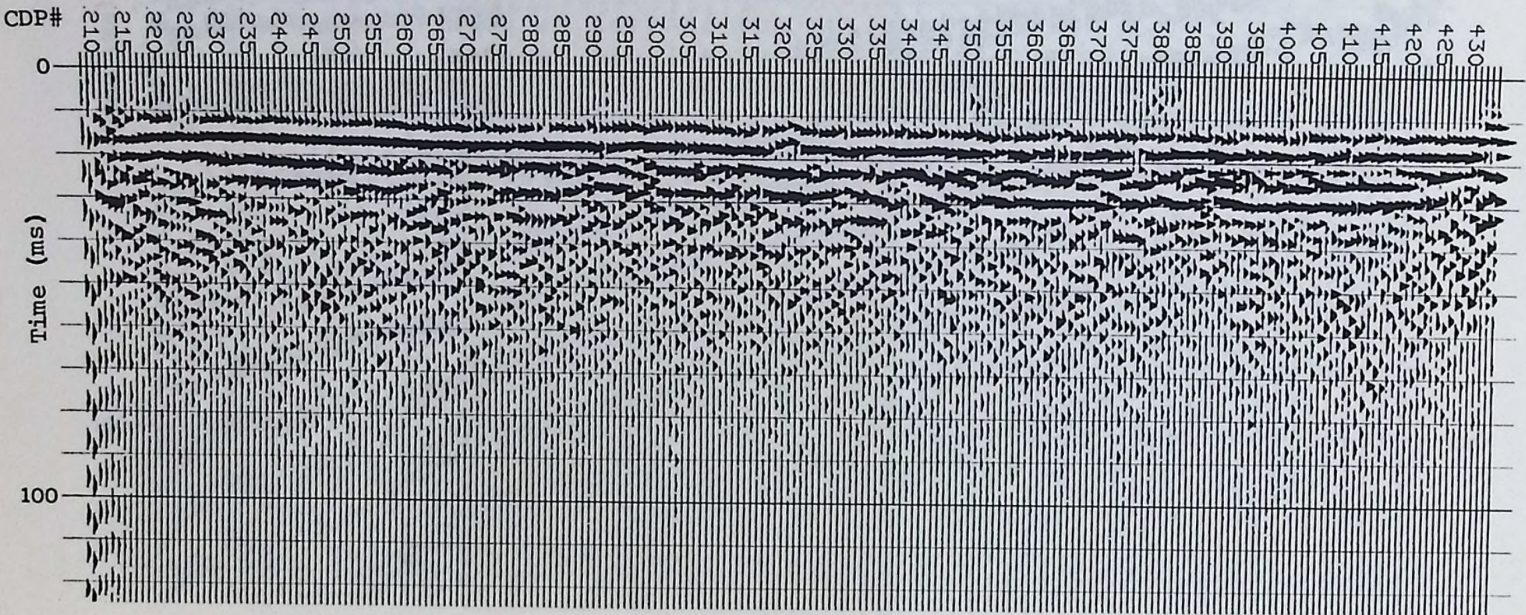
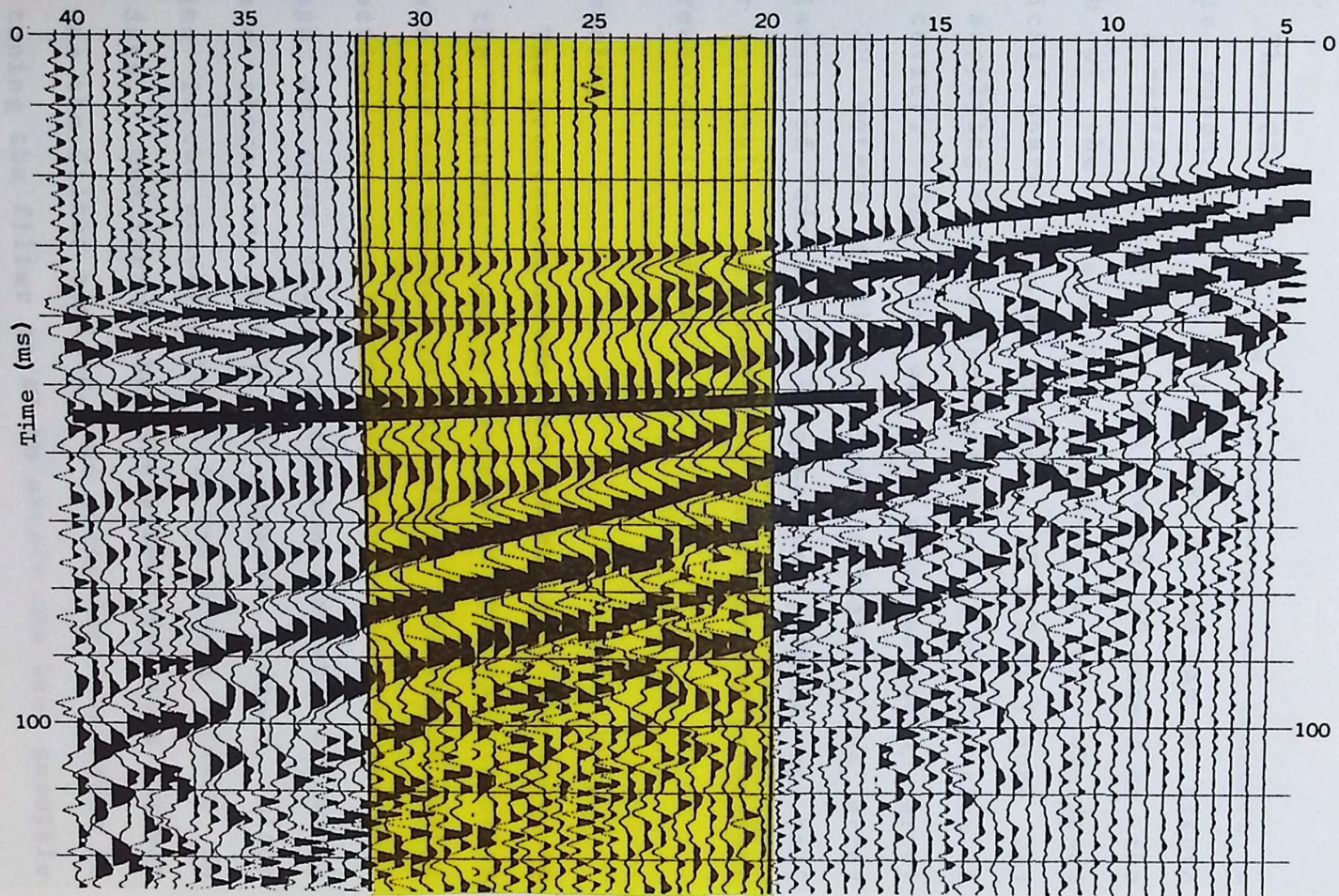


Figure 20: Walkaway noise test from the Frontenac site using the 50 caliber source. The event underlined at 50 ms appeared to be a possible reflection event on the field plots. The shaded area represents the 24-channel window used to collect the CDP data.

Offset From Source , meters



chosen to be the best window to use for collecting the data.

The CDP line was located so as to transect a single subsurface cavity as shown on the map in figure 21. A surface depression was present 50 meters to the south of the line at the location of an abandoned vertical shaft (labeled mine no. 37 1/2 on figure 21) thus supplying surface information as to the location of the cavity. The line was shot using an end-on array with 20 meters as the nearest offset. The array consisted of single 100 Hz geophones planted at half meter intervals. A summary of the recording parameters is presented in table 4.

Processing

The processing steps were essentially the same as for the Pittsburg data, except a residual statics process was not applied to this data. Elevation static corrections were not necessary because the line was shot through an open field which was essentially flat. Because there was no obvious moveout present, minor changes in the stacking velocity had little effect on the data. One factor that did affect the data a great deal was the filter applied, so great care was taken in fine tuning the filter so as to attain the best possible

Figure 21: Map showing the location of the Frontenac 50 caliber seismic line over the known cavity. (from Brown, 1933)

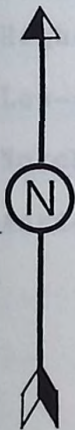
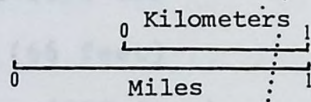
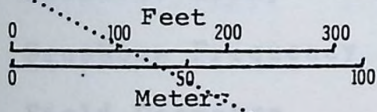
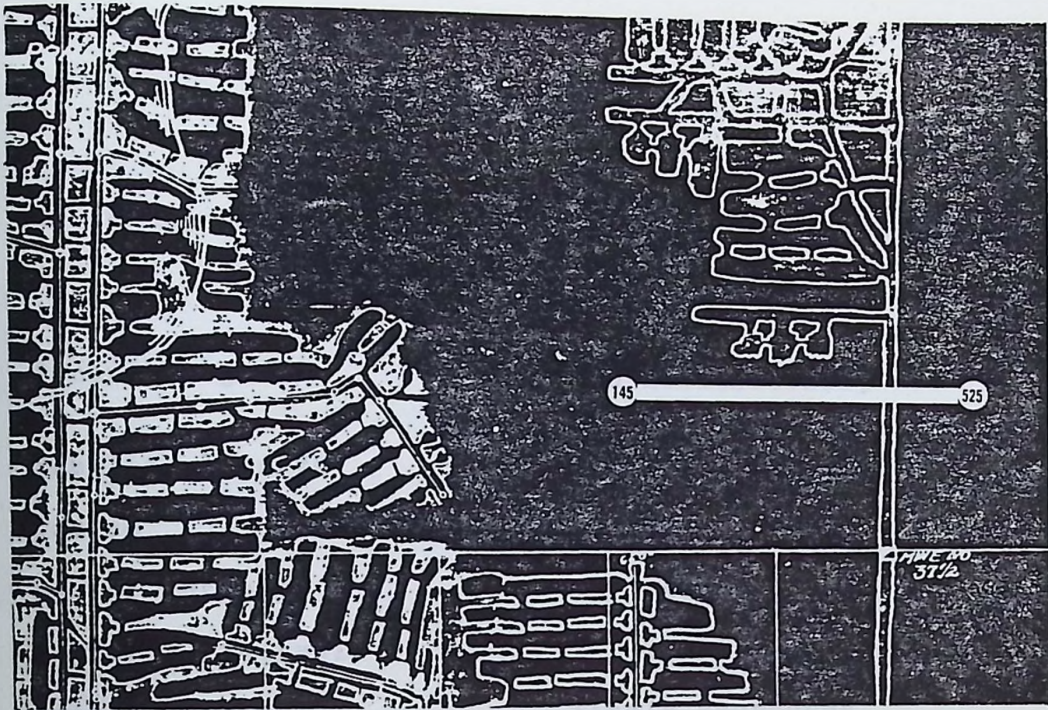


TABLE 4

Recording parameters for the Frontenac 50 caliber lines.

Record Length	250 milliseconds, chopped to 125 ms
Sampling Interval	250 microseconds
Source	50 caliber rifle
Source Interval	1/2 meter (1.6 feet)
Receiver Interval	1/2 meter (1.6 feet)
Receiver Array	Single geophones
Geophone Frequency	100 Hz
Field Geometry	End-on, 12-fold CDP
Near Offset	20 meters (66 feet)
Far Offset	31.5 meters (103 feet)
High-cut Filter	Out
Low-cut Filter	340 Hz
Notch Filter	Out
Anti-alias Filter	2000 Hz

data set. A summary of the processing steps and parameters is presented in table 5.

Interpretation

The 50 caliber CDP seismic section is presented in figure 22. The portion of this section from CDP's 145 to 335 is presented in figure 23 with an interpreted version in figure 24. The fault discussed earlier appears to actually be a system of faults. Each of the faults which comprise this fault zone seem to exhibit reverse fault characteristics. There are two diffraction events which are also characteristic of faulted areas. These diffractions are located at about 50 to 60 ms and centered at CDP locations 196 and 280 on the sections. These diffraction events may be due to radial scattering of energy upon contact with the reflectors edges at the fault. The velocity calculated for these diffractions, however, is very near the acoustic velocity of air, suggesting that these events could be due to echoes from an object on the surface. It is unclear whether the events on the section are reflected or refracted events, so detailed calculations are not possible.

The portion of the seismic section from CDP's 335 to 525 is presented in figure 25 with an interpreted version in figure 26. The location of the cavity is not

TABLE 5

Processing steps and parameters for the Frontenac 50
caliber data.

CDP sort

Bad trace edit

Frequency spectral analysis

Velocity analysis

Air blast mute

CDP stack:

Stacking velocity
 $V_s=1900$ m/s

Filter:

West to East Line

90-180-500-650
Bandpass

East to West Line

120-200-500-650
Bandpass

Figure 22:50 caliber seismic section of line shot west
to east.

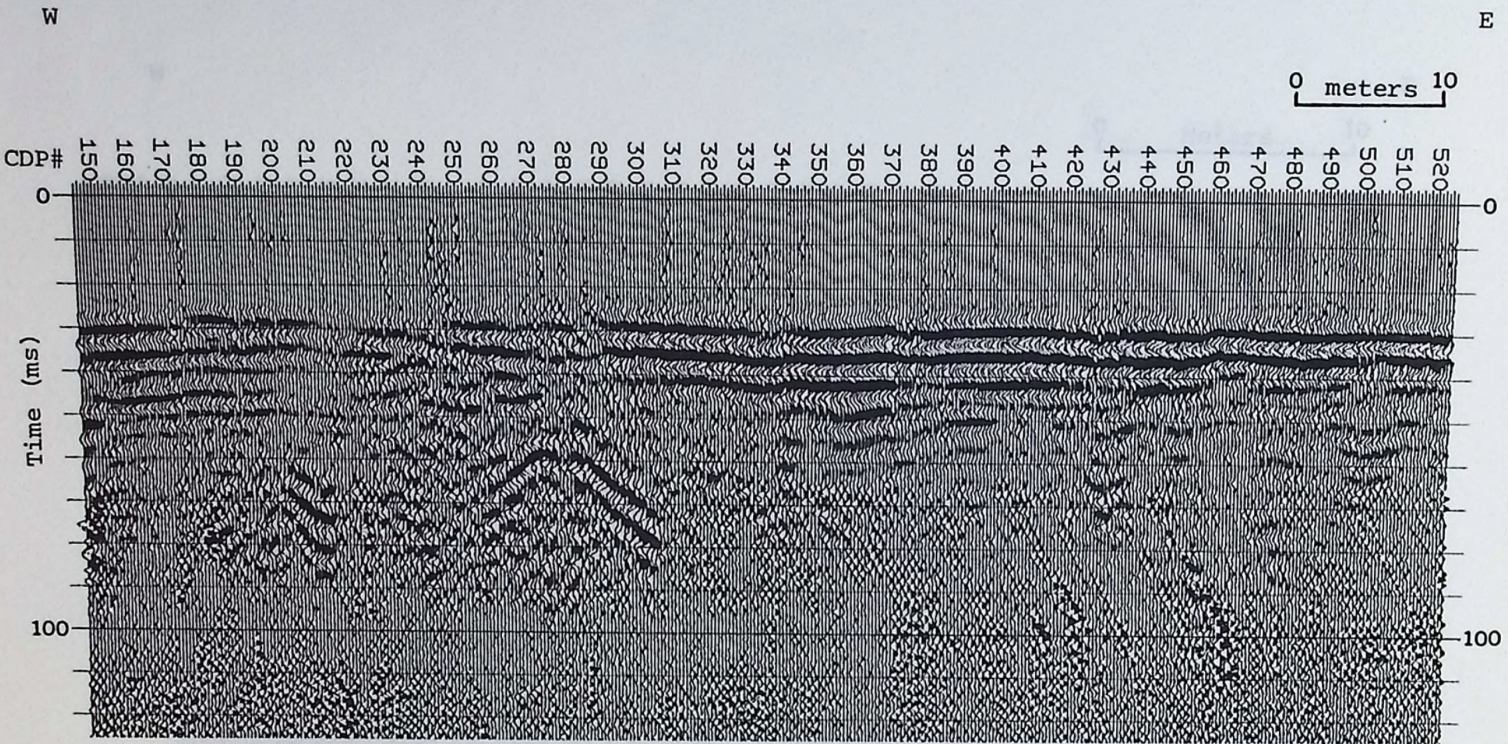


Figure 23:CDP's 145 to 335 of the 50 caliber line shot
west to east.

SEISMIC SECTION

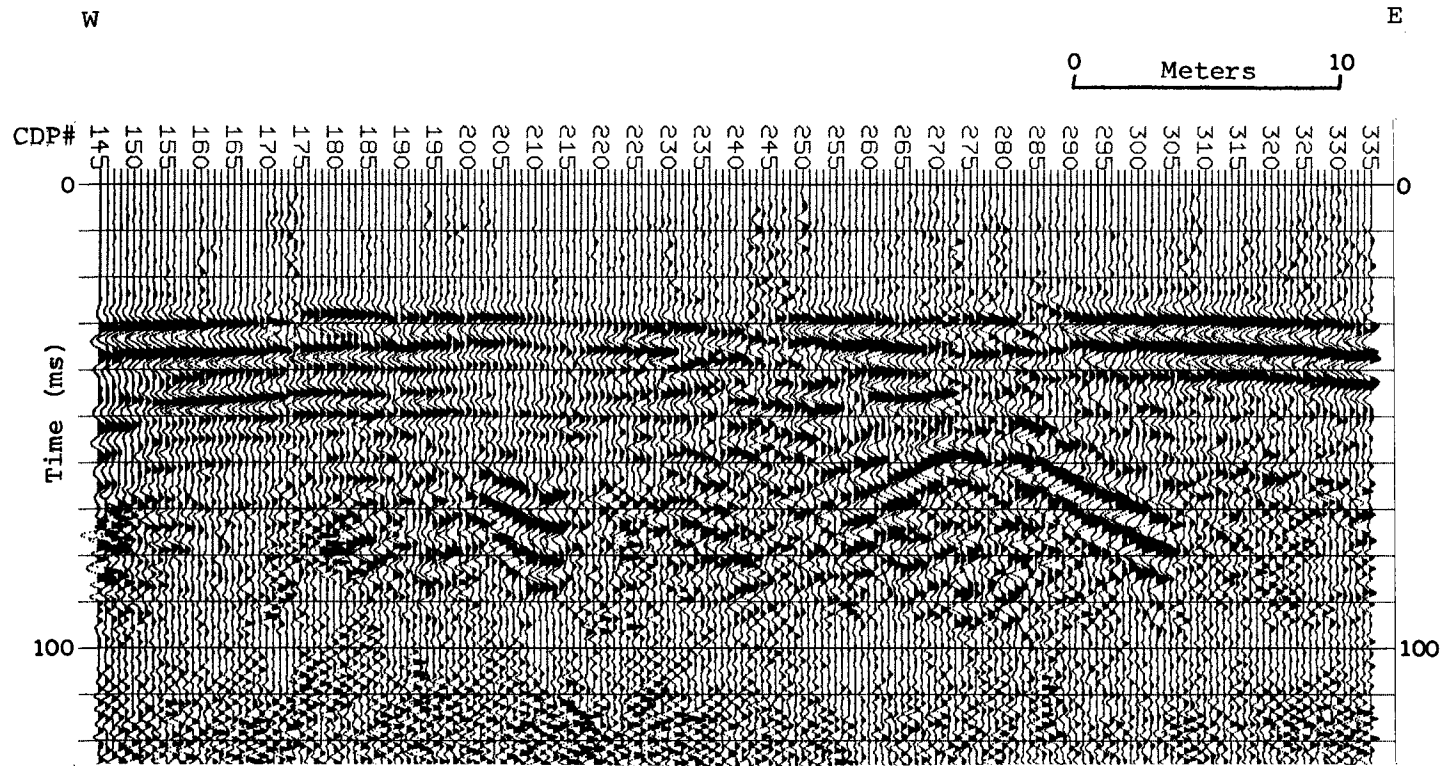


Figure 24: Interpreted version of the seismic section in
figure 23.

INTERPRETED SEISMIC SECTION

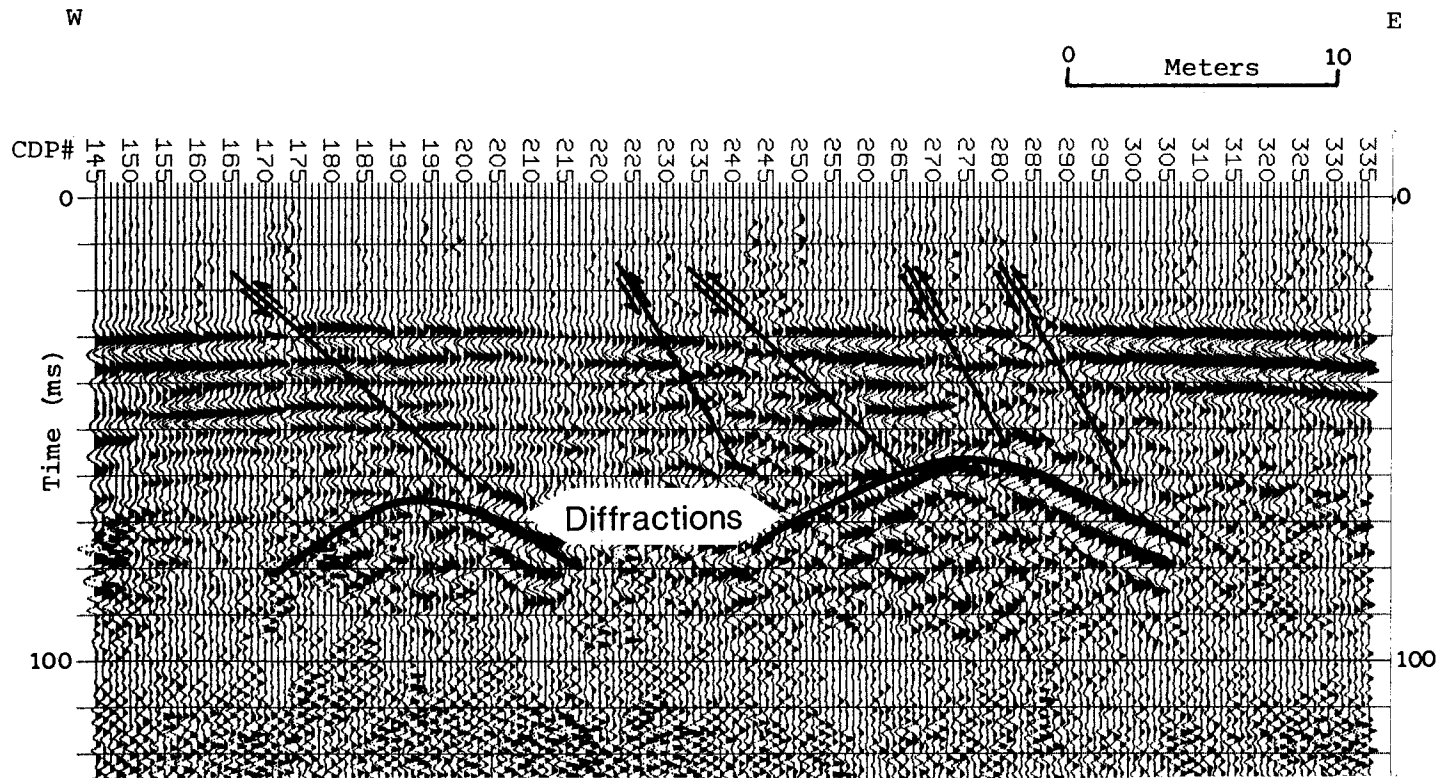


Figure 25:CDP's 335 to 525 of the 50 caliber line shot
west to east.

SEISMIC SECTION

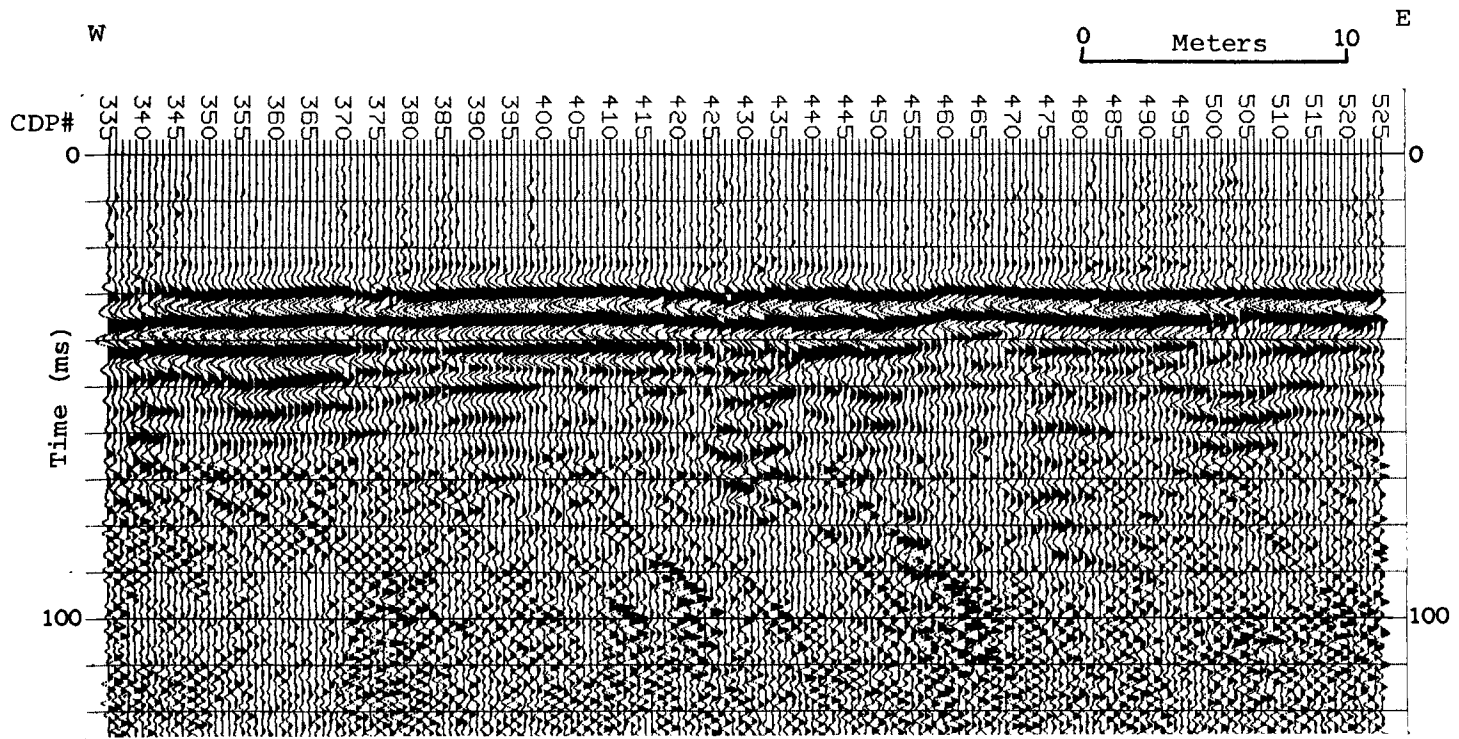
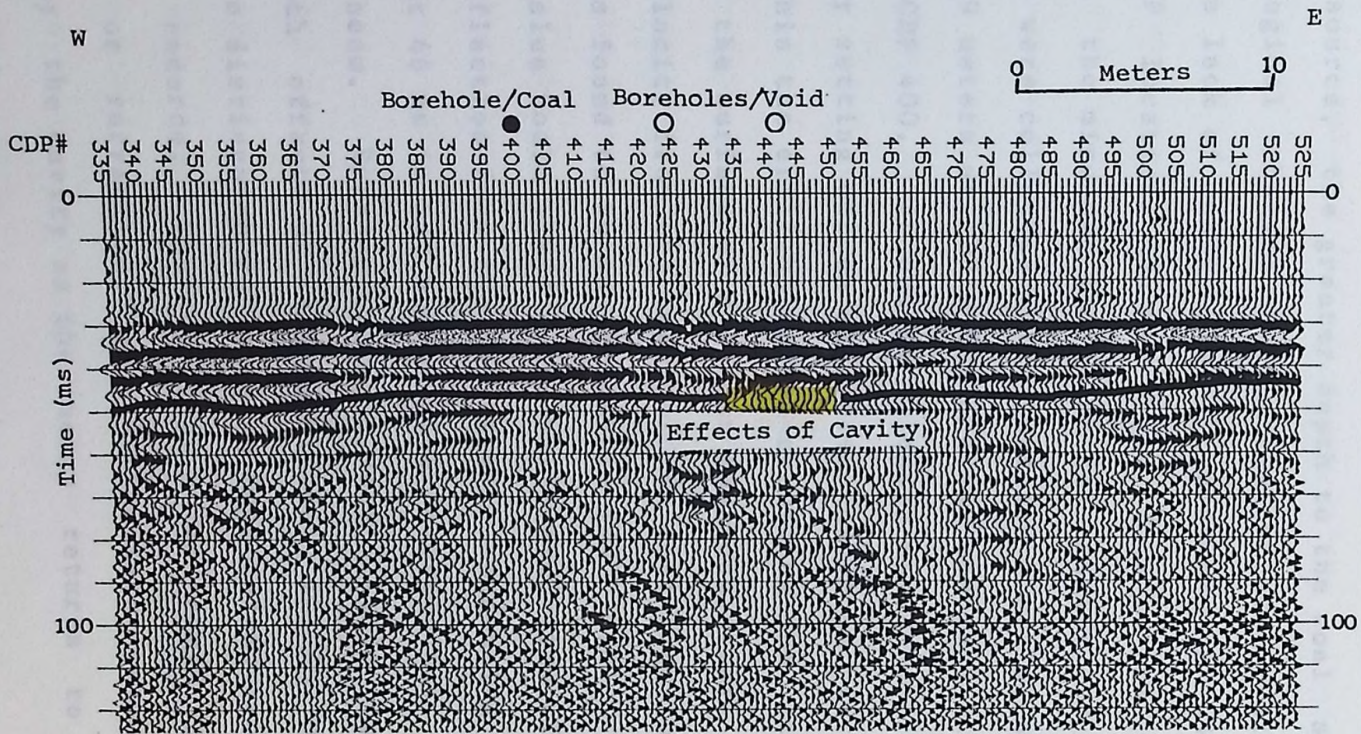


Figure 26: Interpreted version of the seismic section in figure 25.

INTERPRETED SEISMIC SECTION



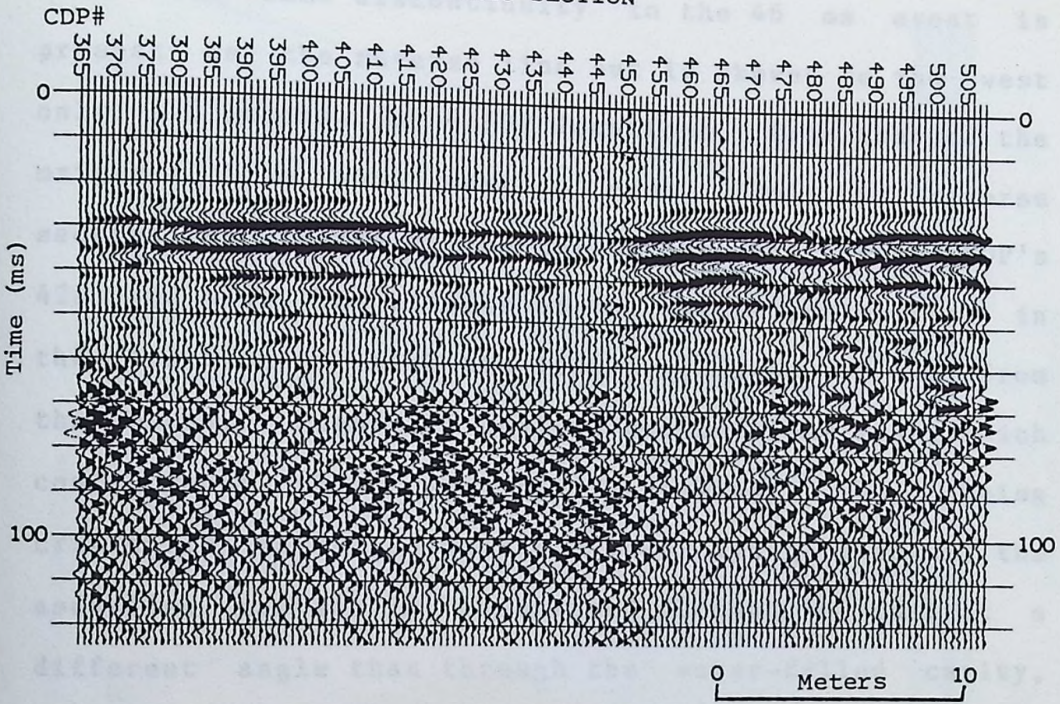
obvious on this section, in contrast to the Pittsburgh Industrial Park data. This is attributable to the different source, the greater depth to the coal seam, and lithological changes between the two study sites. There is a lack of continuity in the event at 46 ms between CDP locations 434 and 452. This is the same area where the mine map indicates the cavity to be. Drill data were collected which revealed a cavity at a depth of 19 meters at CDP's 424 and 442 and coal at 19 meters at CDP 400. An uphole velocity survey was also conducted by setting off an explosive charge at various depths within the drill-holes and recording the signal received at the surface by a linear geophone array. The average velocity from the depth of the coal seam to the surface was found to be approximately 1400 m/s. This velocity value would yield a two-way travel time of 27 ms for a reflection from the coal seam, suggesting that the event at 46 ms is not a reflected P-wave event from the coal seam. Because there is very little normal moveout with offsets of this magnitude, it is often difficult to distinguish reflections from refractions on the field records. The event at 46 ms could be a reflection or refraction from a deeper layer which is affected by the cavity as the energy returns to the surface.

The event at 46 ms is continuous as far to the east as CDP location 434, but drill data reveals that there is cavity beneath CDP 424, suggesting an apparent horizontal shift of the effects of the cavity. The possibility of S to P-wave mode conversion at the coal seam was considered. This would cause a horizontal shift of the effects of the cavity since the raypaths would be asymmetrical. S to P-wave mode conversion would also account for the difference in the time at which the event is recorded since the S-wave velocity is roughly one half that of the P-wave velocity. This apparent shift of the data could also be due to fringe effects at the edges of the cavity which cause the cavity to appear smaller than its actual extent, or, the effects of the cavity may be skewed to one direction due to bending of the raypaths returning to the surface.

A short reverse line was shot east to west directly over the cavity. If S to P-wave mode conversion were occurring, a similar shift of the cavity effects should be observed in the opposite direction as observed on the west to east line. The CDP seismic section of this reversed line, presented in figure 27, reveals only a slight shift. The magnitude of the shift on this reverse line was not enough to confirm the mode conversion hypothesis.

Figure 27: CDP seismic section of the 50 caliber line
shot east to west with an interpreted
version.

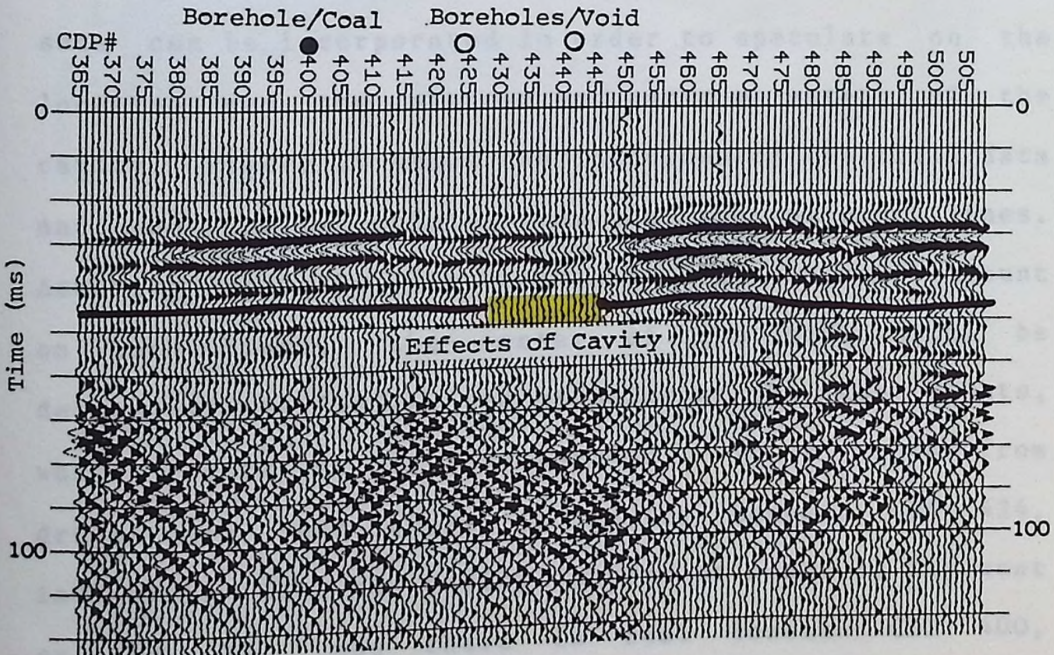
SEISMIC SECTION



W

INTERPRETED SEISMIC SECTION

E



The same discontinuity in the 46 ms event is present on the reverse line but is skewed to the west only 1.5 meters, or 6 CDP locations, from that of the original line shot west to east. On this reverse section the effects of the cavity are seen between CDP's 428 and 446. The effects of the cavity are shifted in the direction in which the line progresses, or away from the source. Figure 28 depicts one possible model which could cause this type of phenomenon. Upon being critically refracted within a lower lying stratum, the ascending raypath is transmitted through the coal at a different angle than through the water-filled cavity, producing a shadow zone. This shadow zone will be skewed in the direction away from the source.

Information from the forward and reversed data sets can be incorporated in order to speculate on the location and the minimum and maximum extent of the cavity. Figure 29 shows the locations of the drill data and the cavity effects from the two seismic lines. Assuming that the data were shifted by the same amount on both lines, the center of the cavity can be determined by finding the midpoint of the two events, which occurs at CDP location 440. It is known from drill data that there is cavity beneath CDP 424, indicating that the cavity extends at least as far west as CDP 423, and there is coal beneath CDP 400,

Figure 28:Diagram of a model that produces a shadow zone and causes a shift of the effects of the cavity away from the source. Upon being critically refracted within a layer beneath the coal, the ascending raypath is transmitted through the coal at a different angle than through the water-filled cavity. Not drawn to scale.

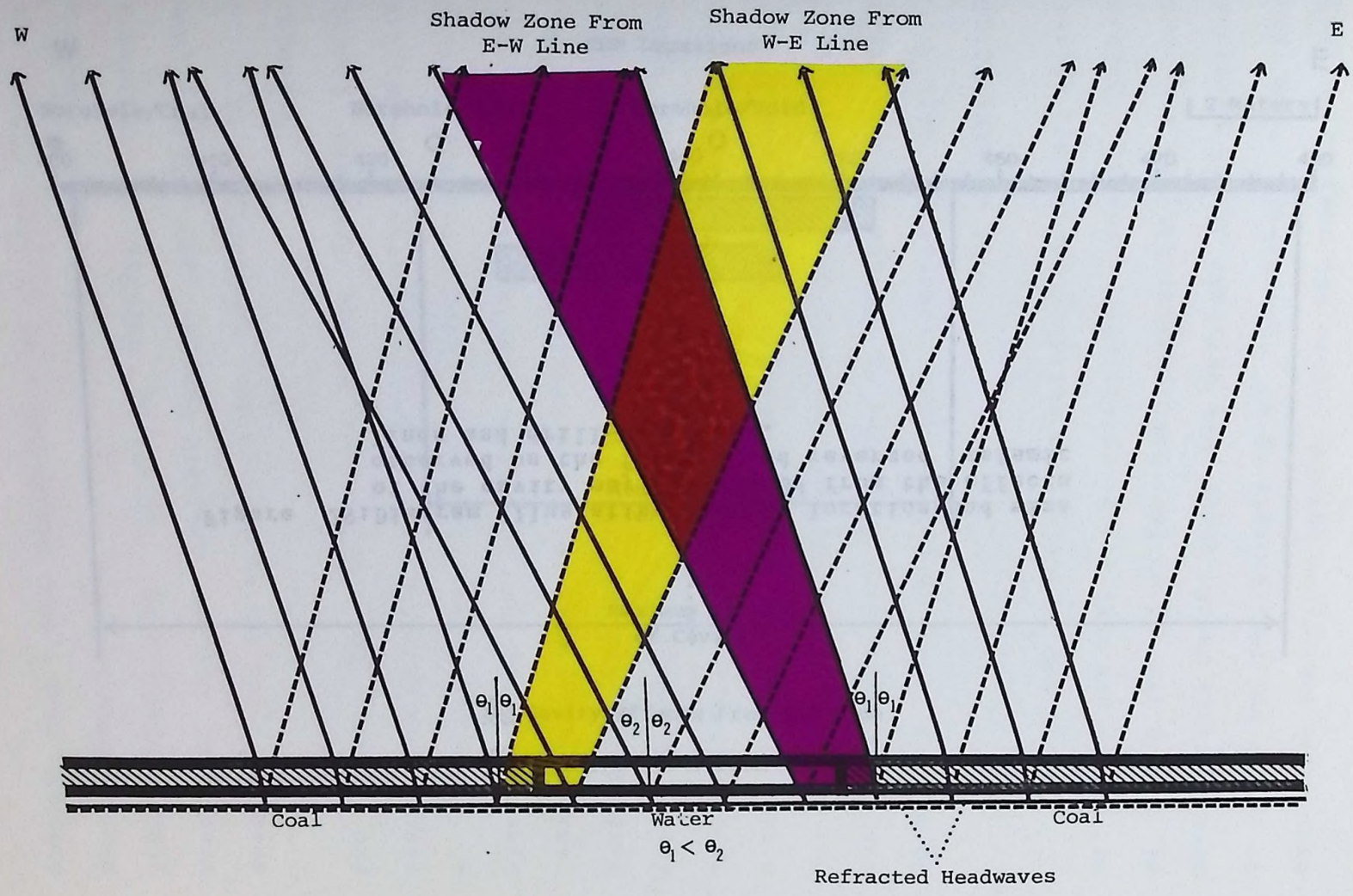
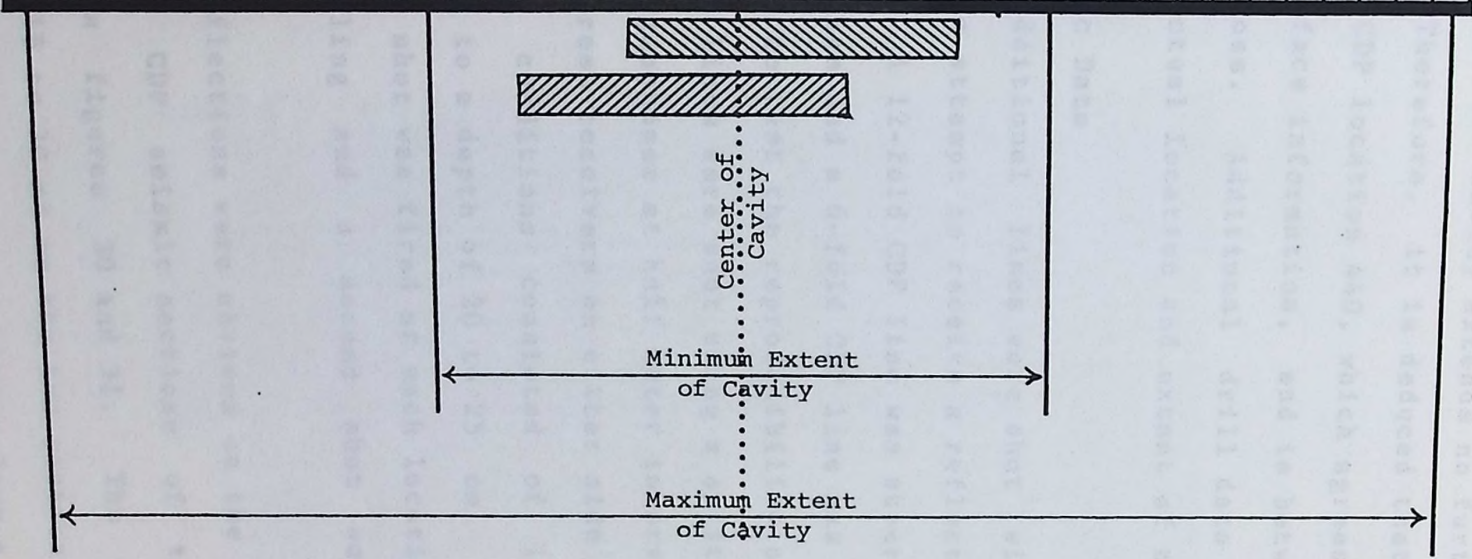




Figure 29: Diagram illustrating how the location and size of the cavity may be deduced from the effects observed on the forward and reversed seismic lines and drill-hole data.

W CDP Locations E

Borehole/Coal Borehole/Void Borehole/Void [2 Meters]

400 410 420 430 440 450 460 470 480



 Cavity Effects From W-E Line
 Cavity Effects From E-W Line

indicating that the cavity extends no further west than CDP 401. Therefore, it is deduced that the cavity is centered at CDP location 440, which agrees with the mine map and surface information, and is between 9 and 19 meters across. Additional drill data are needed to verify the actual location and extent of the cavity.

30.06 Seismic Data

Two additional lines were shot with the 30.06 rifle in an attempt to receive a reflection from the coal seam. A 12-fold CDP line was superposed over the 50 caliber line and a 6-fold CDP line was shot 15 meters to the north to test the reproducibility of the method. These 30.06 lines were shot using a split-spread array with single geophones at half meter intervals, dropping the two nearest receivers on either side of the source. The surface conditions consisted of loose, freshly plowed soil to a depth of 20 to 25 cm. Therefore, a preliminary shot was fired at each location to improve source coupling and a second shot was fired and recorded.

No reflections were obvious on the field records nor on the CDP seismic sections of the two lines presented in figures 30 and 31. The doublet event centered at 18 to 20 ms on the two sections appears from the field files to be a refraction from a near surface

Figure 30: CDP seismic section of the Frontenac 30.06 line superposed over the previous 50 caliber lines.

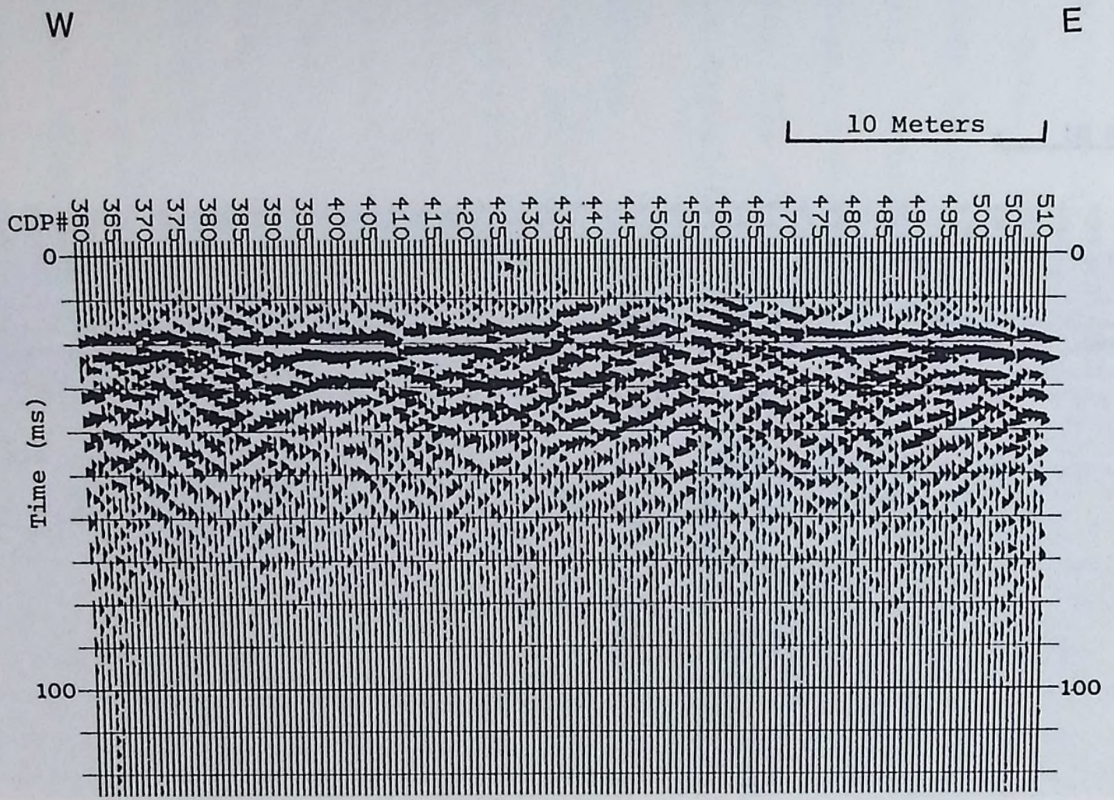
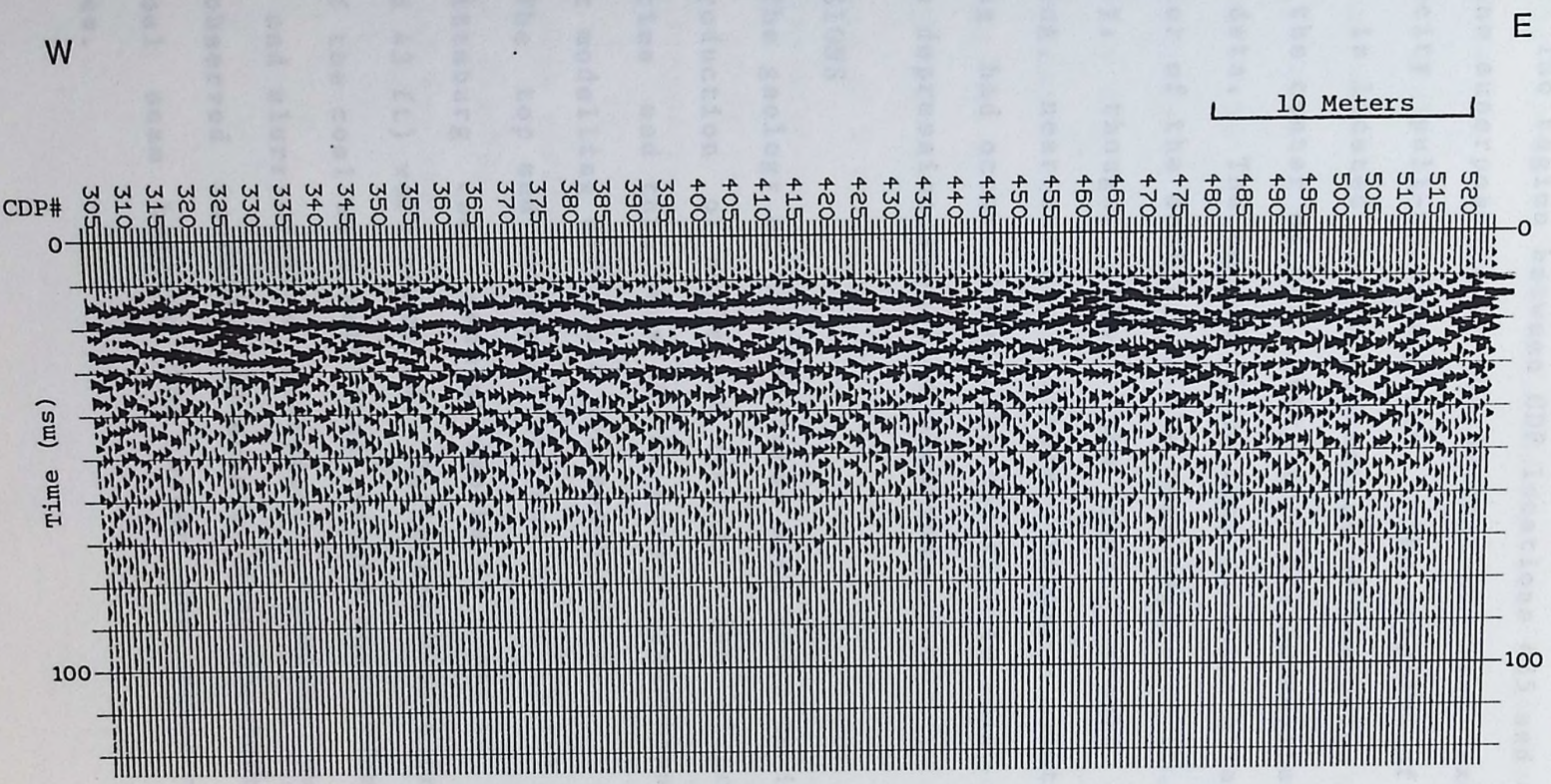


Figure 31: CDP seismic section of the Frontenac 30.06
line located 15 meters north of the previous
50 caliber lines.



layer. The region between CDP locations 435 and 470 on the line superposed over the 50 caliber line exhibits a velocity pull-up phenomenon. The midpoint of this region is located within 2.5 meters of the point found to be the center of the cavity from the 50 caliber and drill data. The second 30.06 line exhibits a loss of character of the doublet in the same region. It seems unlikely, though, that the cavity should affect overlying, near-surface layers unless substantial slumping had occurred over the cavity, in which case a surface depression should be observed.

CONCLUSIONS

The geology at the Frontenac site seems to inhibit the production of reflected events. The alternating velocities and thin beds of the Kansas cyclothem make seismic modelling difficult and speculative.

The top and bottom of the one meter (3 ft) thick Weir-Pittsburg coal seam at depths of 9 and 13 meters (29 and 43 ft) were resolved. Reflected events from the top of the coal seam exhibited reduced amplitudes over water and slurry-filled cavities. Velocity pull-ups were observed in reflected events from the bottom of the coal seam beneath the water and slurry-filled cavities.

The location of cavities in the Weir-Pittsburg coal seam at depths of 9-13 meters (29-43 ft) were located with good resolution. The edges of these cavities were located to within an estimated 1 to 1.5 meters (3 to 5 ft) horizontally at this depth.

For the coal seam at a depth of 19 meters (63 ft) the accuracy of determining the location and extent of the cavity diminished greatly. The center of a cavity at this depth was located to within an estimated 3 to 4 meters (10 to 13 ft). However, the edges of a cavity at a depth of 19 meters were determined only within a tolerance of 9 to 10 meters (30 to 33 ft).

The high-resolution seismic reflection method has proven to be very promising for locating abandoned coal mine cavities in southeastern Kansas if the coal seam is within 9 to 13 meters (29 to 43 ft) of the surface. Since most surface collapses occur over mines at these shallow depths, this detection method has potential practical application.

REFERENCES CITED

- Abernathy, G.E., 1944, Mined areas of the Weir-Pittsburg coal bed: Kansas Geological Survey Bulletin, no.52, part 5, pp. 214-228.
- Asten, M.W., Grezl, K.J., and Leung, L., 1982, In-seam seismic techniques for coal exploration: Australian Coal Geology, vol.3, part 1, pp. 21-29.
- Biot, M.A., 1952, Propagation of elastic waves in a cylindrical bore containing a fluid: Journal of Applied Physics, vol.23, no.9, pp. 997-1005.
- Brown Bros. Coal Co. Mine Map, 1915, Sec.18-30-25: Available for inspection at the Kansas Geological Survey.
- Brown, J.C., 1933, Map of the Standard Coal Co. mine in Sec.3-30-25: Available for inspection at the Kansas Geological Survey.
- Cook, J.C., 1965, Seismic mapping of underground cavities using reflection amplitudes: Geophysics, vol.30, no.4, pp. 527-538.
- Fisher, W., 1971, Detection of abandoned underground coal mines by geophysical methods: USEPA Water Pollution Control Res. Ser., Project 14010EHN, 94 p.
- Fry, R.C., and Orange, A.S., 1982, High-resolution seismic; A practical approach to coal exploration: Utah Geological and Mineral Survey, Bulletin 118, pp. 211-218.
- Greaves, R.J., 1985, Coal prospect evaluation using high-resolution reflection seismology; A case study: Mining Engineering, vol.37, no.8, pp. 1061-1064.
- Harris, J.W., 1984, Stratigraphy and depositional environments of the Krebs Formation - Lower Cherokee Group (Middle Pennsylvanian) in southeastern Kansas: Unpublished M.S. thesis, University of Kansas, 127 p.
- Hasbrouck, W.P., and Padget, N., 1982, Use of shear wave seismics in evaluation of strippable coal resources: Utah Geological and Mineral Survey, Bulletin 118, pp. 203-210.

REFERENCES CITED (cont'd)

- Hawkins, L.V., Whiteley, R.J., Holmes, W.H., and Dowle, R., 1982, Downhole-crosshole high resolution seismic reflection profiling to resolve detailed coalseam structure: Soc. Explor. Geophys. 52nd Annual Meeting, expanded abstracts, pp. 423-426.
- Heckel, P.H., Brady, L.L., Ebanks, W.J., and Pabian, R.K., 1979, Pennsylvanian cyclic platform deposits of Kansas and Nebraska: Ninth Inter. Congress of Carboniferous Stratigraphy and Geology, Guidebook Series 4, Kansas Geological Survey, 79 p.
- Howe, W.B., 1956, Stratigraphy of pre-Marmaton Desmoinesian (Cherokee) rocks in southeastern Kansas: Kansas Geological Survey, Bulletin 123, 132 p.
- Knapp, R.W., and Steeples, D.W., 1986, High-resolution common-depth-point reflection profiling; Field acquisition parameter design: Geophysics, vol.51, no.2, pp. 283-294.
- Pierce, W.G., and Courtier, W.H., 1938, Geology and coal resources of the southeastern Kansas coal field: Kansas Geological Survey, Bulletin 24, 122 p.
- Rodriguez, R., April 1986, personal communication.
- Schoewe, W.H., 1959, Coal resources of the Cherokee Group in southeastern Kansas: Kansas Geological Survey, Bulletin 134, part 5, pp. 183-222.
- Sheriff, R.E., 1980, Seismic stratigraphy: International Human Resources Development Corp., Boston, Ma., pp. 127-131.
- Telford, W.M., Geldart, L.P., Sheriff, R.E., and Keys, D.A., 1976, Applied Geophysics: Cambridge Univ. Press, New York, N.Y., 860 p.
- Watkins, J.S., Godson, R.H., and Watson, K., 1967, Seismic detection of near-surface cavities: U.S. Geological Survey, Professional Paper 599-A, 12 p.
- Widess, W.B., 1973, How thin is a thin bed?: Geophysics, vol.38, no.6, pp. 1176-1180.
- Wolfe, P.J., Holdeman, P.G., and Richard, B.H., 1983, Seismic guided wave transmission in the Lower Freeport Coal: AIME 112th Annual Meeting, abstract.

REFERENCES CITED (cont'd)

Zeller, P.E., 1968, The stratigraphic succession in
Kansas: Kansas Geological Survey, Bulletin 189, 81
p.

APPENDIX A

Justification of Field Parameters

The quality of the data obtained from a seismic reflection profile depends on the field recording parameters. The parameters are determined by the objectives of the survey, available resources, and geologic locality (Knapp and Steeples, 1986).

The record length should be long enough to insure the arrival of events from all horizons of interest. Considering that the depth of the coal seam is less than 20 meters at all of the sites, a 125 millisecond record length was found to be sufficient.

The sampling interval - the time between recorded sample points - must be small enough to avoid aliasing the highest frequency expected (Knapp and Steeples, 1986). The Nyquist frequency - the highest resolvable frequency at a given sample interval T - is defined as $f=500/T$, where T is in milliseconds. Frequencies of 250 to 350 Hz were expected, therefore, a sampling interval of 1/4 ms, which yielded a Nyquist frequency of 2000 Hz, was chosen.

The 50 caliber and 30.06 rifles were chosen because of their portability and cost-effectiveness. The 50 caliber rifle provided more energy than the 30.06 for reaching the greater depths at the Frontenac site.

The half meter receiver interval was chosen so as to yield adequate horizontal resolution. This interval yielded quarter meter intervals between CDP locations, therefore, a 3 meter wide cavity would have 12 point coverage. The half meter source interval yielded the maximum 12-fold CDP coverage.

The Pittsburg data were shot with a split-spread field geometry. During walkaway field testing, the events of interest were seen on only 6 to 8 traces with off-end geometry. By using a split-spread geometry with offsets centered around this 6-8 trace window on both sides of the shot, the events receive essentially double coverage with each shot. The end-on field geometry was chosen for the Frontenac 50 caliber data. This geometry provided twice the range of offsets, since all 24 channels were recorded on one side of the shot. This greater range of offsets shows more moveout, and thus provides more velocity information.

The nearest and furthest offsets were determined from walkaway noise tests, such as the one presented in figure 20 of the text. Traces near the source are subjected to noise from ground-roll and air blast, which can overpower any signal of interest. On traces further from the source the signals weaken due to dissipation of energy. Offsets showing the greatest signal-to-noise

ratio can be identified and an optimum recording window can be determined from such a test.

A high-cut filter is used to avoid aliasing and to damp high frequency noise. Since an anti-alias filter was applied and high frequency noise was not a problem, the high-cut filter was left out.

A low-cut filter of 340 Hz was applied to the data to damp the effects of ground-roll and other low frequency noise, and to increase the dominant frequency of the data. Field tests revealed that the 340 Hz filter was the highest low-cut filter which could be applied to the data without weakening the events of interest.

A 60 Hz notch filter was applied to the Pittsburg data to eliminate any effects from nearby powerlines. No powerlines were present at the Frontenac site, so a notch filter was not necessary.

APPENDIX B

Seismic Data Processing Steps

CDP sorting involves rearranging the data into common depth point gathers. Each gather contains all of the traces which are reflected from a common subsurface location.

Bad trace editing involves scanning all of the data visually and deleting any traces which are judged to have unacceptable signal-to-noise ratios.

Frequency spectral analysis involves generating a frequency versus amplitude spectrum plot, such as the one presented in figure 12 in the text. This type of plot gives some indication as to which frequencies are predominantly signal and which are noise. A filter can then be designed to enhance the signal and damp the noise.

Velocity analysis was done by a trial-and-error method of stacking, or summing, all of the traces within a CDP gather at various normal moveout (NMO) velocities until the events of interest show the greatest continuity.

Correcting for elevation statics involves shifting each trace up or down to adjust to a common datum. This accounts for variations in travel times due to elevation differences between surface locations.

The frequency spectral analysis gives a general idea of the filter needed for a given data set, but with high frequency data such as was obtained in this study, a subtle change in the filter applied can cause considerable changes in the data. The stacked CDP data can be run through a series of finely varying filters to establish the ideal filter for enhancing the events of interest.

The residual statics process forces the crosscorrelation of a pilot trace and the actual traces to determine the residual static correction. The pilot traces are composed of summed CDP's. The purpose of this process is to correct static inconsistencies not resolved by other static processes.

The air blast mute applied to the 50 caliber data mutes or zeroes out that portion of the data where the air coupled wave dominates. This prevents the noise from the air coupled wave from interfering during the stacking process.