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INTRODUCTION

It is common in coal-mining states that some mined-out areas do not have adequate mine maps available to public authorities (Fisher, 1971). It is also common that instances of either gradual or catastrophic subsidence occur without warning in such areas. Such occurrences often require an emergency response to minimize further damage to buildings and/or transportation facilities as well as ground water contamination. The environmental and economic damage in such localities is sometimes severe, and the emotional stress imposed on nearby residents may be substantial.

Locating subsurface mines has long been a problem. Inaccuracies in mine maps (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 report demonstrates developments in seismic techniques for the detection and evaluation of underground mined cavities in coal. The majority of this report describes results and observation associated with compressional wave reflection data. Work with surface waves and shear waves is also described.

Research was conducted at two sites in Pittsburg, Kansas and one site each in the La Cygne, Kansas and Frontenac, Kansas areas (Figure 1). Specific site selection was accomplished with assistance in Pittsburg from the city engineers and in the La Cygne area from the P&M Mining Company. The Frontenac site was chosen after a detailed study of old mine maps. The results presented here show potential for future widespread use of seismic techniques for void detection.

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 Padget, 1982) all with limited success. Most of the research done on coal mine detection has involved refraction seismology or S-wave reflection seismology. The work reported here is the first to locate water-filled coal mine cavities at depths of less than 30 m (100 ft) by high-resolution P-wave reflection seismology techniques.

Most researchers using seismic techniques for cavity detection cite three phenomena as evidence of a cavity: free oscillations or resonance of the cavity walls, anomalous amplitude attenuations, and delay of arrival time (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 (V_s) 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 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 more than energy reflected from the same deeper horizon that never encountered the cavity; thus, 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 theoretically will not propagate through 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 m (490 ft) 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 30 m (100 ft) thick coal seam in Wyoming buried at a depth of 180 m (600 ft) (Greaves, 1985). A similar study was conducted over two coal seams approximately 15 to 30 m (50 to 100 ft) thick buried at a depth of 670 m (2200 ft) in central Utah (Fry and Orange, 1982). Neither of these studies, however, involved cavity detection of previously mined areas.

GEOLOGICAL BACKGROUND

The study areas are located in the Cherokee basin and the Forest City basin both bounded on the east by the Ozark uplift, on the west by the Nemaha Ridge, and are separated from each other by the Bourbon arch (Figure 2). Terrigenous sediments were supplied to these basins from the Appalachian, Ouachita and Arbuckle-Wichita mountains, as well as the Canadian Shield.

Depositional Environment

The various phases of the Cherokee and Marmaton 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 coals studied here are the culmination of aggrading sedimentation on delta plains. The idealized sequence of lithologies in these cyclothems reflects progradation of a clastic wedge: dark marine shale with rare limestone, gray sideritic shale, gray silty shale with thin sandstone interbeds, rare cross-bedded sandstone, thin-bedded sandstone, siltstone and shale, and underclay with coal.

REFLECTION SEISMOLOGY

Reflection seismology involves introducing a mechanical wave into the ground (typically by some form of explosion or weight-drop), and then monitoring energy returning to the surface after reflection from various subsurface acoustic boundaries. The surface monitoring is done by a system coupled to the ground by a geophone (a velocity sensitive device which converts mechanical motion into electronic pulses) which produces electronic time-varying modulations of frequency and amplitude that are amplified, filtered, and then recorded onto digital tape by a portable seismograph.

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

$$R = (Z_2 - Z_1) / (Z_2 + Z_1)$$

where: Z_1 = Acoustic impedance of upper layer

Z_2 = 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 (5200 ft/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 (3738 ft/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 (3738 ft/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 (Mayne, 1971). This method involves summing or stacking together signals from different shot and geophone locations which are reflected from a common point in the subsurface.

Figure 3 illustrates the CDP method. This figure shows how two consecutive shot points, 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).

Resolution

Obtaining the necessary high resolution seismic data requires a good signal-to-noise ratio and a broad high-frequency spectrum. Since wavelength (λ) is inversely proportional to frequency (f) ($\lambda \propto 1/f$) data recorded with a higher dominant frequency will possess shorter wavelengths and is therefore capable of resolving thinner beds. In order to record data with high dominant frequencies, an extreme pre analog-to-digital (A/D) low-cut filter, a smaller impulsive source, high natural frequency geophones and careful attention to details during parameter selection are necessary considerations (Knapp and Steeples, 1986a,b).

Knowing that the coal seams in question are approximately 1-m (3-ft) thick, the frequency needed to resolve the coal seam can be determined. 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 is the wavelength of the $\lambda/4$ where (λ) 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 judgment of the interpreter.

Assuming an average velocity for coal of 1000 m/s (3,250 ft/s) and knowing the coal thickness to be about 1 m (3 ft) , the frequency necessary for resolution can be calculated as follows:

$$\lambda/4 = V_1 / 4 f = (1000 \text{ m/s})/4 f = 1 \text{ m}$$

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

Common Offset Gathers

Sorting and displaying seismic data according to consecutive common source-to-receiver offsets reveals any energy dependence with angle of incidence. This cost effective sorting technique is commonly used on high signal-to-noise engineering seismic data in place of CDP type processing (Hunter et al., 1984). Variations in phase and amplitude that result from anomalous acoustic zones can be detected when the seismic data traces are grouped according to offset (from source-to-receiver) distance. Common offset gathers are an effective way of observing localized variations in the acoustic properties or structure of geologic units.

PROCESSING

The data were processed on the Data General MV-20000 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, velocity analysis, static correction, CDP stacking, filtering and scaling. In addition, a residual statics process was applied to some of the stacked data to remove non-uniform variations in the coal reflector resulting from near surface velocity anomalies.

GENERAL FIELD PROCEDURES

Acquisition of shallow high-frequency reflection data requires extreme attention to detail (Knapp and Steeples, 1986b). Prior to the acquisition of any CDP or Common-Offset data set extensive testing was performed to determine the optimum recording equipment and parameters. Testing included: source-receiver offsets and spacing, energy source size and type, geophone type and number, pre analog-to-digital (A/D) high-cut and low-cut filter values, notch filter, and sample rate/number of total samples.

For data acquired on this project an Input/Output DHR 2400 seismograph was used to digitally record all the data on half-inch magnetic tape in modified SEG-Y format with A/D conversion of 11 bits plus sign. The amplifiers have a factory noise specification of 120 nV root-mean-square (rms), providing a fixed gain dynamic range of 72 dB. Total system response as a function of frequency using various low cut filter settings is shown in figure 4.

Source determination depended on the specific target depth, type of energy to produce, and near surface conditions. For the shallow P-wave work in the Pittsburg Industrial Park, the trailer park, and the La Cgyne area a modified 30.06 rifle was used. The 30.06 rifle is easily capable of producing frequencies in excess of 200 Hz (Miller et al., 1986). The 50-caliber gun was used for the deeper target at the Frontenac site. It too is capable of over 200 Hz energy generation. For the S-wave work at the Industrial Park, the source was a two-bladed arrow that produced a shear wave when forced 0.5 m (1.6 ft) into the ground and hit sideways. This S-wave source was developed and built at the Kansas Geological Survey for this project. The surface wave source was a simple steel plate vertically impacted by a sledgehammer. All the sources were tested and compared with a multitude of others and were determined to be the optimum energy source for the specific need.

Receiver selection was dependent upon the type of wave to be generated and recorded, the maximum frequency of useful seismic energy to be recorded and the amount and type of energy intended to constructively or destructively interfere at the receiver points. For all the compressional wave and surface wave work performed during this study single 100 Hz Mark Products L-40A geophones were used. Geophones with natural frequencies with 10, 28, 40 and 100 Hz were all tested. For all shear wave work horizontally sensitive single 40 Hz geophones were used with the primary geophone axis oriented according to the intended direction of sensitivity.

Research we performed in a faulted area of southwestern Oklahoma conclusively showed the advantage of two 100 Hz geophones in series to attenuate

unwanted energies and to increase the amplitude of recorded signal (Myers et al., 1987). By using two 100 Hz geophones in connected series, parallel to the direction of the gusting wind and separated by 0.5 m (1.6 ft) a drastic (about 12 dB) reduction in the effects of the wind noise and an increase in amplitude of recorded seismic signal resulted. These results could have been useful if the additional geophones had been available for this study.

STUDY AREAS

The areas chosen for this study are in the eastern Kansas coal fields (see Figure 1). The Mulberry coal bed and Weir-Pittsburg coal bed have been extensively mined in this area by both subsurface and strip-mining methods. The subsurface mines leave behind a maze of interconnecting cavities. The mined coal seam of interest at the La Cygne site is the Mulberry coal of the Marmaton group, and at the Pittsburg site is the Weir-Pittsburg coal bed of the Cherokee group. Most of the region around the study areas have been undermined, many with cases of localized subsidence.

Pittsburg Sites

The first site is located in the Pittsburg Industrial Park on the northeast edge of the city of Pittsburg, Kansas (Figure 5). This location was selected because of drill-hole data that encountered both coal and voids at depths of 6-15 m (20-49 ft) and the presence of numerous subsidence areas generally indicative of subsurface cavities.

The second site is located within a mobile home park on the west edge of Pittsburg (Figure 5). 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 m.

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 m (60 ft) with undisturbed coal on either side. A portion of this mine map is displayed in figure 17. 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.

La Cygne Site

The La Cygne area site was selected because of its close proximity to a tailings pile and an extensive drilling program previously completed in the area by P&M Mining Company (Figure 6). The subsurface cavity encountered by drilling was at a

depth of approximately 12 m (39 ft). The overburden consisted of alternating limestones and shales of the Marmaton group.

SEISMIC TECHNIQUE DEVELOPMENT

Detection of voids in coal theoretically can be accomplished using various seismic techniques. Compressional and shear wave reflections and surface wave phase variations were the specific seismic techniques used during this study to verify the existence of known voids in coal. All work detailed in this report is associated with specific technique development.

Compressional wave (P-wave) research was primarily conducted in the Pittsburg, Kansas Industrial Park with supplemental work in Frontenac, Kansas, La Cygne, Kansas and a trailer court in Pittsburg, Kansas. Most of the significant conclusions in this report were derived from data collected in the Pittsburg Industrial Park. The near-surface conditions were most conducive at that site for the propagation and recording of high frequency P-wave reflection energy. The site was occupied on 2 different occasions in an attempt to show repeatability in the technique and to see what effect the injection of coal-ash slurry has on seismic character in a void area.

S-wave research was conducted exclusively in the Pittsburg Industrial Park since favorable results had been obtained there during previous P-wave experiments. The majority of the research involved variation of CDP type acquisition and processing techniques on opposite directional data sets. The two directional data sets obtained on each profile used horizontally sensitive receivers and an impulsive source with direction of impact 180 degrees apart for each data set.

Surface wave research was also conducted exclusively in the Pittsburg Industrial Park. The majority of the effort in surface waves was focused on the acquisition and processing of common-offset type data. The most likely means of detecting voids with surface waves involves the study of interference phenomena at wavelengths proportional to the depth of the void.

Pittsburg Industrial Park P-Wave Seismic Data

Data were collected at the Pittsburg Industrial Park site in July of 1985 and June of 1987. Two intersecting lines were shot in 1985 tying together information from three drill holes with a third line shot in 1987 along exactly the same path of line 1 in 1985 (Figure 7). The three lines were shot using a split-spread source/receiver geometry, single 100 Hz geophones as receivers and a modified 30.06 rifle as an energy

source. Both source and receiver stations were separated by 0.5 m (1.6 ft). This source and receiver spacing produced quarter meter CDP intervals. Assuming the mine cavities are at least 2 to 3 m (6 to 10 ft) across, this should provide adequate sampling to detect the voids.

Because of surface subsidence and irregular surface topography, a relative elevation survey was carried out to allow the application of surface static corrections. Surface static corrections adjust the time of each trace to account for differences in the lengths of the travel paths due to elevation variations. This correction is critical when dealing with high frequency data such as that needed for this study. For example, with a near-surface velocity of 500 m/s (1,625 ft/s), an elevation difference of only 0.6 m (2 ft) will result in a difference in two-way travel time of 2.4 ms. If the frequency of an event is 200 Hz, one cycle will be 5 ms long. Thus an error of 2.4 ms will cause a phase error of about a half cycle (180 degrees) causing the data to stack destructively.

An analog 340 Hz low-cut filter was selected in an attempt to increase the recorded dominant frequency of the data. The frequency versus amplitude plot was taken from a representative trace (Figure 8). This frequency spectrum reveals that a dominant reflection frequency of about 275 Hz was attained. Therefore a one m (3 ft) thick coal seam should be detectable and possibly even resolvable.

A 24-channel field file was selected from line 1 in which part of the geophones were located over the mined void (figure 9). The reflection wavelet (or lack of) sampling the void area is clearly different than the reflection wavelet returning from the competent intact coal seam. A normal moveout (NMO) velocity of 500 m/s (1625 ft/s) was calculated for this event.

An uphole survey was conducted in a borehole located at CDP 340. An explosive charge was detonated at the depth of the coal seam. The one-way travel time from the coal seam to the surface was measured. This uphole survey revealed that the reflection event identified in Figure 9 was in fact from the coal seam.

The stacked CDP seismic section of line 1 was shot across two boreholes, one at CDP location 260 and one CDP location 346 (Figure 10). The geologic cross section derived from the interpreted CDP stacked data correlates with the drill data indicating void at CDP 260 and intact coal at CDP 346 (both 9 m (29 ft) deep). The surface subsidence between CDP locations 350 and 405 is approximately 0.7 m (2.3 ft) deep. In some areas surface subsidence can be indicative of subsurface collapse.

The event which occurs at 23-25 ms throughout most of the section was confirmed by the uphole survey as a reflection from the coal seam. Areas in which

this event becomes discontinuous are interpreted as void of coal. The loss of amplitude of this event over the water-filled cavities is attributed to the contrast of the reflection coefficients. The acoustic velocity of the water in the cavities, of the shales overlying the coal, and even of the surrounding clays is greater than the acoustic velocity of the coal. 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. This yielded a reduced reflection amplitude over the water-filled cavities.

The signal-to-noise ratio and overall data quality were not as high on line 2 as on line 1 (Figure 11). High frequency pulses of amplitude modulated radio signals occasionally saturated the seismic amplifiers. Line 2 was shot across two boreholes, one at CDP location 834 (indicating void) and one at CDP location 894 (indicating coal). The specific field recording parameters and equipment were identical to those used on line 1. The reflected event identified as the coal seam arrives between 23 and 30 ms over most of the profile.

Two interpretations of line 2 between CDP locations 835 and 847 are possible as a result of different data processing techniques. The seismic section in Figure 11 has a residual statics process applied while the seismic section in Figure 12 has no residual statics applied. Using the static processed section a coal pillar can be interpreted within the established void area between CDP 810 to 885. There is no indication on the non-static shifted data that a coherent event (indicating coal) between 835 and 847 is present at 23 to 30 msec. Therefore, two possible interpretations exist; 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 on the static processed section between CDP's 835 and 847 are merely a manifestation of the residual statics process. Considering the extent of the surface collapse, it is most likely that the region is underlain by cavity. Further drilling would be necessary to verify which hypothesis is correct.

The foregoing example shows that seismic methods are not likely to completely replace drilling in the immediate future. It does illustrate, however, that drill sites can be chosen to answer specific questions raised by the seismic surveys. In other words, drilling can be done for verification purposes and to help choose between hypotheses inferred from the seismic surveys. During the summer of 1987 a second P-wave data set was collected at the Pittsburg Industrial Park. The purpose of this profile was to determine repeatability and what effect coal-ash slurry has on the seismic reflection wavelet. After the collection of lines 1 and 2 during 1985 the Office

of Surface Mining had supervised the injection of coal ash slurry into mined cavities at this site.

Line 3 was collected along the same surface traverse as line 1 two years earlier (Figure 7). The specific field recording parameters and equipment were identical to those used in 1985 on line 1 and line 2. The data for line 3 was processed differently (by a different graduate student) than line 1; therefore, slight differences in frequency content and wavelet character exist (Figure 13). However, after careful examination, the void on line 1 at CDP 260, previously correlated to the drill data, is still present on both line 1 and line 3. A potential void previously uninterpreted on line 1 may be present at CDP 280 on line 3. The void area interpreted on the southwest end of line 1 can still be identified on line 3, however, the drop in signal-to-noise observed within the interpreted void on line 1 is not as pronounced on line 3. This could be the result of only partial filling of the voids with coal-ash slurry.

Even with the almost 100 Hz drop in the dominant frequency of line 3 significant information can be derived. The distortion of the refraction wavelet at CDP 252 might be an indication that shallow geologic units are being affected by the presence of the voids interpreted on both line 1 and line 3. A second potential void is interpreted only on line 3 at CDP 280. This feature was not as clearly evident on line 1 as line 3, possibly due to the secondary statics correction made during processing. The void beneath the surface collapse between CDP 362 and 405 clearly appears as an amplitude drop in the coal reflection. The coherency present on line 3 through the collapse, not present on line 1 may be a result of partial filling of the void with coal-ash slurry. An amplitude drop from the slurry reflection in comparison to the coal reflection on line 3 would be expected as the result of an acoustic impedance contrast difference between the coal and the overburden and slurry and the overburden.

The repeatability of the technique and the effect of partial filling of the void is evident upon comparison of line 1 and line 3. From the seismic data only, one could conclude from amplitude considerations that the void beneath the surface subsidence is now completely filled with the slurry, whereas the voids at CDP 250 and 280 are not completely filled. If this were verified with drilling, the technique could be used not only to detect voids, but also to determine if injection procedures were effective and complete.

Pittsburg Mobile Home Park - P-Wave Seismic Data

Data were collected at the Pittsburg mobile home park site in July of 1985. These data were shot with the 30.06 rifle using the same recording parameters that

were used for the industrial park data. The processing steps were also the same as for the industrial park data.

The seismic line was shot over a known mine area (Figure 14). A recent surface collapse, with a depth of approximately 0.7 m (2.3 ft), was located 15 m (49 ft) south of the line. Buildings and other cultural obstructions prevented orienting the line north-south, so as to transect the mined area. Therefore, the line was shot east to west with no assurance of an underlying cavity.

The CDP stacked section confirms that the seismic line did not pass over a mined cavity, as evidenced by the continuous character of the events present (Figure 15). The CDP stacked data exhibits the same type of events seen over the coal seam at the industrial park site.

Frontenac P-Wave Seismic Data

Data were first collected at the Frontenac site in January of 1986. Since the coal seam is roughly twice the depth (20 m (65 ft)) as the previous sites in Pittsburg, a more powerful source than the 30.06 rifle was needed. A 50-caliber single-shot rifle was chosen as the source.

A walk-away noise test was conducted to determine the optimum offsets to use for recording the CDP line (Figure 16). Single 100 Hz geophones were placed in a line at 0.5 m (1.6 ft) intervals with the source located 5 m (16 ft) from the nearest phone. From the seismograph records in the field, the event at about 50 ms was interpreted as a possible reflection.

The CDP line was located so as to transect a single subsurface cavity (Figure 17). A surface depression was located 50 m (163 ft) south of the seismic line at the approximate location, (according to the old mine map), of an old vertical shaft (Figure 17). This correlation supplied surface information necessary to exactly locate the main horizontal shaft. The line was shot using an end-on array with 20 m (65 feet) as the nearest offset. The array consisted of single 100 Hz geophones planted at 0.5 m (1.6 ft) intervals. A summary of the recording parameters is presented in Table 4.

The 50-caliber CDP seismic section possesses several good quality reflection events (Figure 18). The location of the cavity is not obvious on this seismic section using the same criteria to identify a void here as at the Pittsburg Industrial Park. This variation could be attributed to the different source, the greater depth to the coal seam, and lithological changes between the two study sites. Drilling by the Kansas Geological Survey produced a type stratigraphic section for the upper 23 m (75 ft) (Figure 19). There is a lack of continuity in the event at 46 ms between CDP locations

434 and 452. Drill data revealed a cavity at a depth of 19 m (62 ft) at CDP's 424 and 442 and coal at 19 m (62 ft) at CDP 400.

An uphole velocity survey sampling various depths was conducted in the drill hole at CDP 400. The average velocity from the depth of the coal seam to the surface was found to be approximately 1400 m/s (4500 ft/s). This velocity value yields a two-way travel time of 27 ms for a reflection from the coal seam. That suggests the event at 46 ms is not a reflected P-wave event from the coal seam. Since reflectors with offsets this large possess very little curvature, it is often difficult to distinguish shallow reflections from refractions on field records. The event at 46 ms could be a reflection or a refraction from a deeper layer.

If the loss of signal at CDP 434 and the eventual regaining of signal at CDP 445 was a result of the void, the two-way reflection time of 46 ms suggests a simple first order P-wave reflection from the void was not what detected the shaft (figure 20). Correlating the drill data to the seismic data suggests an apparent horizontal shift of 10 CDP points between the effects of the cavity on the seismic data and the physical evidence provided by the drill data. An S- to P-wave mode conversion at the coal seam would cause a horizontal shift in the calculated source/receiver midpoint as a result of the asymmetrical raypaths. This asymmetry would cause an incorrect shift during the correction to vertical incidence of each seismic trace. Therefore, if interaction with the cavity did take place, the horizontal location of the effect of the cavity on the seismic data would be incorrect. The mode conversion hypothesis would also account for the difference in the two-way travel time of the event since the S-wave velocity is roughly one half that of the P-wave velocity. The apparent inconsistency between the drilling formation and seismic interpretation could also be due to fringe effects at the edges of the cavity causing the cavity to appear smaller than it actually is. This fringe effect would be most prominent if the event was a reflected SV from the top and sides of the water filled void. If the event was an SV, the delayed arrival time could easily be compensated for.

A short reverse line was shot east to west directly over the cavity (Figure 21). If S- to P-wave mode conversion were occurring, a similar shift of the cavity's effects should be in the opposite direction as observed on the west to east line. The CDP seismic section of this reversed line reveals only a slight shift (6 CDP's). The magnitude of the shift was only half enough to confirm the mode conversion hypothesis.

Information from the forward and reversed data sets can be incorporated in order to approximate minimum and maximum extent of the cavity. Figure 22 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 would be 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 and there is coal beneath CDP 400, therefore the cavity extends at least as far west as CDP 423 but no further west than CDP 401. It can then be deduced that the cavity is centered at CDP location 440, and is between 9 and 19 m (29 and 62 ft) across. This deduction agrees with the mine map and surface information. Additional drill data are needed to verify the actual location and extent of the cavity.

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 superimposed over the 50-caliber line and a 6-fold CDP line was shot 15 m (49 ft) to the north to test the reproducibility of the method (Figure 23 and Figure 24). These 30.06 lines were shot using a split-spread array with single geophones at 0.5 m (1.6 ft) 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 0.20 to 0.25 m (0.6 to 0.8 ft). Therefore, a preliminary unrecorded shot was fired at each location (to improve source coupling) followed by a second shot which was recorded.

No reflections were obvious on the field records nor on the CDP seismic sections of the two lines (Figures 23 and 24). 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 layer. The region between CDP locations 435 and 470 on the line superimposed over the 50-caliber line exhibits a velocity pull-up phenomenon. The midpoint of this region is located within 2.5 m (8 ft) 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 change in character of the doublet in the same region. This implies that the cavity is affecting overlying, near-surface layers. If the near surface layers have been affected resulting in slumping of the layers over the cavity, a surface depression should have been or will be observed in the near future.

Problems encountered at the Frontenac site were believed to be a result of a very shallow high velocity material overlain by a low velocity soil layer. In order to test this suspicion, we conducted an experiment at the underground limestone mines in Lenexa, Kansas. That experiment was funded separately by the U.S. Army Corps of Engineers. The mined out area was beneath a 50-foot-thick shale capped by a thin limestone, beneath a soil veneer. As expected, the recorded refraction arrival was an oscillating wavelet with a duration of as many as 5 complete cycles (Figure 25). This

situation makes the recording of reflection information of lesser amplitude, later on the record nearly impossible. In a further attempt to isolate more of the characteristics of the reflection technique responsible for the previously noted "ring" of the the refraction arrival, an experiment was conducted near Lyndon, Kansas at a site possessing ideal geologic conditions for testing this hypothesis. The walk-away noise survey showed conclusively that the ring was independent of source and receiver, and was directly related to depth of burial of the near-surface limestone (Figure 26). From these observations we concluded, until a method of reducing or removing the repetitive refraction wavelet produced by near-surface high velocity materials is perfected the seismic reflection technique would not be effective in some geologic settings.

La Cygne P-wave Data

The P-Wave reflection data collected in the La Cygne, Kansas, area was targeting the Mulberry coal at a depth of about 12 m (38 ft). The data were acquired using modified 30.06, and single 100 Hz geophones both using 0.6 m (2 ft) intervals. The data were filtered with 340 Hz pre A/D low cut resulting in a dominant frequency of 180 Hz. The overburden consisted of a thick 5 m(15 ft) shale overlain by a 3 m (8 ft) thick limestone with 3 m (10 ft) of alluvium between the surface and the limestone. These near-surface conditions were similar to those at the Pittsburg Industrial Park with two exceptions: the 3 m (10 ft) thick near surface limestone unit and the greater depth to coal.

Many anomalous areas can be observed on the processed CDP stack (Figure 27). In order to determine which of these anomalous zones were the result of voids and which were near-surface effects unrelated to old mine works, an extensive drilling program was undertaken by the P&M Mining Company. From the drill data a general geologic cross section was produced and compared to the seismic section. The correlation of the CDP stacked seismic data and the drill data confirmed the presence of old mine works at CDP 545. The character and frequency as well as phase and velocity features of the void at CDP 545 on the seismogram were noted and compared to the Pittsburg area voids.

Continued experimentation in the La Cygne area would increase the confidence level associated with void identification from CDP stacked seismic data in that area. Several more lines are proposed and continued coordination with P&M Mining Company should result in a technique and the associated localized parameters necessary to implement industrial use.

Lawrence S-Wave Test Site

Detailed research at our Lawrence, Kansas, test facility and in the Pittsburg, Kansas, area resulted in many significant advances in the S-wave reflection technique. However, none of the research yielded a high confidence S-wave technique to detect voids in coal.

Specific experiments at the Lawrence test site included: source development, radiation pattern determination, SV-vs-SH comparisons, receiver orientation and natural frequency dependence, and 3 component energy correlation. Testing began in the spring of 1986 and continued until the summer of 1987. The composite results of the S-wave tests were considered during the collection of the data at the Pittsburg Industrial Park.

Pittsburg Industrial Park S-Wave Data

The data sets were acquired using field parameters designed to produce and receive the SH component of shear wave energy. The source was the 2-bladed arrow (previously described) and the receivers were 40 Hz horizontally sensitive geophones both source and receivers were at 1.2 m (4 ft) spacing. Two shots-per-shot points were collected, each from opposite directions but both with the intended direction of particle displacement perpendicular to the survey line. Due to the directional nature of SH-waves the resultant data sets can be reversed and then added to enhance S-waves and cancel P-waves, Raleigh waves and random noise.

The CDP method as described earlier was used in an attempt to enhance S-wave reflections from the coal seam. Due to the nature of Love waves (surface wave), any coherent high frequency shear-wave reflections within the upper 100-150 msec were destructively interfered with by Love waves. Experience gained from previous testing allowed confident identification of refractions, reflections, and surface-wave energy on CDP stacked sections.

The coherent events on the stacked section are refractions from an acoustic boundary probably above the coal (Figure 28). The lack of coherency of even the refraction events is indicative of low source energy and/or severe static shifts caused by near-surface low-velocity materials. In order to take full advantage of the properties of shear waves to detect water filled voids, we must develop a source that can consistently produce shear wave energy and a field geometry that can help enhance the S-wave reflections and diminish the effects of Love wave energy.

Pittsburg Industrial Park Surface-Wave Data

Surface waves are dispersive, travel a linear path from source to receiver, and their depth of penetration is directly proportional to their wavelength. Therefore, if the proper wavelength surface wave is generated and recorded, consistent variations in phase angle at a given time could be a direct result of a subsurface anomaly.

Since surface waves travel a linear path from source to receiver, the CDP method of analysis on surface waves would not be meaningful. The surface wave data from the industrial park were therefore collected with the intent of grouping each recorded trace according to its source-to-receiver distance. These common-offset-gathers allowed direct comparison of phase angle from geophone location to geophone location as a source and receiver moved down the line at a consistent offset distance.

The specific type of surface waves generated and collected for this survey were Raleigh waves. Raleigh waves have a displacement that is retrograde elliptical in the same vertical plane as the direction of propagation of the wave. This means that theoretically an anomaly encountered by the wave should cause a phase distortion. The resultant phase angle distortion should have a gradational effect at the anomalies boundaries and become most severe within the anomaly. The amount of phase distortion will depend on the size of the anomaly and its acoustic impedance contrast with the surrounding material.

Surface-wave data were collected along the same surface line as line 1 and 3. The receivers were single 100 Hz geophones and the source was a sledge hammer vertically impacting a steel plate both on 1.6 m (4 ft) spacings. The data were collected in a CDP type roll-along fashion with the intent to later separate each trace into its appropriate common-offset group.

A phase shift toward time zero is obvious on most of the common offset gathers on the northeast end of the profiles (figure 31). This anomalous phase zone is centered on CDP 260 and is probably a direct result of the drill verified void at that location. This disturbance in the surface wave phase is most severe on about channel 18, which has a source to receiver offset of 12.3 m (40 ft). The interference phenomena effects a window of about 15 traces (18.5 m (60 ft)) within which gradual progression from zero phase distortion to almost 180 degrees is observed.

Gathers closest to the source (channels 20-24) show some indication that the void on the southwest (responsible for the surface subsidence) end of the line may have been detected (Figure 29). Only the traces closest to the source could have had a source to receiver travel path that encountered the southwesternmost void.

Correlating the frequency and wavelet character of the data within the void with that unaffected by the void, suggests the phase shift here is greater than 180.

The characteristics (velocity pull-ups and drop in signal-to-noise ratio) associated with the voids on P-wave data collected in the Industrial Park both in 1985 and 1987 correlate to a strong phase shift in the surface wave arrivals on data collected along the same surface line as line 1 and 3. Both the P-wave and surface wave anomalies occur at approximately the same surface locations, possibly indicating that these different types of waves are detecting the void and responding in different ways in accordance with their own unique physical properties. Identification of the void areas can most easily be accomplished with the surface wave data, since the magnitude of the disturbances associated with the voids are on the order of 10 to 15 ms. The advantage to the P-wave data is in the precision possible in depth, horizontal location, and thickness determinations.

CONCLUSIONS

Reflected events from the bottom of the Weir-Pittsburg coal seam at the Pittsburg Industrial Park exhibited reduced amplitudes and occasionally velocity pull-ups over water and slurry-filled cavities. The location of cavities in the coal seam at depths of 9-13 m (29-43 ft) were located with good resolution. The edges of these cavities were located to within an estimated 1 to 1.5 m (3 to 5 ft) horizontally at this depth.

The P-wave data collected at the industrial park in 1985 correlates well with the data collected there in 1987. The drilled void at the northeast end of line 1 and line 3 affected the frequency, character, and amplitude of the seismic signal on both line 1 and line 3 in a similar fashion. This clearly shows repeatability in the technique in this area. The void interpreted on line 1 beneath the surface subsidence area on the southwest part of the line, possesses a uniquely different character on line 1 than it does on line 3. If this difference is a direct result of the injection of coal-ash slurry late in 1985 (after the collection of data on line 1) P-wave reflection data could be used to estimate the localized structural soundness of slurry-filled void areas in comparison to surrounding material.

For the coal seam near Frontenac at a depth of 19 m (63 ft) the accuracy of determining the location and extent of the cavity was less than at the Pittsburg Industrial Park. The center of a cavity at this depth was located with seismic data to within an estimated 3 to 4 m (10 to 13 ft). However, the edges of a cavity at a depth of

19 m (62 ft) were seismically determined only within a tolerance of 9 to 10 m (30 to 33 ft).

The P-wave data set collected in the La Cygne area has several anomalous seismic zones. Conformation drilling allowed the identification of the physical properties of P-wave reflections and necessary recording parameters of P-wave reflections influential in the detection of voids in that area.

Shear wave reflections were not produced and/or recorded at any of the test sites with sufficient amplitude or coherency to discern them from linear arriving events. Many significant advances were made en route to an eventual documentable set of parameters and equipment that would be necessary to use S-wave reflection on a routine industrial basis.

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 m (29 to 43 ft) of the surface and there is no high-velocity layer near the surface. Since most surface collapses occur over mines at these shallow depths, this detection method has practical industrial application.

The results of this study clearly show the utility of high-resolution seismic methods in void detection. It is also clear that while seismic reflection will not replace drilling, it can reduce the amount of drilling necessary in some cases by an order of magnitude. Using drilling to confirm seismic information would greatly enhance the time and economics of shallow underground mine mapping with surface techniques.

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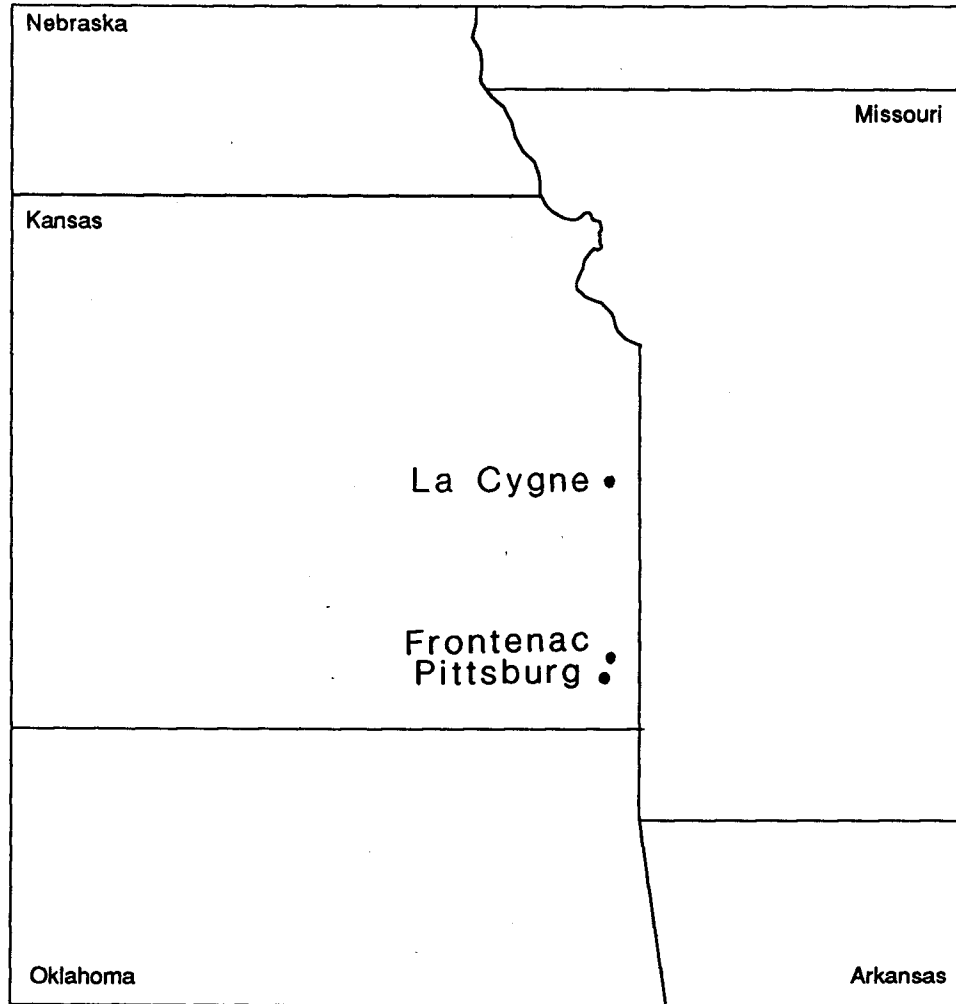
FIGURE CAPTIONS

- FIG. 1. Map showing study areas, which were located in southeastern Kansas.
- FIG. 2. Map showing the regional structural features surrounding the study areas.
- FIG. 3. 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.
- FIG. 4. The entire recording system's analog response to signal using the indicated low-cut filtering. The response curve is affected by both the 100 Hz geophones and the pre-amp analog filtering.
- FIG. 5. Map of mined areas of the Weir-Pittsburg coal bed around the study area. (from Abernathy, 1944)
- FIG. 6. Topographic map of the La Cygne area with the location and orientation of the reflection line indicated.
- FIG. 7. Map of the Pittsburg Industrial Park study site showing locations of the seismic lines, drill-holes and surface collapse.
- FIG. 8. Frequency spectrum plot of the Pittsburg data indicating a predominant frequency of 275 Hz.
- FIG. 9. A 24-channel field file with part of the geophones located over intact coal and others over cavity. The event in the box represents the signal received over the coal seam. The area shaded represents the signal received over the void.
- FIG. 10. CDP seismic section of Pittsburg line 1 with interpreted geological cross-section.
- FIG. 11. CDP seismic section of Pittsburg line 2 with interpreted geological cross-section. Residual statics applied.
- FIG. 12. CDP seismic section of line 2 with no residual statics applied.
- FIG. 13. CDP seismic section of line 3 with drill data and interpreted geologic cross-section.

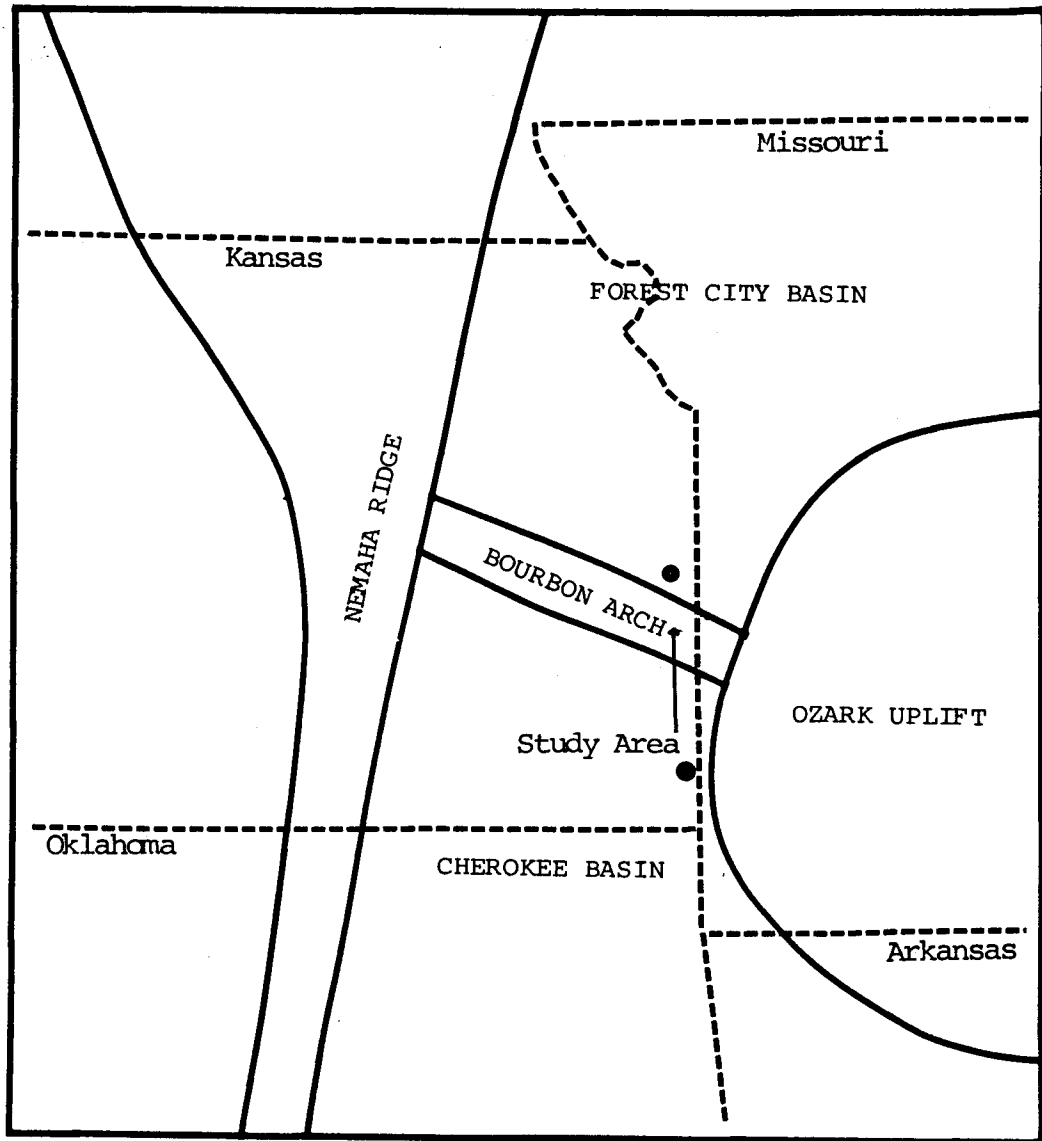
- FIG. 14. Mine map of the Pittsburg mobile home park study site showing the locations of the seismic line and the surface collapse. The west end of the line is located 475 ft north and 5 ft east of the southwest corner of the SE 1/4 of sec. 18. (from Brown, 1915)
- FIG. 15. CDP seismic section of the Pittsburg mobile home park line.
- FIG. 16. Walkway-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.
- FIG. 17. Map showing the location of the Frontenac 50-caliber seismic line over the known cavity. (from Brown, 1933)
- FIG. 18. 50-caliber seismic section of line shot west to east.
- FIG. 19. Stratigraphic section from the Weir-Pittsburg coal bed to the surface, based on drill cuttings during confirmation drilling by the Kansas Geological Survey. The resistant layers shown are based on drilling resistance.
- FIG. 20. Interpreted seismic section with the effects of the cavity darkened between CDP 435 and CDP 454.
- FIG. 21. CDP seismic section of the 50-caliber line shot east to west with an interpreted version.
- FIG. 22. 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.
- FIG. 23. CDP seismic section of the Frontenac 30.06 traversing the line the previous 50-caliber data was collected over.
- FIG. 24. CDP seismic section of the Frontenac 30.06 line located 15 meters north of the previous 50-caliber lines.
- FIG. 25. Walkaway-noise test from the underground limestone mines in Kansas City. The "ring" responsible for many of the problems encountered at the Frontenac site is clearly evident here.
- FIG. 26. This walkaway-noise test conducted near Lyndon, Kansas, clearly shows the results of a near-surface limestone. The limestone outcrop can be determined as well as the critical depth of burial.

- FIG. 27. This 12-fold CDP stack and geologic cross-section is from the La Cygne site. The seismic data have several anomalous velocity and amplitude zones. The geologic cross-section was produced from drilling at the indicated locations along the seismic line. Drilling based on this data indicated void at the interpreted anomaly at CDP 545.
- FIG. 28. 24-fold S-wave CDP data from the Pittsburg Industrial Park. Two shots were fired per shot point, the second shot 180 out of phase of the first. One shot was reversed and then added to the other. The data were then CDP sorted and stacked resulting in the psuedo 24-fold section. No reflections can be confidently interpreted on this section.
- FIG. 29. Common-offset-gathers of surface wave data collect along the same line in the Pittsburg Industrial Park as line 1 and line 3. The gathers clearly show the dependence with offset of the surface wave data. On channel 18 the drilled void correlates with the + 180 phase shift on the northeast end of the profile. On channel 22 the surface subsidence area correlates with the + 180 phase shift observed on the southwest end of the line.

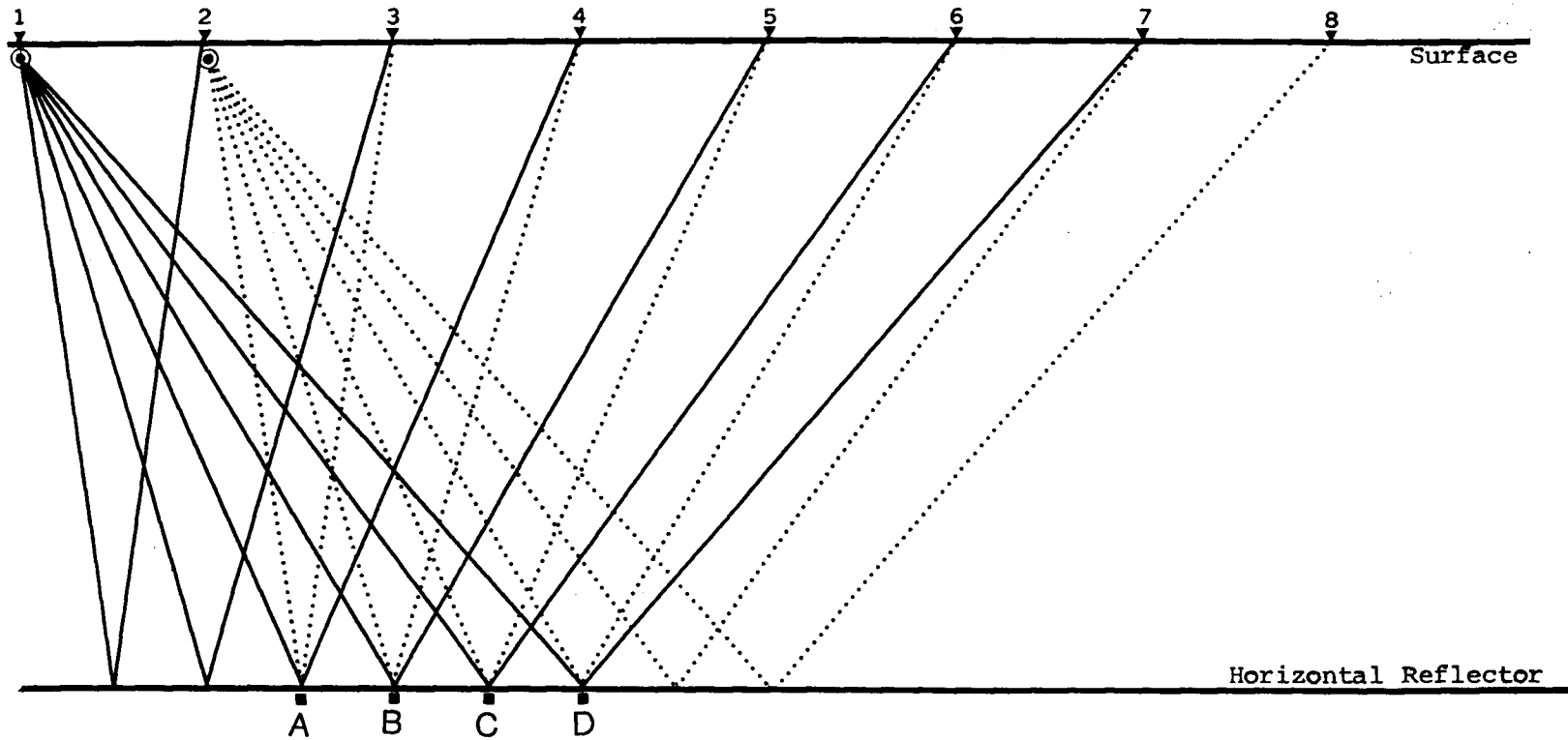
LOCATION MAP



0 50 100 mi



0 50 100
Miles

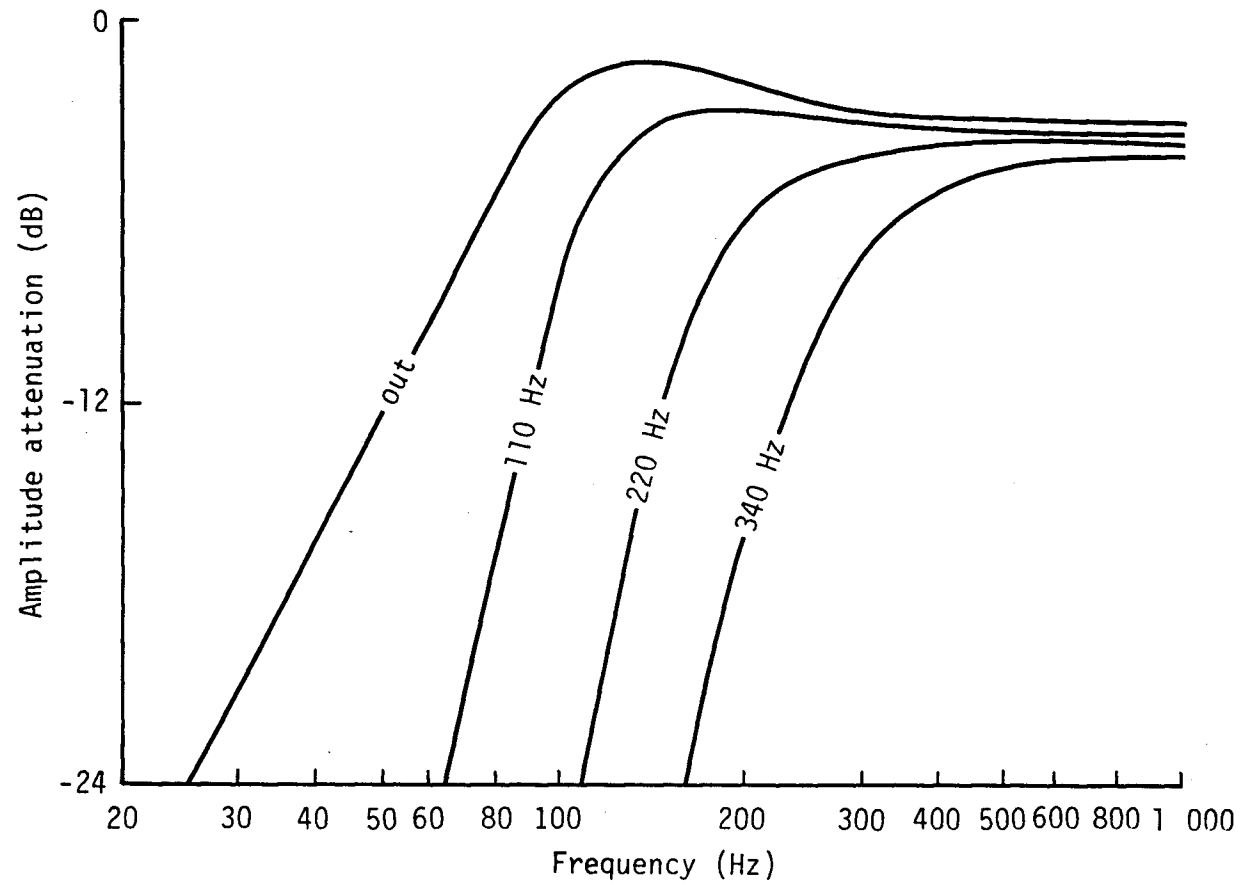


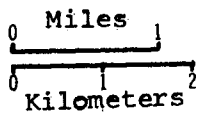
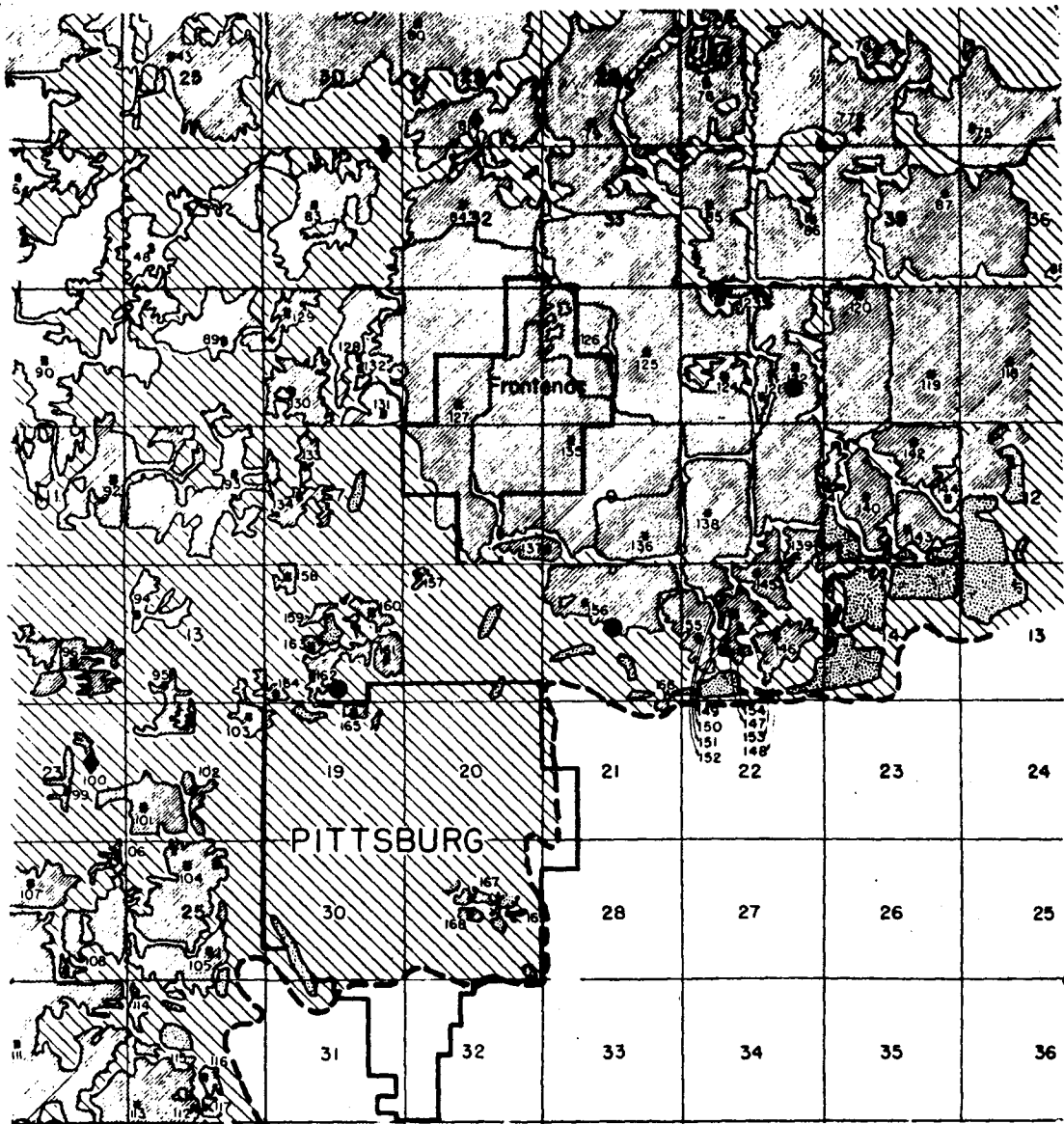
⊙ Shot location

▼ Geophone location

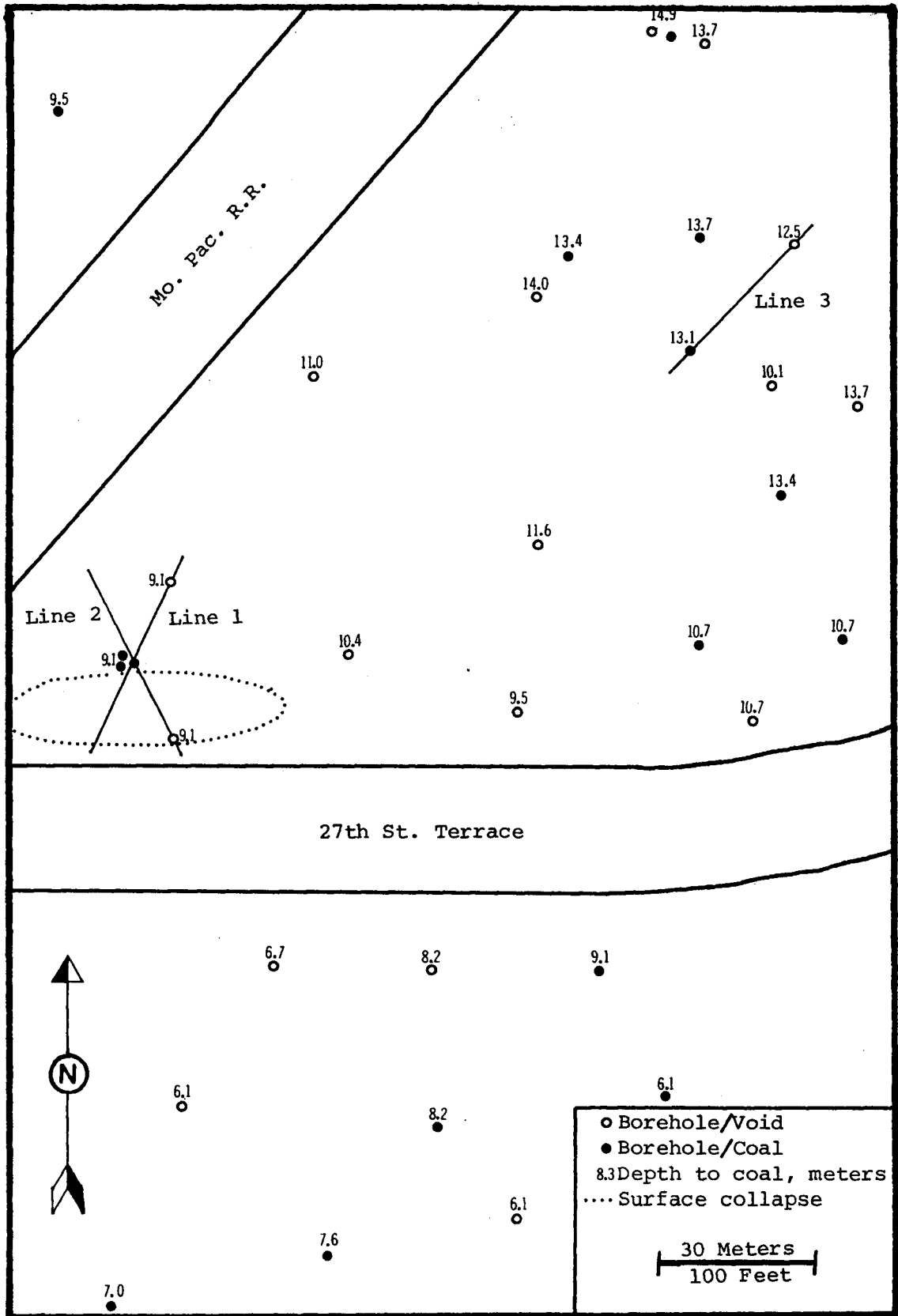
■ Common reflection point

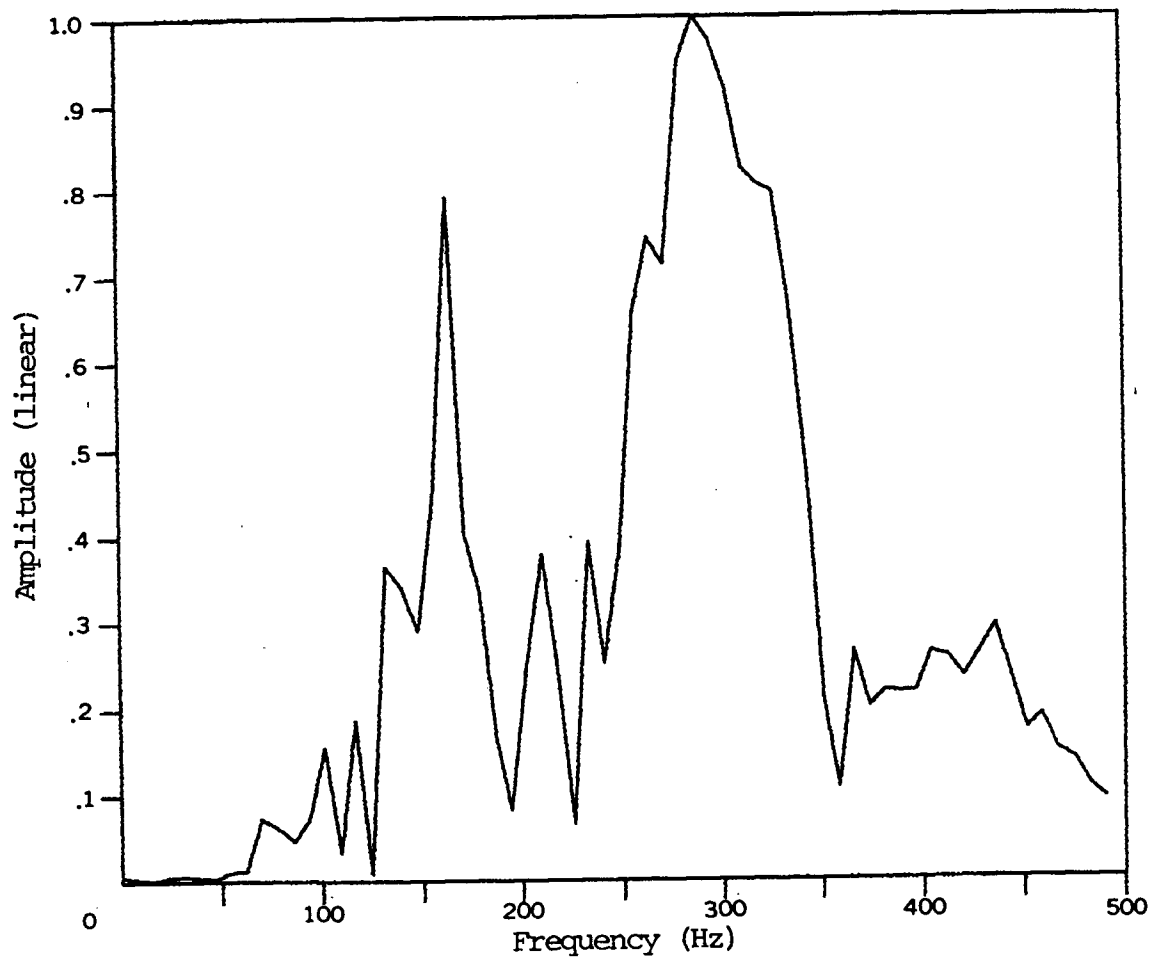
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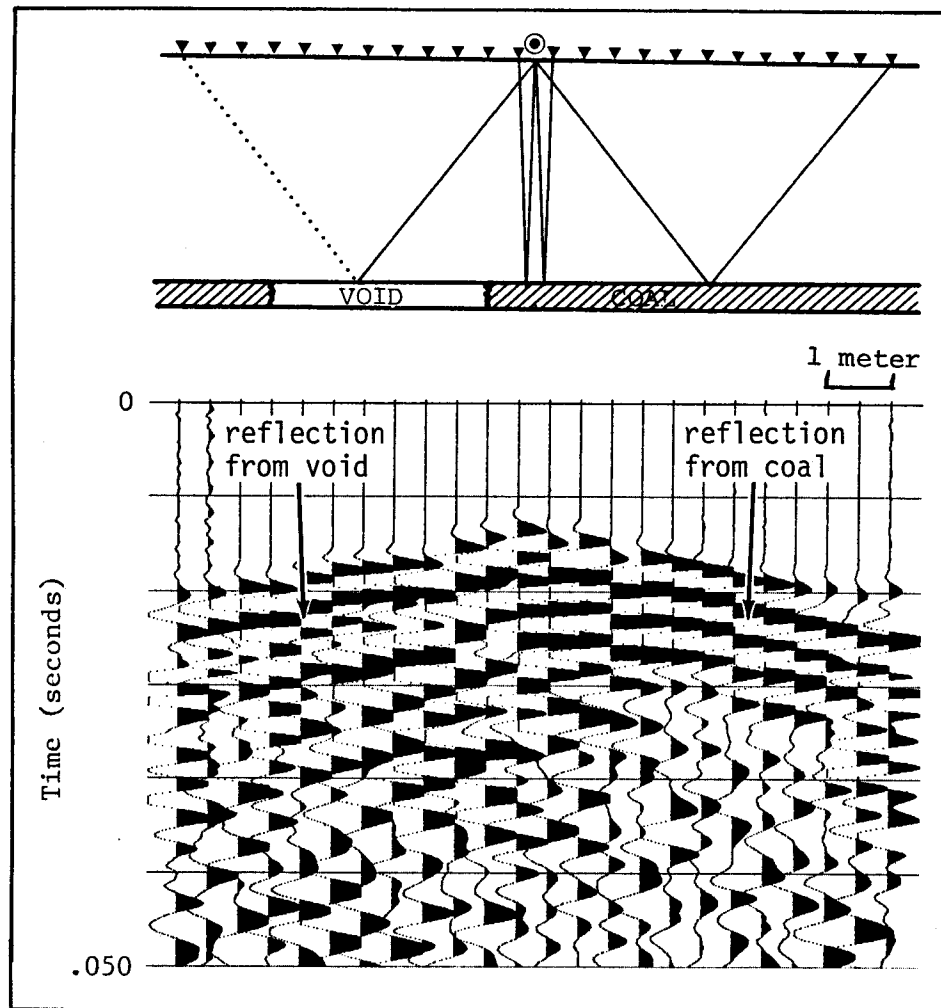




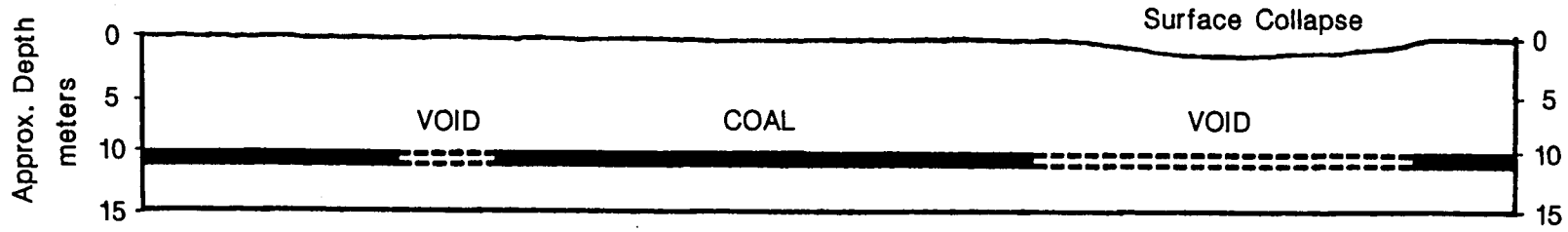
- Study sites
- Mined area
- Unmined area
- Mine index number
- Stripped area
- Approximate outcrop of Weir-Pittsburg coal



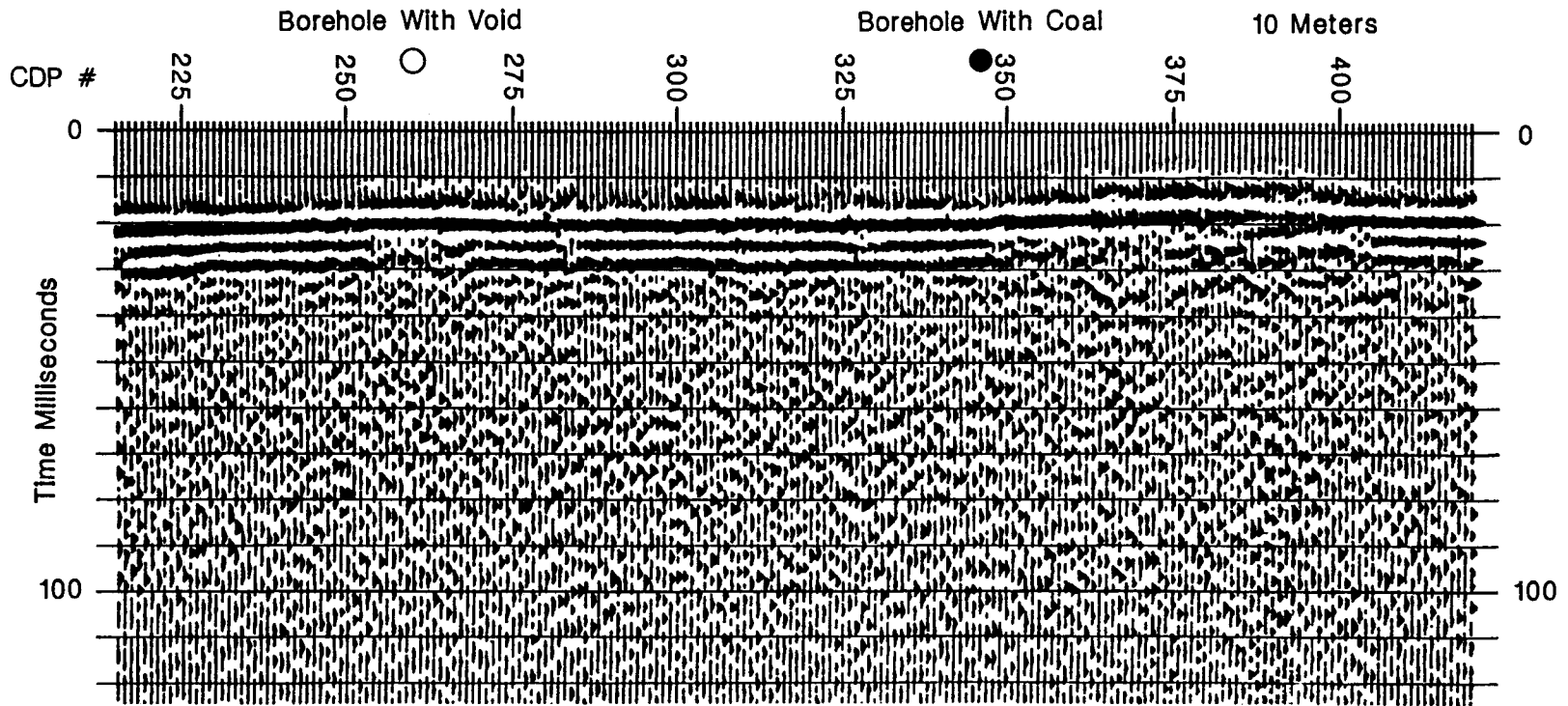




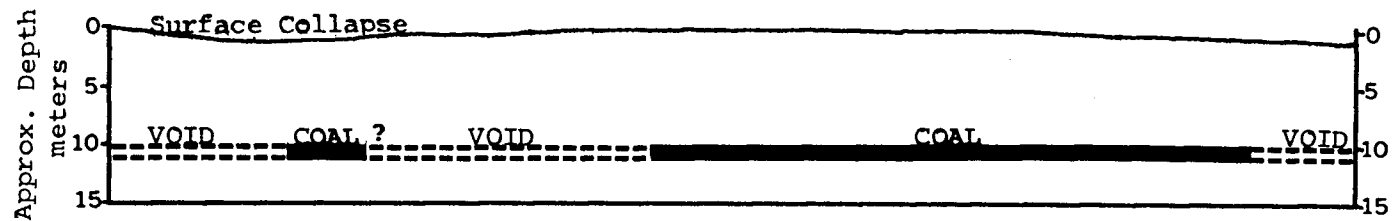
GEOLOGICAL CROSS SECTION



NE SEISMIC SECTION SW



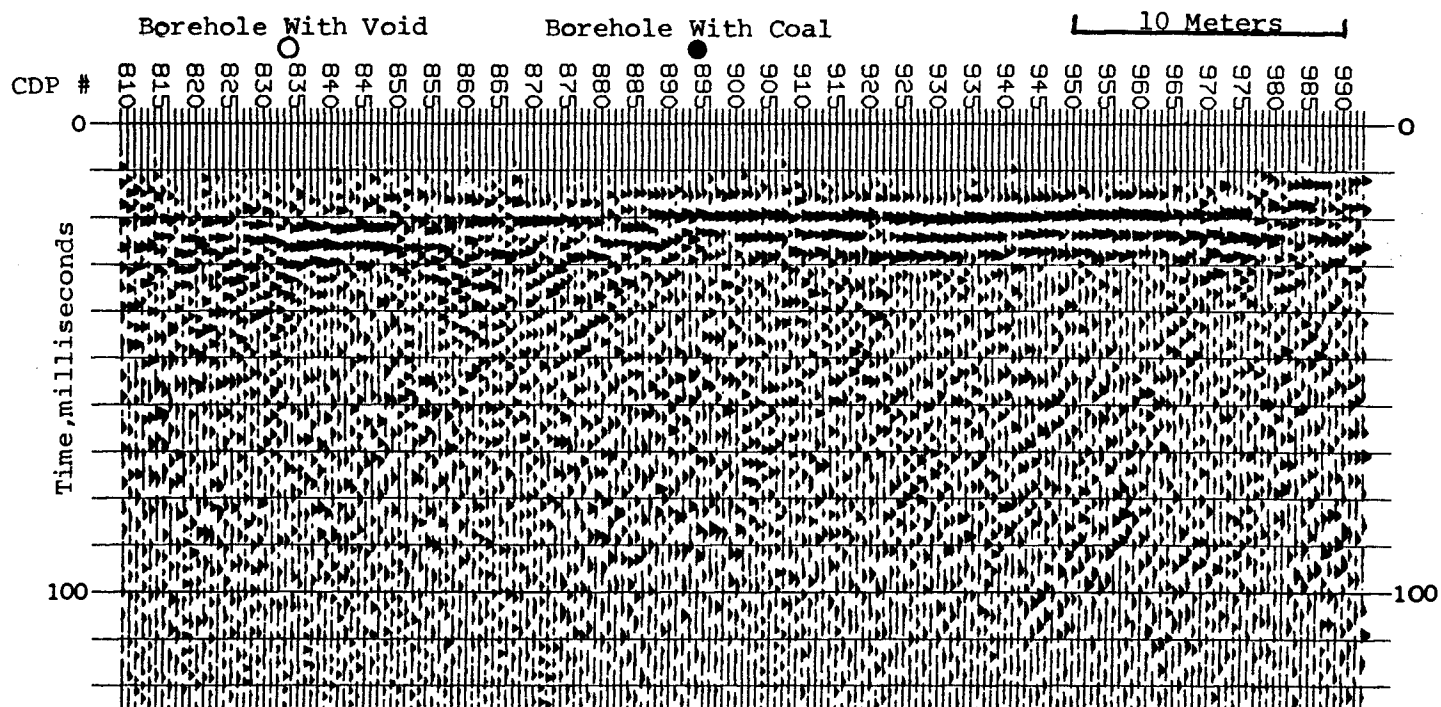
GEOLOGICAL CROSS SECTION



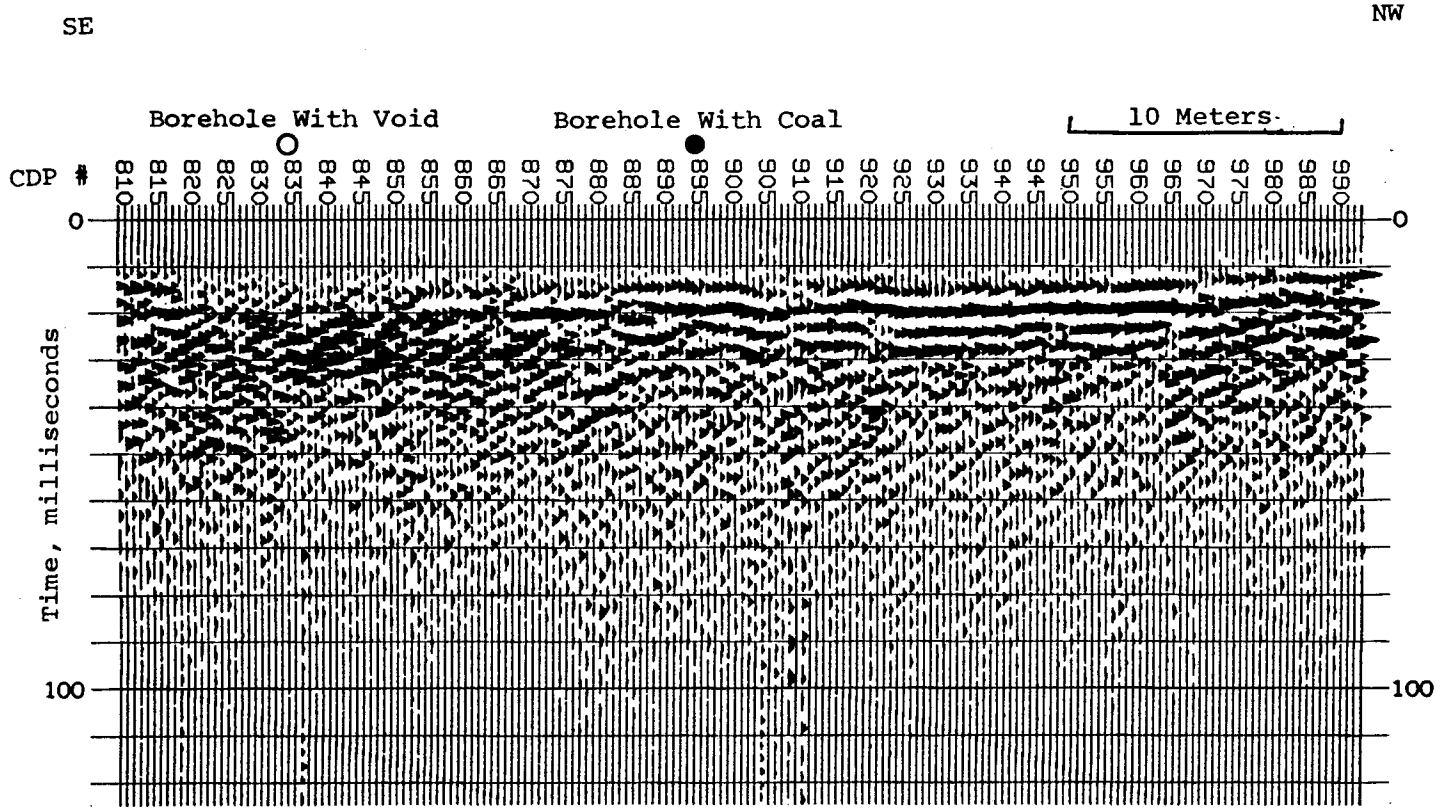
SE

SEISMIC SECTION

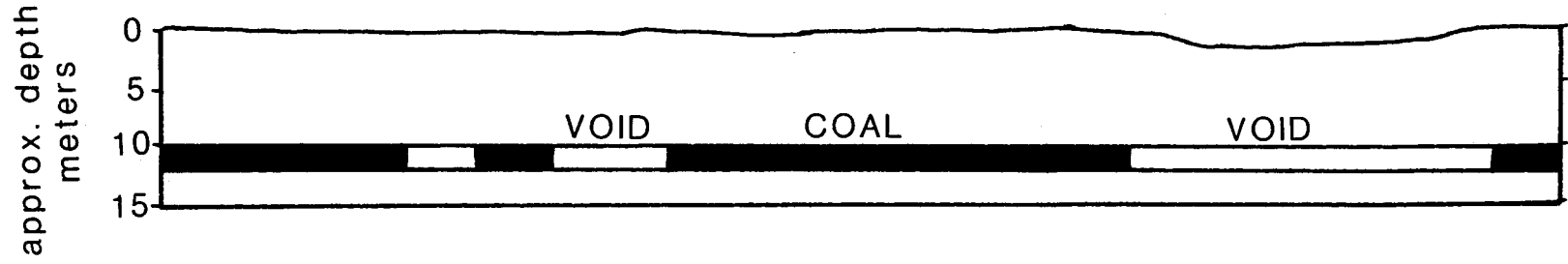
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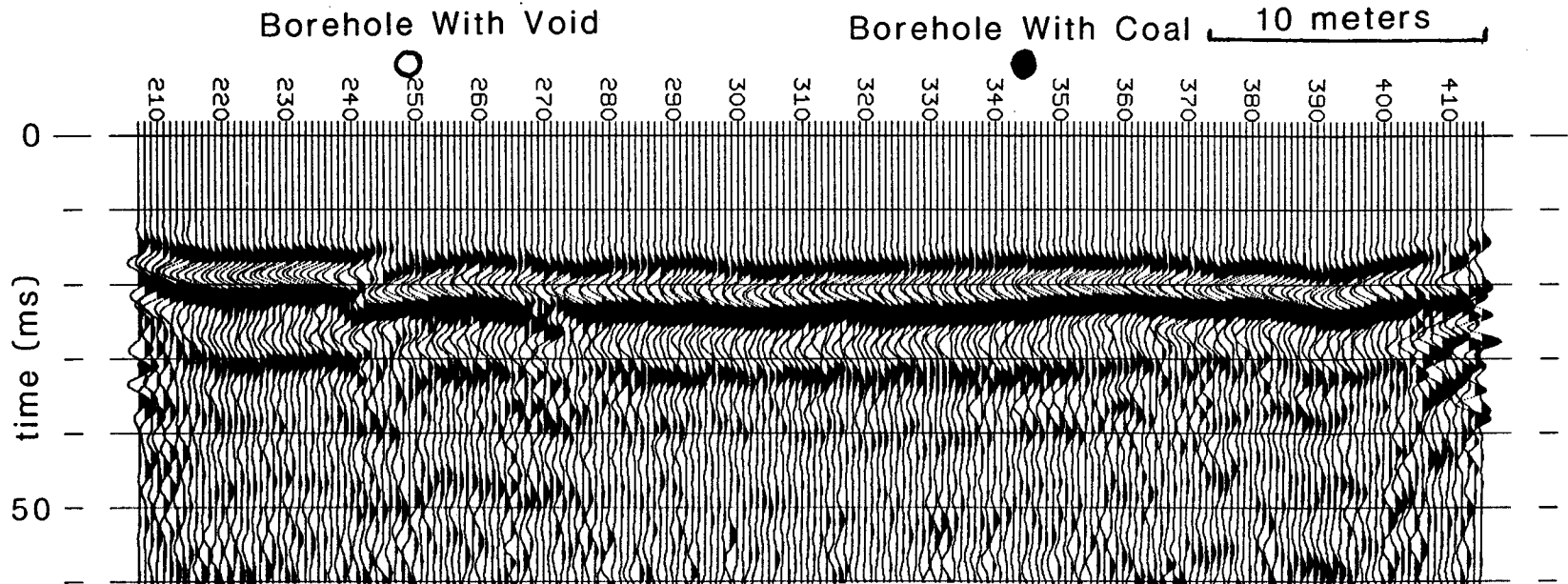
← Surface Collapse →

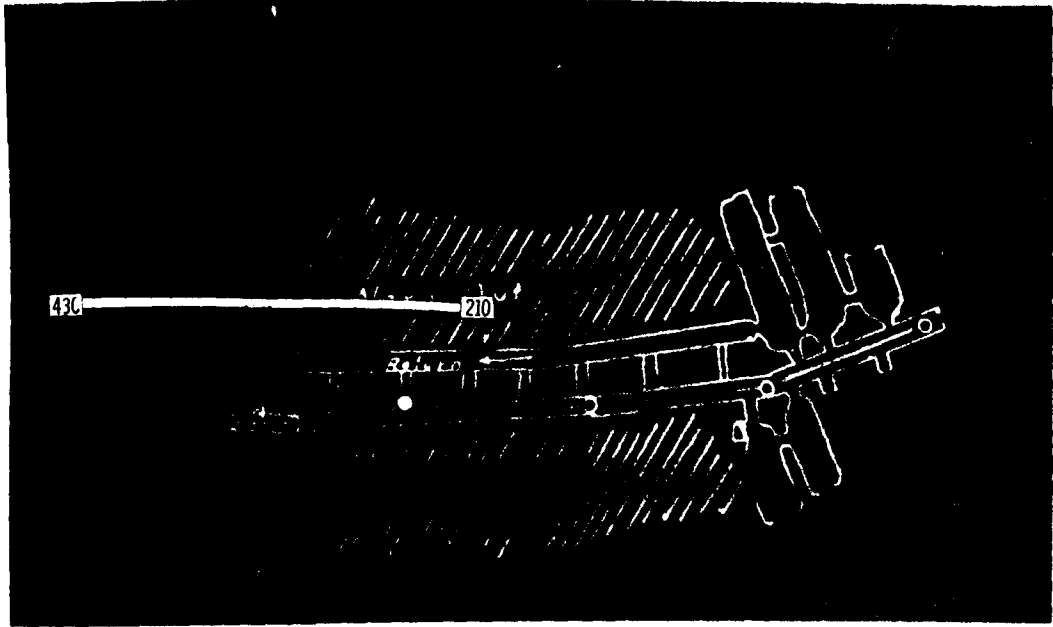


GEOLOGIC CROSS SECTION



SEISMIC SECTION





100 feet
30 meters

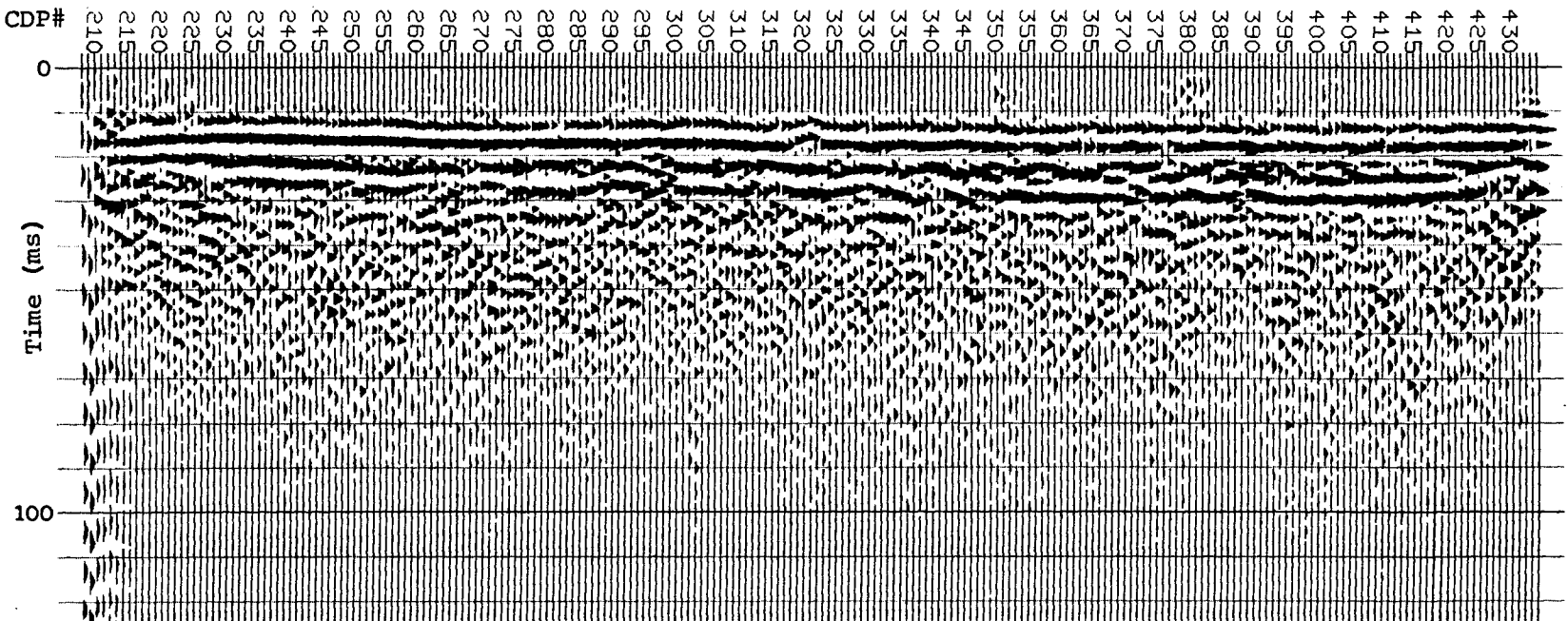


○ Surface Collapse

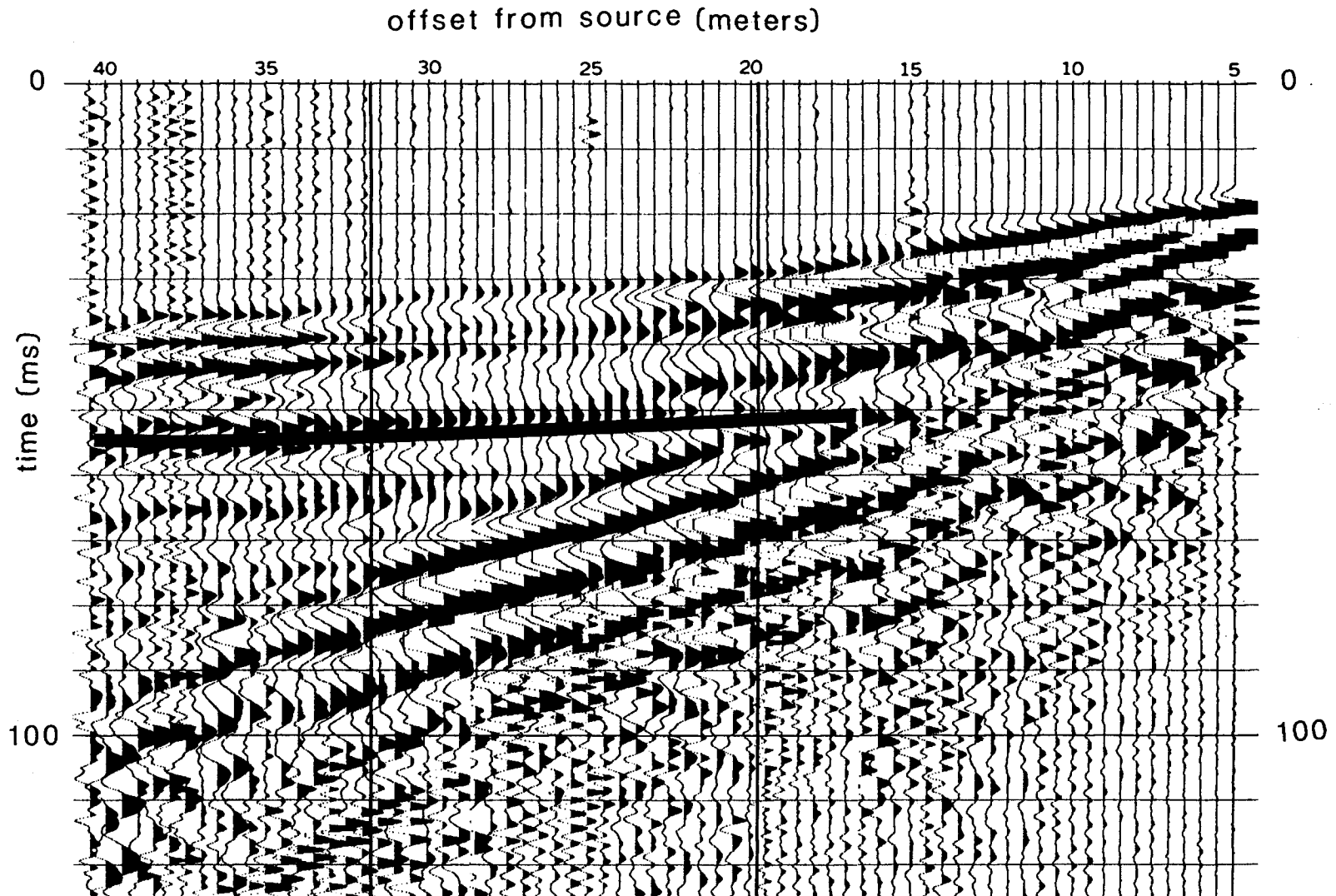
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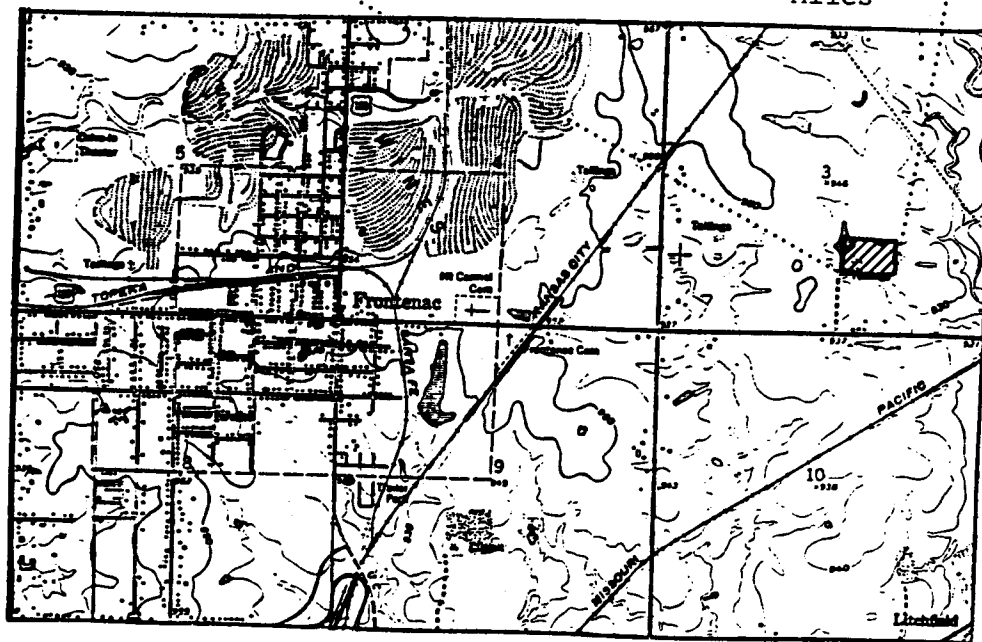
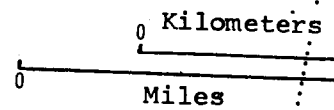
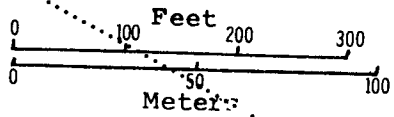
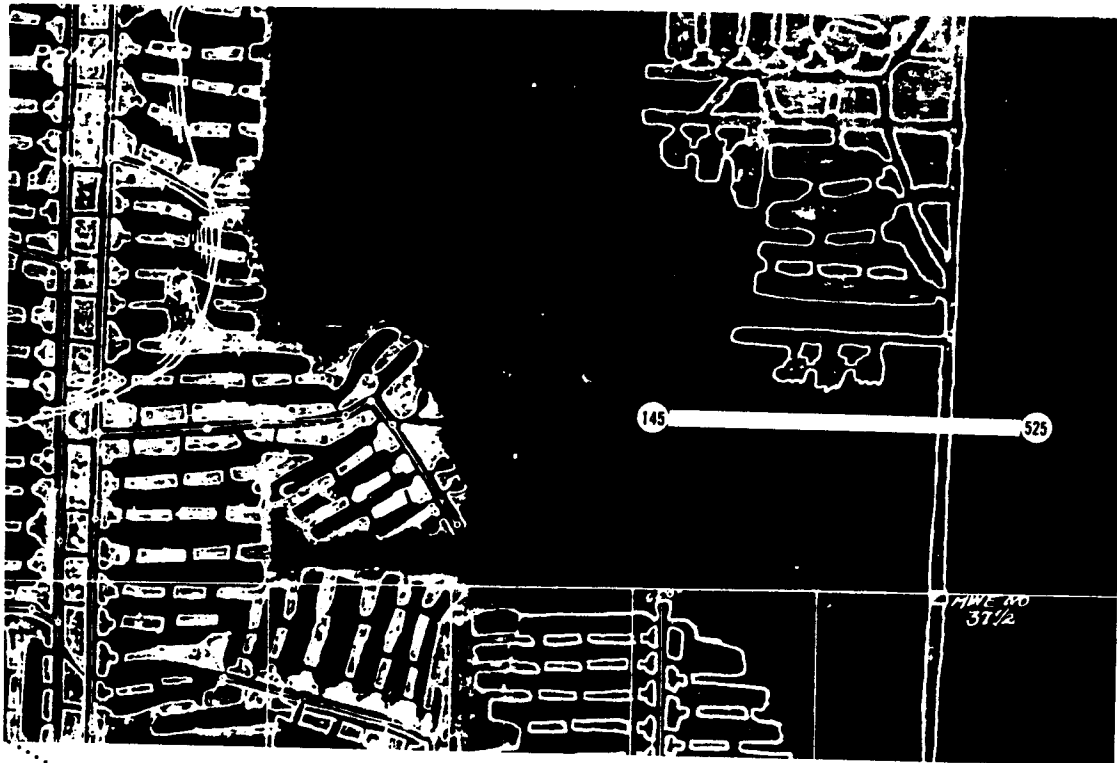
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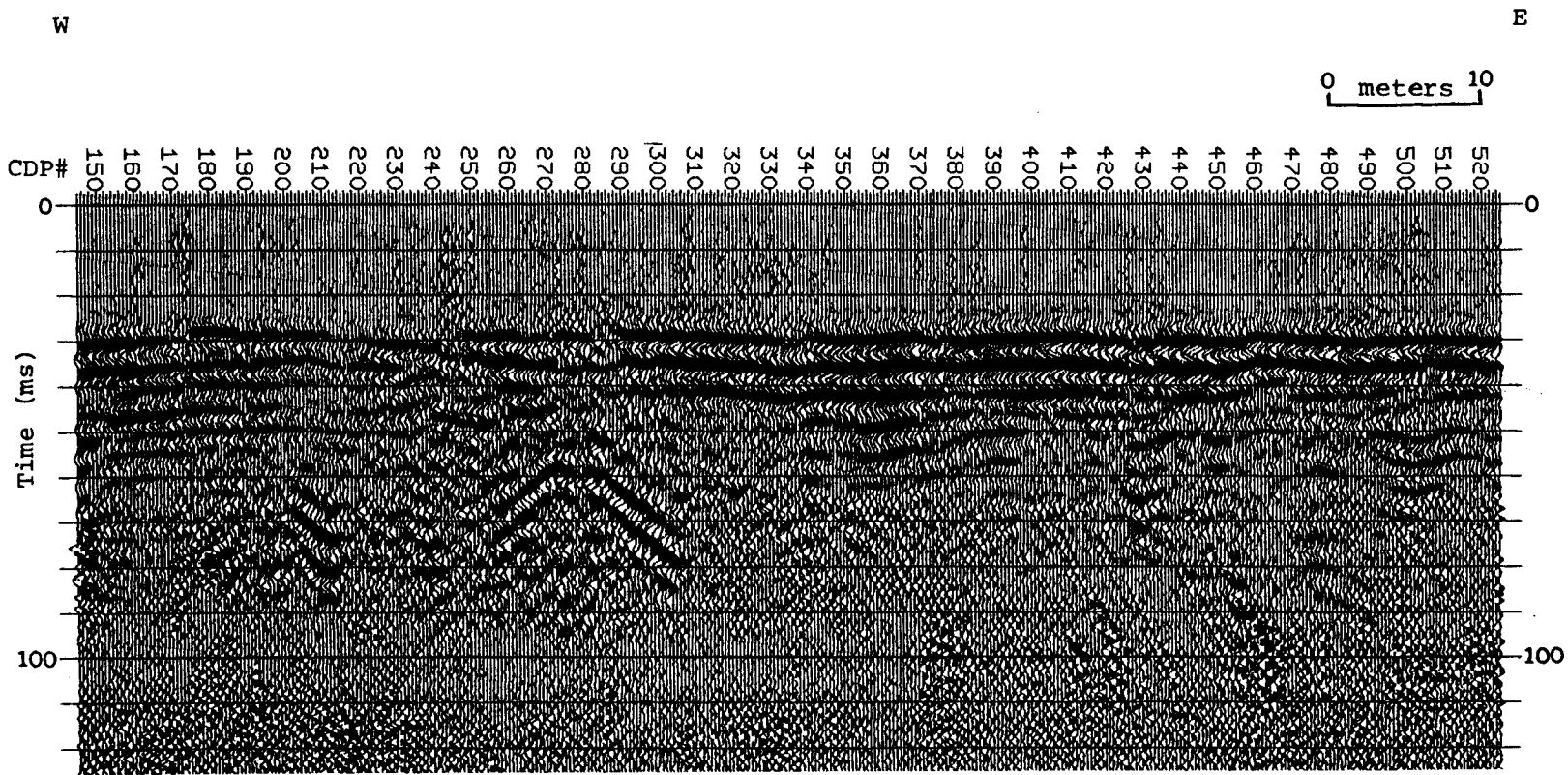
10 meters

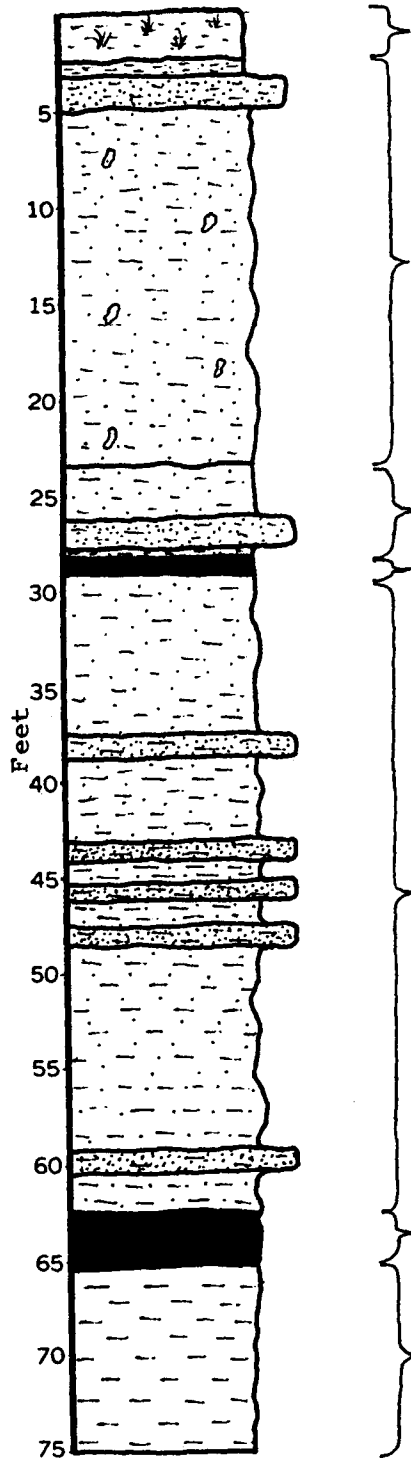


WALKAWAY NOISE TEST FRONTENAC, KANSAS









Soil

Alternating sandstone and sandy shale. Dominant color light brown with some yellow, gray, and red clay present. Ironstone nodules present.

Alternating sandstone and sandy shale. Dominant color dark gray to black.

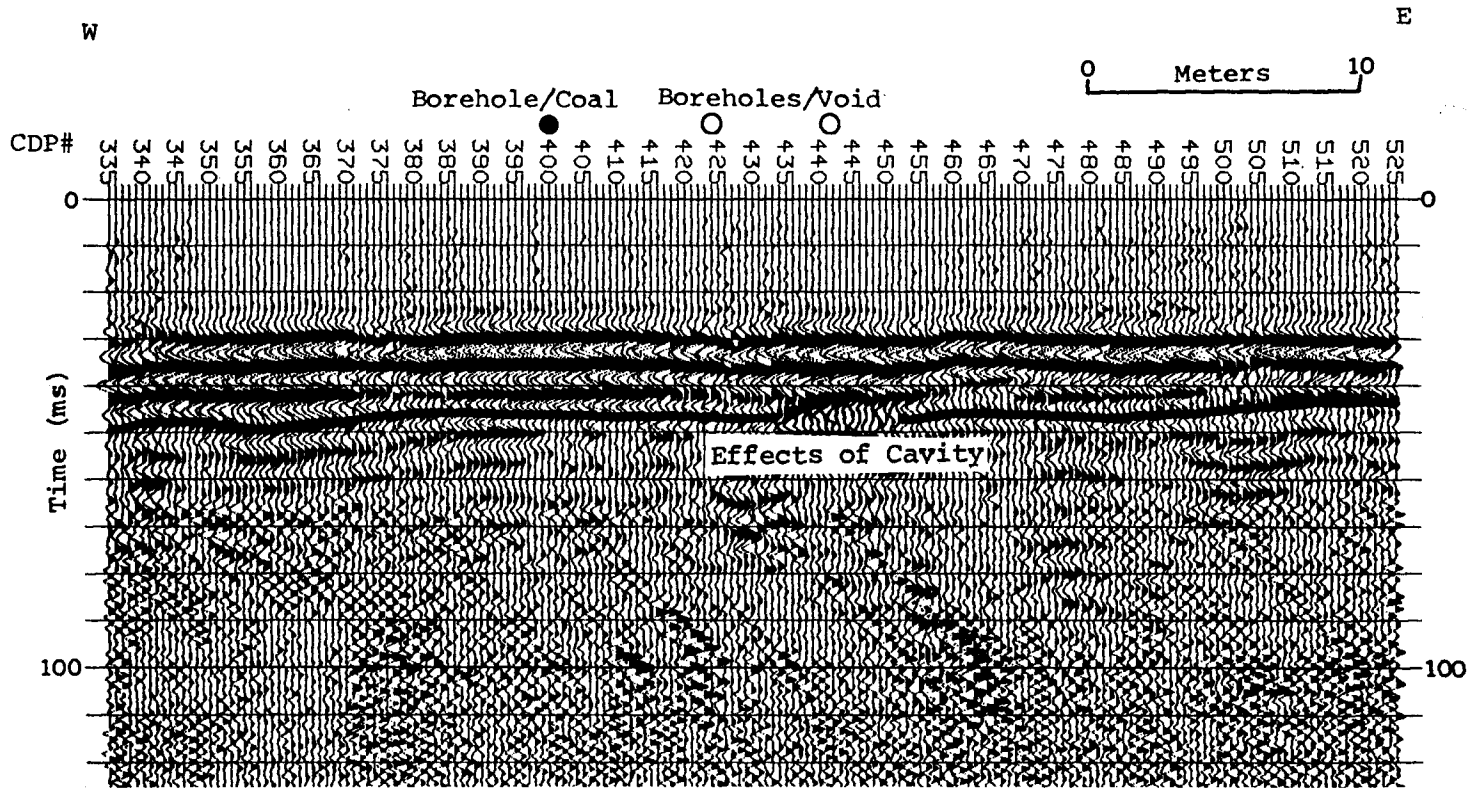
Tebo Coal Bed

Alternating sandstone and sandy shale. Dominant color light gray.

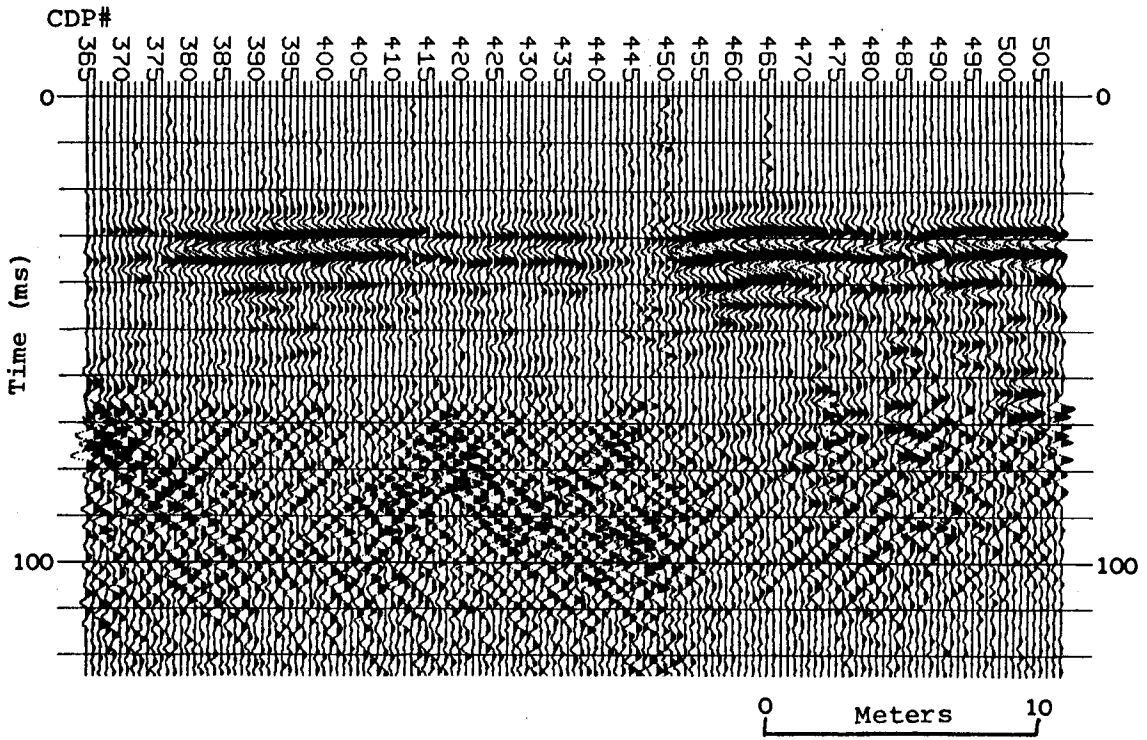
Weir-Pittsburg Coal Bed

Light gray clay and black shale.

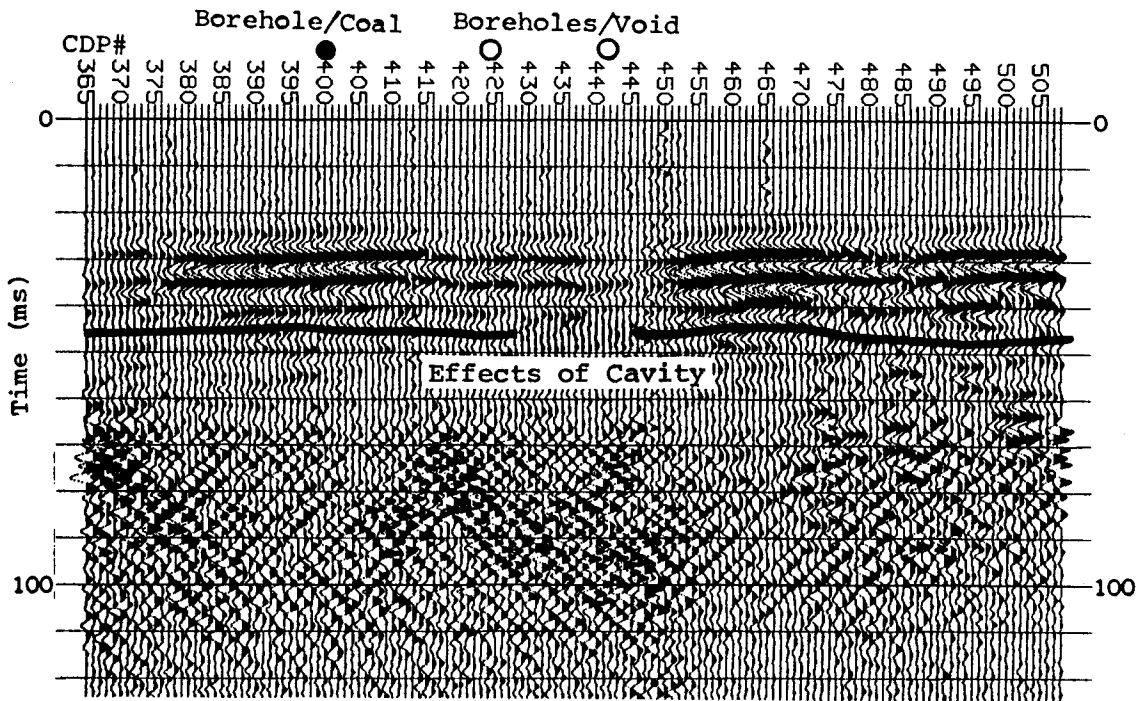
INTERPRETED SEISMIC SECTION

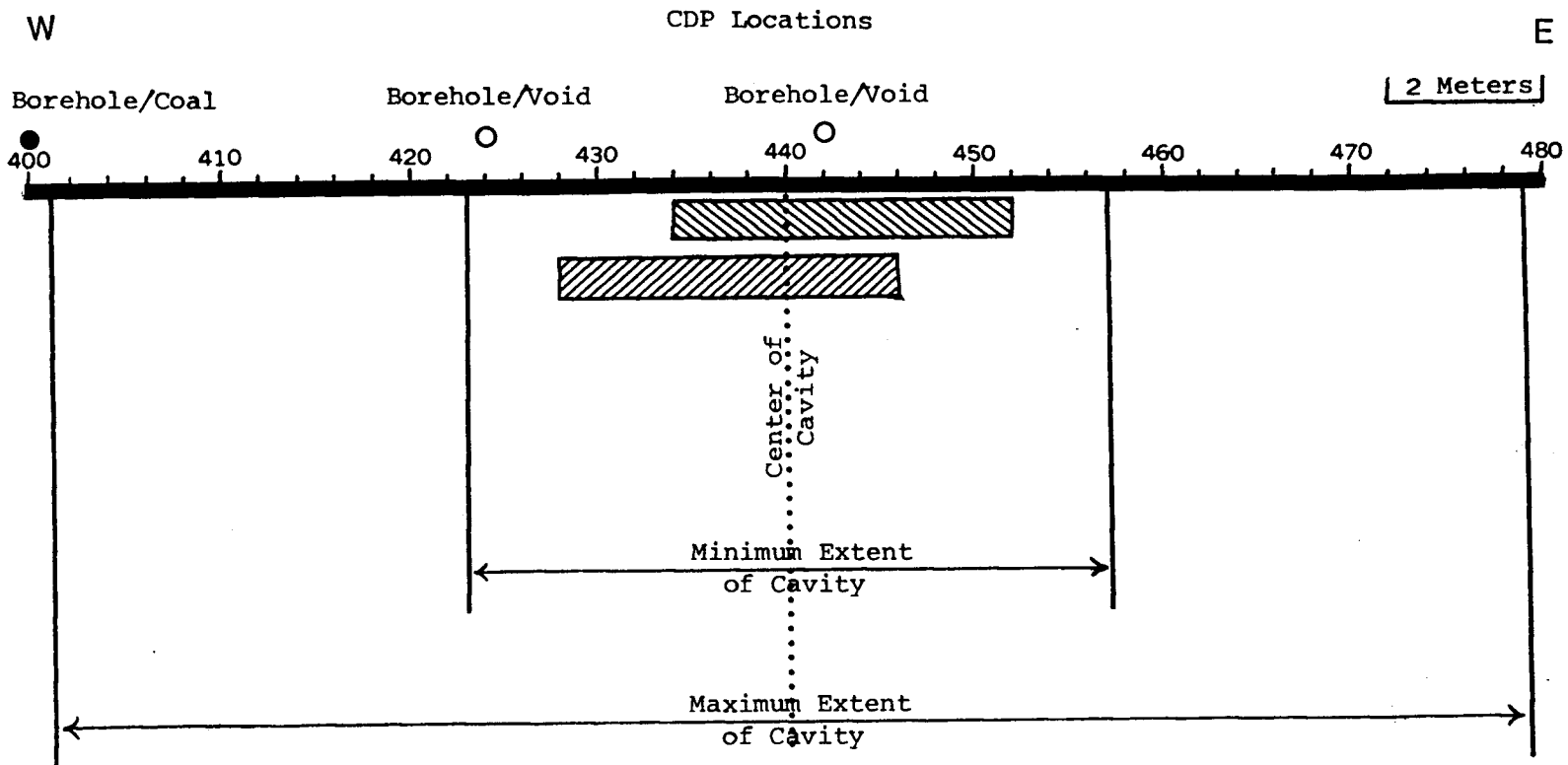


SEISMIC SECTION

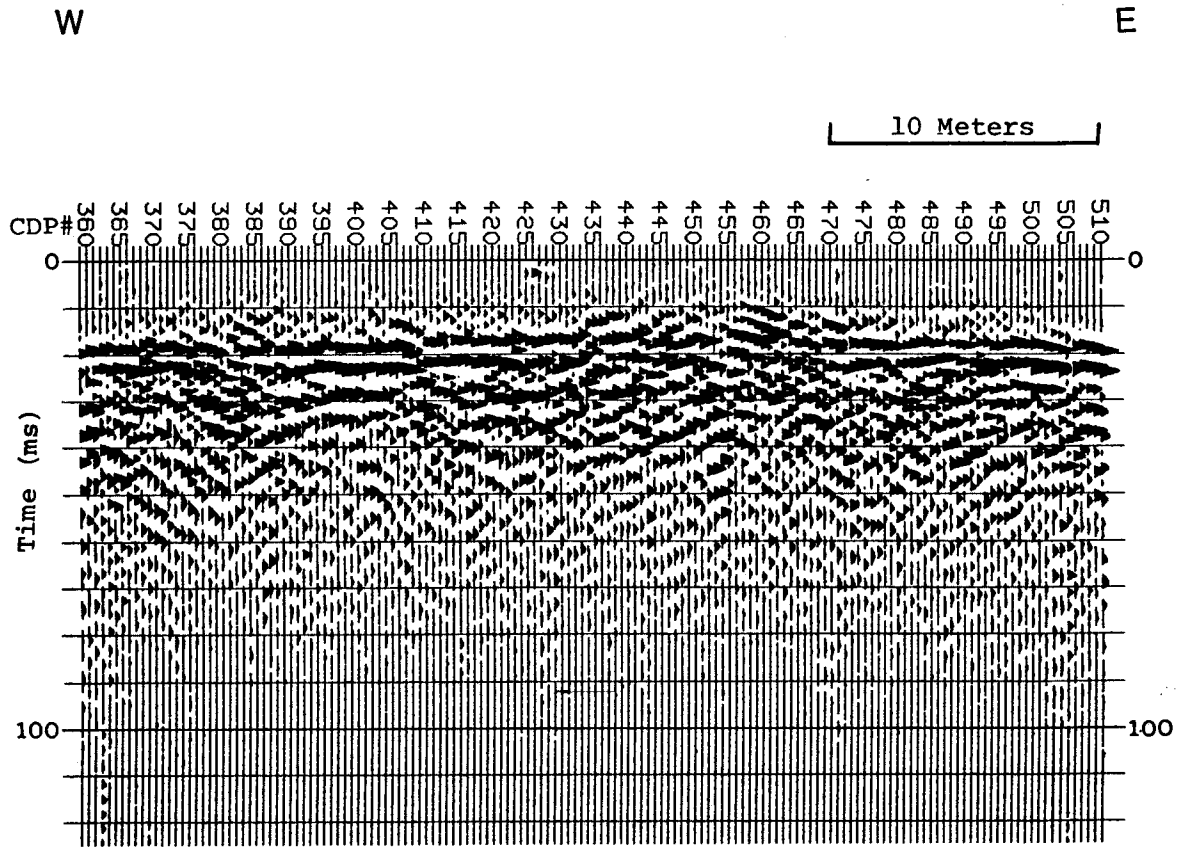


W INTERPRETED SEISMIC SECTION E





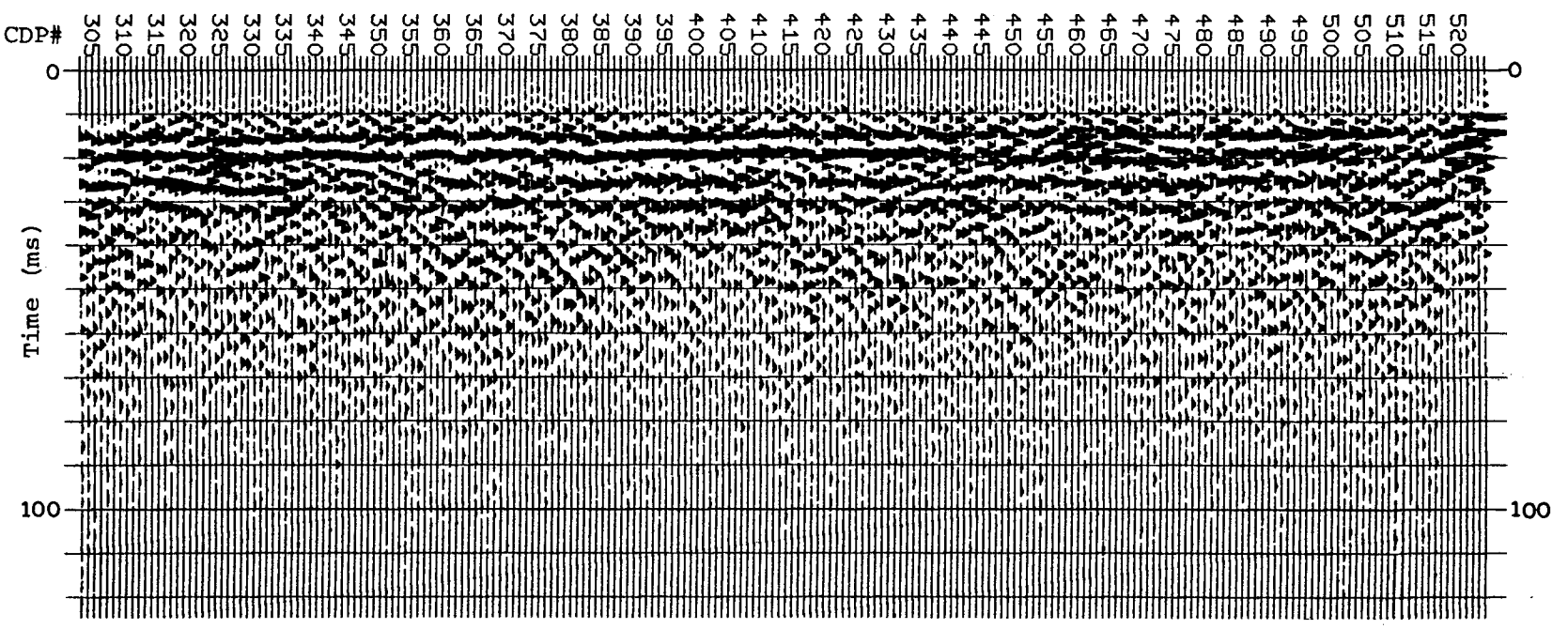
- ▨ Cavity Effects From W-E Line
- ▩ Cavity Effects From E-W Line



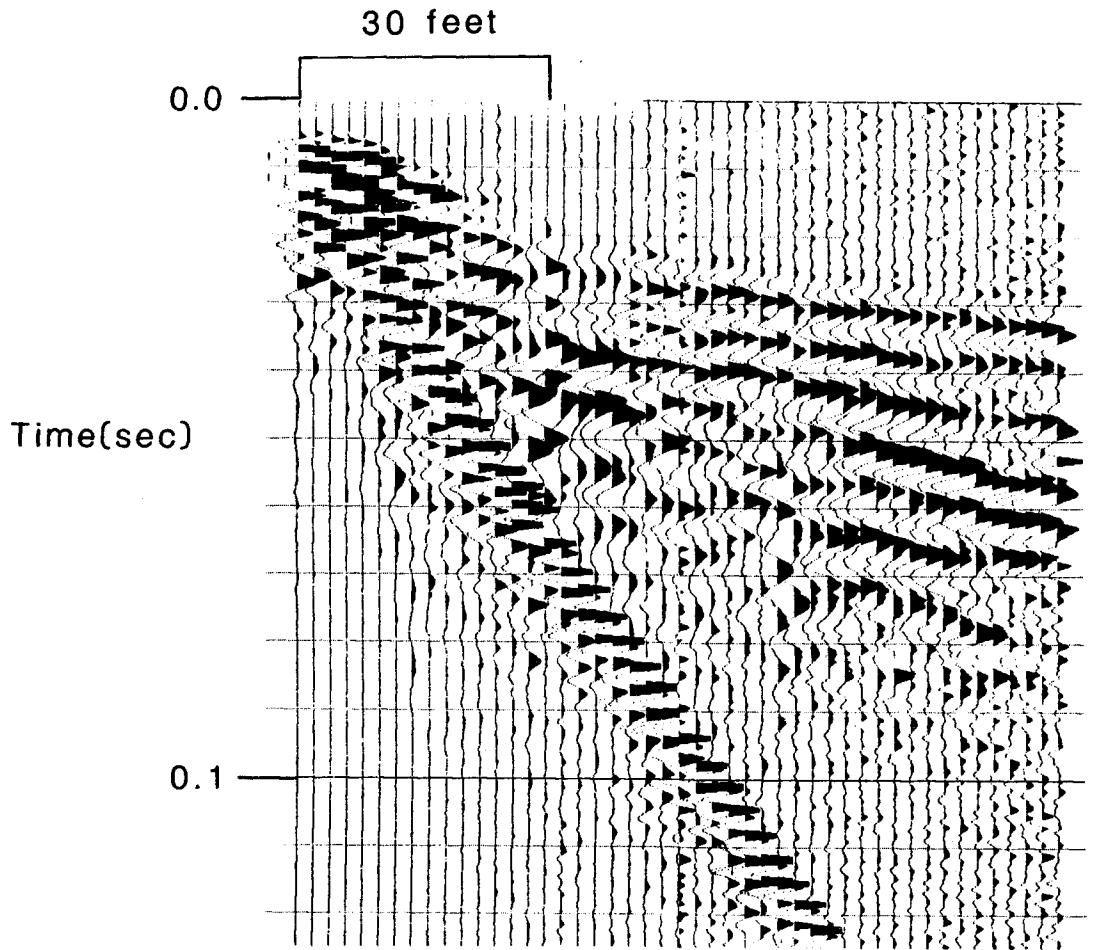
W

E

10 Meters

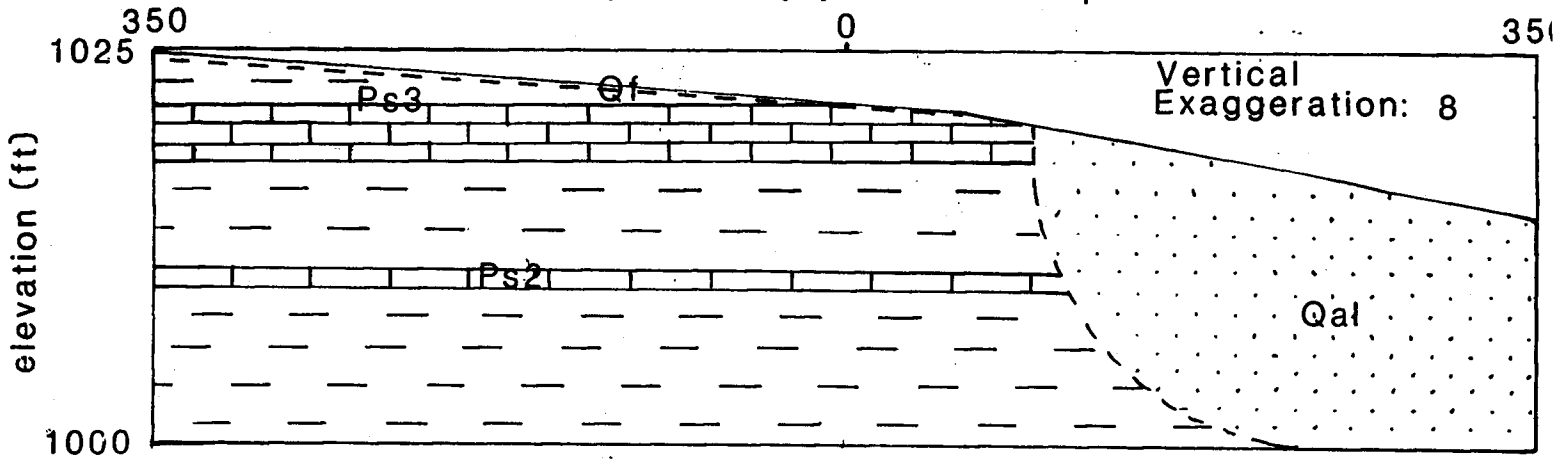


Underground Limestone Mine
Test Site near Lenexa, Ks



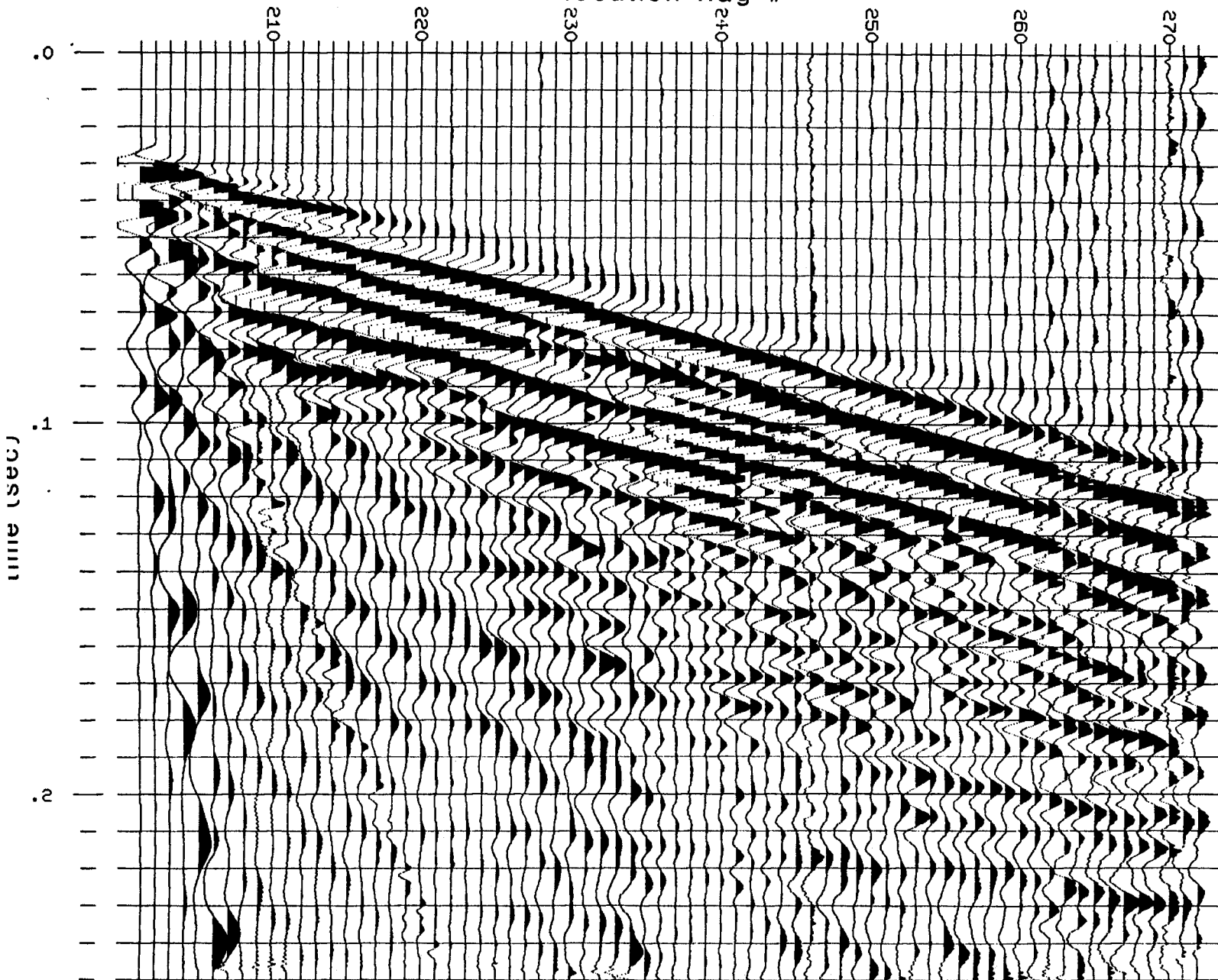
GEOLOGIC CROSS SECTION

distance (ft) from outcrop



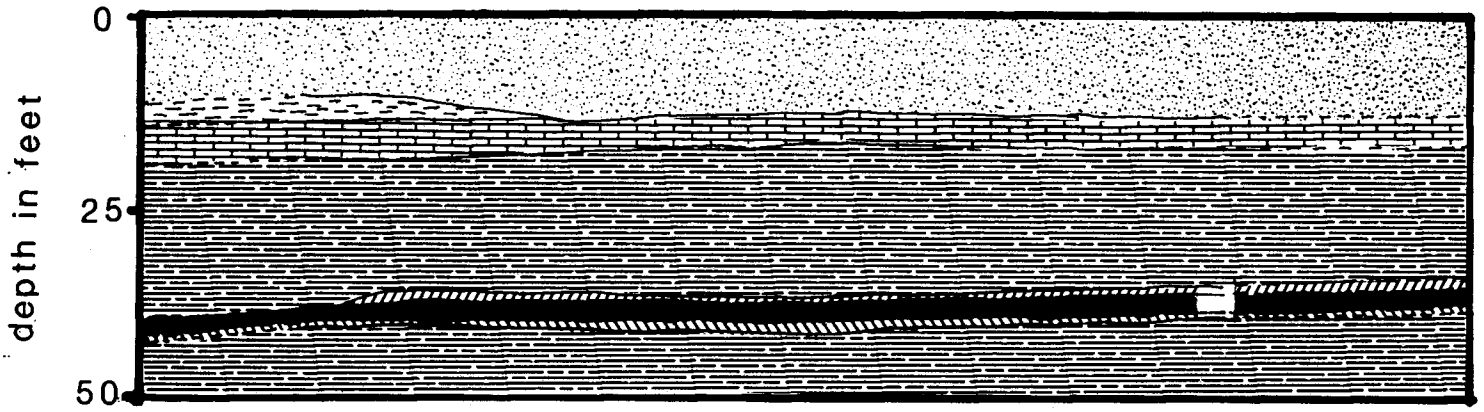
SEISMIC SECTION

location flag #

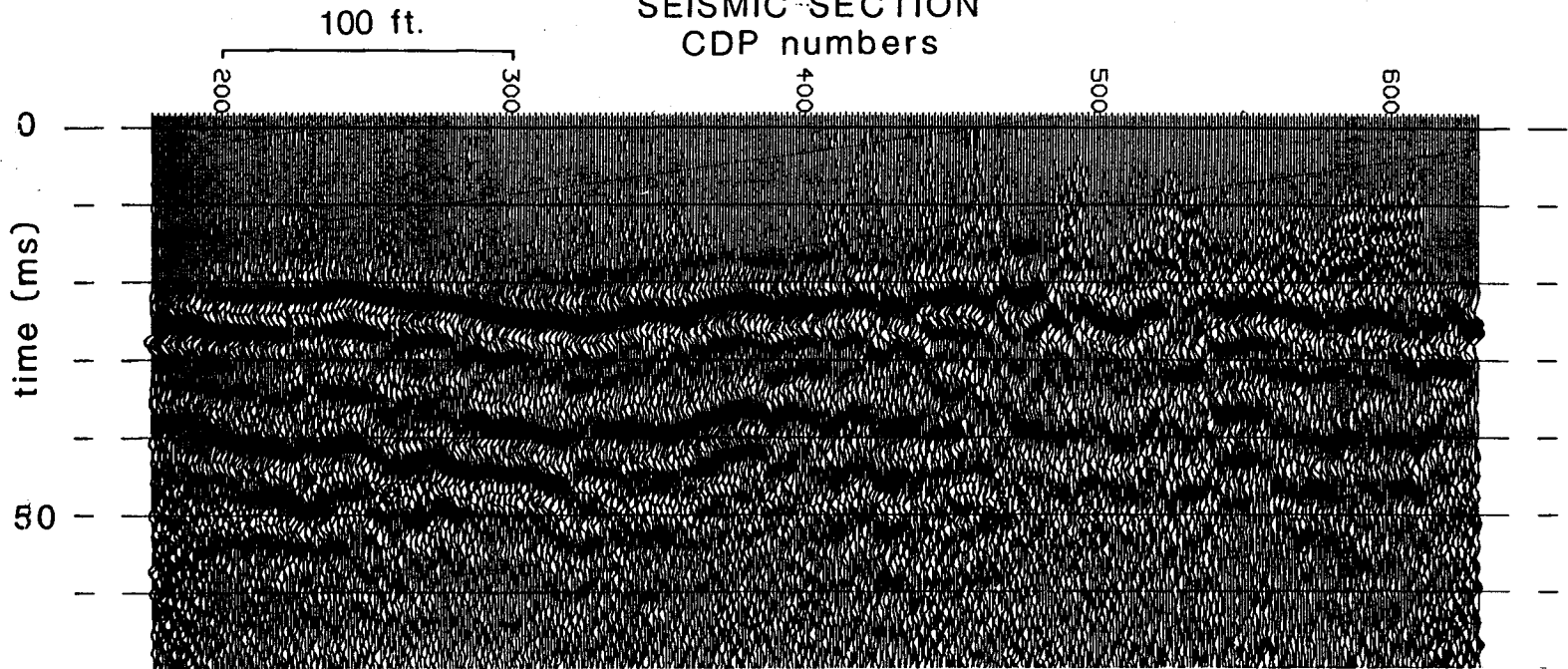


LaCygne Kansas Site

GEOLOGIC CROSS SECTION



SEISMIC SECTION CDP numbers



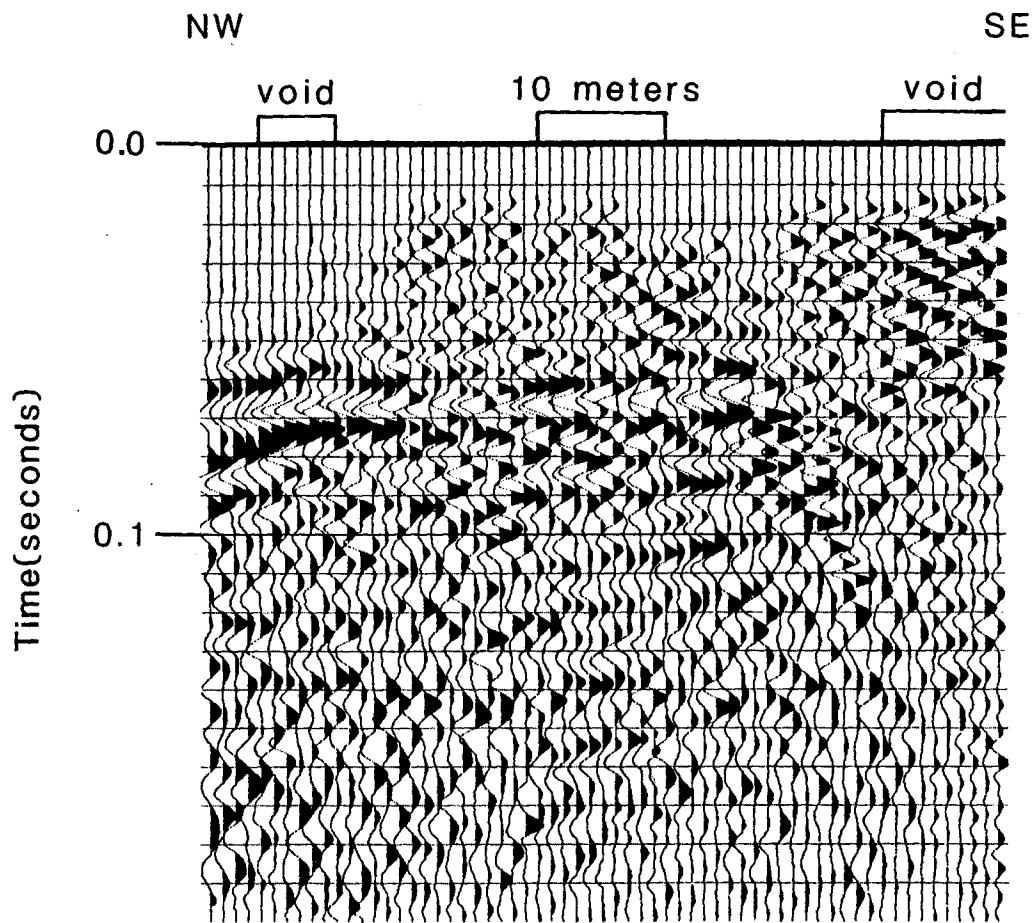
borehole with coal ● borehole with void ○

soil & clay [stippled] gr. sh. [horizontal lines] lst. [vertical lines] calc. sh. [diagonal lines] dk. sh. [horizontal lines] coal [diagonal lines] fire clay [solid black] [diagonal lines]

Pittsburg Industrial Site

June 9, 1987

Pseudo 24-fold CDP S-wave Stacked Section



SURFACE WAVE COMMON OFFSET GATHERS PITTSBURG, KANSAS

Channel Numbers/Offset Distance (ft)

SI

