IMSRP VIII

Application of Surface Geophysics to Detection and Mapping of Mine Subsidence Fractures in Drift and Bedrock

P.J. Carpenter, C.J. Booth, and M.A. Johnston
Northern Illinois University

Illinois Mine Subsidence Research Program

Cooperating agencies

ILLINOIS STATE GEOLOGICAL SURVEY
Department of Energy and Natural Resources

BUREAU OF MINES
United States Department of the Interior

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Department of Geology
Northern Illinois University
DeKalb, Illinois 60115

Illinois Mine Subsidence Research Program

ILLINOIS STATE GEOLOGICAL SURVEY
Jonathan H. Goodwin, Acting Chief

Natural Resources Building
615 East Peabody Drive
Champaign, Illinois 61820-6964

CONTENTS

FIGURES

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ABSTRACT

Electrical resistivity and seismic surveys were used to map fractures and monitor water levels over subsiding longwall coal mine panels in Saline and Jefferson counties, Illinois. These surveys showed that resistivity soundings can be inverted to obtain minimum estimates for fracture penetration depth, and common-offset seismic reflection profiles can be used to identify fractured bedrock horizons. Inversion of resistivity soundings made during subsidence of panel 2 in Saline County revealed a shallow high-resistivity layer corresponding to fractured unsaturated drift. Resistivity soundings, however, could not detect the presence of these fractures below 5 ft, nor could soundings map the lateral extent of drift fractures or provide information on bedrock fracturing. Azimuthal resistivity variations were consistent with predicted drift fracture directions over panel 2, and repeated azimuthal surveys indicate shallow drift fractures along the centerline had closed within 8 months of subsidence. Interpretation of seismic refraction surveys was hampered by the development of strong lateral velocity variations in fractured materials; these surveys, however, revealed no widespread water table fluctuations during subsidence. Reductions in both resistivity and P-wave velocity were measured at times over static tension zones along the margins of panel 2 in Saline County and panel 3 in Jefferson County. These measurements, if confirmed, may indicate long-term fracturing and downward water seepage along tension zones. Common-offset seismic reflection surveys identified disrupted reflections below the bedrock surface over the southern margin of panel 1 in Saline County 8 months after subsidence. A thin limestone at a depth of 125 ft exhibited enhanced postsubsidence permeability and may be the source of these reflections. Fractures in the subcropping bedrock surface (at a depth of 85 ft) were not detected.

OBJECTIVES AND SCOPE

Geophysical techniques were used to monitor the development of subsidence-related fractures and corresponding water table changes over longwall coal mines in Saline and Jefferson counties, Illinois. Geophysical techniques offer potential advantages over wells and borings because physical property changes over wide areas and volumes can be measured, as opposed to measurements at just one point. Electrical resistivity and seismic surveys were made before, during, and after mining to test the usefulness of these techniques in mapping the lateral extent and depth of subsidence fractures and in monitoring water table changes. The geophysical methods tested included vertical electrical resistivity soundings, resistivity profiles, azimuthal resistivity surveys, and seismic refraction and reflection profiles. Postsubsidence resistivity soundings and seismic refraction profiles were also made over portions of three panels in Jefferson County, Illinois, to test the applicability of these methods at another site.

SALINE COUNTY SITE

Mining History and Geologic Setting

The study site in Saline County is a narrow strip several hundred feet wide crossing longwall mine panels 1 and 2 in northwestern Saline County, Illinois (fig. 1). Approximately 6 ft of the Herrin No. 6 coal was mined from a depth of 370 ft. Panels 1 and 2 were 668 and 618 ft wide, respectively. They were separated by 132 ft, and both were approximately 2 miles long. Panel 1 undermined the study area in December 1989, and Panel 2 in September 1990. The panels advanced at approximately 55 ft/day, and the maximum surface subsidence along the panel centerlines was 4.5 ft (Kelleher et al., 1991).

Panels 1 and 2 are overlain by 85 ft of Pleistocene unconsolidated deposits and a 285 ft thick sequence of gently dipping Pennsylvanian shales, siltstones, thin coals, and limestones. The unconsolidated overburden is composed of loess, Wisconsinan glaciolacustrine deposits and Illinoian drift (Frye et al., 1972; Fehrenbacher et al., 1984). A detailed analysis of the loess and upper soil layers (Seils et al., 1992) identified abrupt density increases at 0.2 m and 1.5 m and a major shear strength increase at 0.5 m. Well logs and borings at the center of panel 1 indicate the Illinoian drift at the base of the unconsolidated deposits is mostly sand and gravel, whereas the overlying glaciolacustrine deposits and loess are primarily clay and silt, with occasional sand and gravel lenses (Van Roosendaal et al., 1992).

Hydrogeology

Four deep drift piezometers, six bedrock piezometers, and one pump well were installed over and adjacent to panel 1; no piezometers or wells were installed over panel 2. The Trivoli sandstone, at

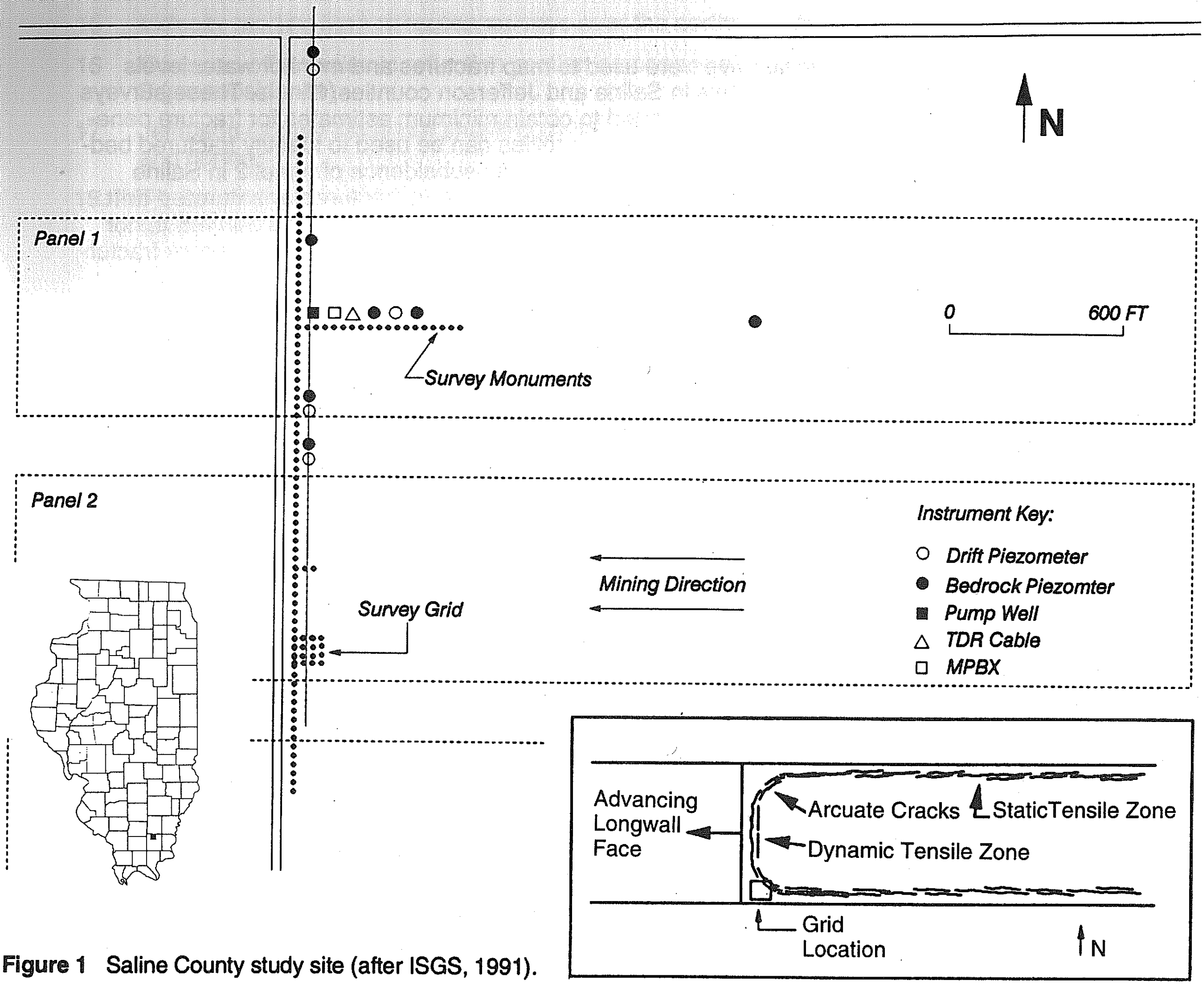

Figure 1 Saline County study site (after ISGS, 1991).

a depth of 175 to 200 ft, is the principal aquifer in the study area. It is medium grained and argillaceous, and it exhibits an average hydraulic conductivity of less than 10^{-6} cm/s when unfractured (Booth and Spande, 1992). During and after subsidence, piezometric levels in the Trivoli declined sharply and showed little or no recovery, although postsubsidence packer tests showed a slight hydraulic conductivity increase to about 10^{-5} cm/s.

Piezometric levels in the basal drift also showed rapid declines during subsidence, but these levels recovered completely within one year. Water levels in the shallow drift were not routinely monitored over the panels. Short-term local water level fluctuations, however, were observed in the drift in response to subsidence over panel 1, and shallow water levels gradually recovered to presubsidence levels (Darmody, 1990). Water levels measured in domestic wells around the panels (Booth and Spande, 1991) and piezometers screened in upper levels of the drift over panel 1 (R.G. Darmody, personal communication, 1992) indicate that most of the year the water table lies within 20 ft of the surface.

Subsidence Fractures and Geotechnical Measurements

Surface displacements, strains, subsidence rate, and subsurface movements were monitored during the subsidence of panels 1 and 2 (Kelleher et al., 1991). Zones of maximum tension (static tensile zone on fig. 1) and compression were located 44 and 144 ft inside the panel margins, respectively (Van Roosendaal et al., 1992). Fractures were aligned parallel to the panel margins over the static tension zones and parallel to the mine face near the panel centerlines (fig. 1). Arcuate fractures occurred elsewhere (Van Roosendaal et al., 1992). Fractures aligned with the mine face near panel centers closed within several weeks as these areas passed from dynamic tension into compression. Eight months after subsidence, tension zone fractures over panel 1 remained open to a depth of at least 5 ft (Seils et al., 1992). Van Roosendaal et al. (1992) used surface strain measurements with a neutral-axis bending model (Kratzsch, 1983) to estimate a maximum penetration depth of 27 to 31 ft for fractures visible at the surface in the static tension zones of panel 2.

PREVIOUS GEOPHYSICAL STUDIES

Few studies have applied surface geophysical methods to mine subsidence, particularly in Illinois. Burdick et al. (1986) successfully used resistivity to locate shallow abandoned mine voids in the Illinois Basin, and Henson et al. (1989) used high-resolution seismic reflection techniques to map sedimentary facies that could lead to roof instability during mining in the Illinois Basin. Most other longwall mine geophysical studies have been in the Appalachian coal fields. Wilson et al. (1988) used seismic methods to identify zones of abnormal P-wave absorption over the edges of longwall mines. He and Wilson (1989) observed velocity decreases over mined-out areas using common-offset seismic reflection profiling, and Rudenko et al. (1989) mapped the position of a longwall mine face during mining using changes in P- and S-wave velocity from seismic refraction surveys. They noted a slight P-wave increase ahead of the longwall face and major decreases in both P- and S-wave velocity behind it; they attributed the decreased velocity to enhanced fracturing in the dynamic tension zone directly behind the mine face. None of these studies, however, have used geophysical techniques to identify subsidence-induced changes in unconsolidated materials, or to characterize hydrogeologic changes accompanying subsidence.

DATA COLLECTION AND RESULTS

Electrical Methods

Resistivity soundings An overview of the electrical resistivity methods used in this study can be found in Telford et al. (1976). The basic electrode configuration used was the Wenner array, shown in Figure 2a. Twenty-five Wenner array vertical electrical soundings were made over selected portions of panels 1 and 2 before, during, and after subsidence (fig. 3). Seasonal apparent resistivity variations were generally less than 2 ohm-m for spacings greater than 10 ft. In response to rainfall and seasonal variations, however, apparent resistivity values changed as much as 20 ohm-m at a 1-ft spacing and as much as 3 ohm-m at a 10-ft spacing.

Soundings were inverted with a least-squares computer inversion procedure (Interpex, 1988) to yield multilayer geoelectrical models. Most resistivity soundings over panels 1 and 2 were modeled with four geoelectrical layers (fig. 4), although in several cases the existence of a thin, conductive upper soil layer required five-layer models. The interpretation of these layers is based on a soil boring made at the center of panel 1 and a roadcut approximately 1/2 mile northwest of the panels (Frye et al., 1972). The uppermost layer of the four-layer model represents moderate-to-high resistivity topsoil and loess (30 to 80 ohm-m, 1 to 3 ft thick). This layer overlies 15 to 20 ft of relatively conductive clayey Wisconsinan lake deposits (10 to 30 ohm-m). Water levels from piezometer and seismic refraction surveys indicate this unit is probably continuously saturated below a depth of 15 to 20 ft. The lowermost 20 to 40 ft of drift is saturated gravelly tills and outwash (30 to 40 ohm-m). The underlying Pennsylvanian shale bedrock has resistivities from 45 to 70 ohm-m that were confirmed through comparison with electrical logs from the area. In many soundings (such as fig. 4), the lower saturated drift cannot be distinguished from bedrock.

The equivalence range (or uncertainty) for each layer's thickness and resistivity was computed by allowing model parameters to vary such that the total root-mean-square (RMS) error of the model fit did not exceed the best RMS by 20%. Geoelectrical layers 1 to 3 were reasonably well constrained for most soundings, and resistivity errors averaged about 10% and depth errors averaged 35%. The thickness of the lowest layer and the resistivity of the bottom (usually bedrock) unit were poorly constrained, with uncertainties commonly as large as 100%. Thus the resistivity soundings were not used to identify fracturing or other subsidence-induced changes in the bedrock. Soundings were also not used to estimate water levels because seismic refraction surveys generally provided better-constrained water table depths.

Effect of fracturing on resistivity Repeated soundings were made during subsidence over the centerline of panel 2 at Monument 98 and at a point 490 ft east of Monument 98. These soundings exhibited major resistivity increases at short spacings during passage of the mine face (figs. 5 and 6a). Later soundings at these locations showed no significant differences from presubsidence soundings. These temporary resistivity increases may reflect shallow air-filled fractures

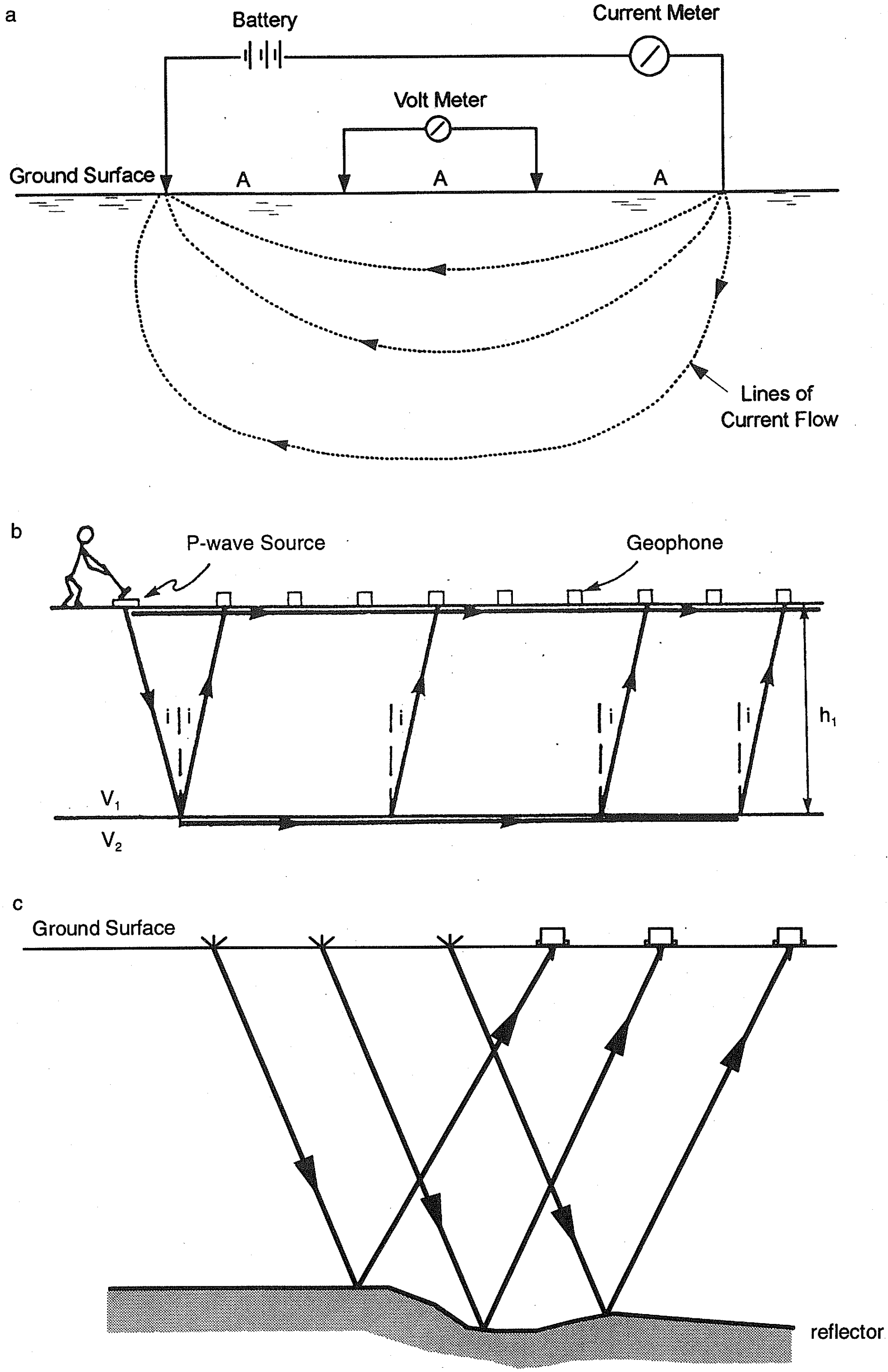

Figure 2 Schematic illustration of the (a) resistivity, (b) seismic refraction, and (c) common-offset seismic reflection methods.

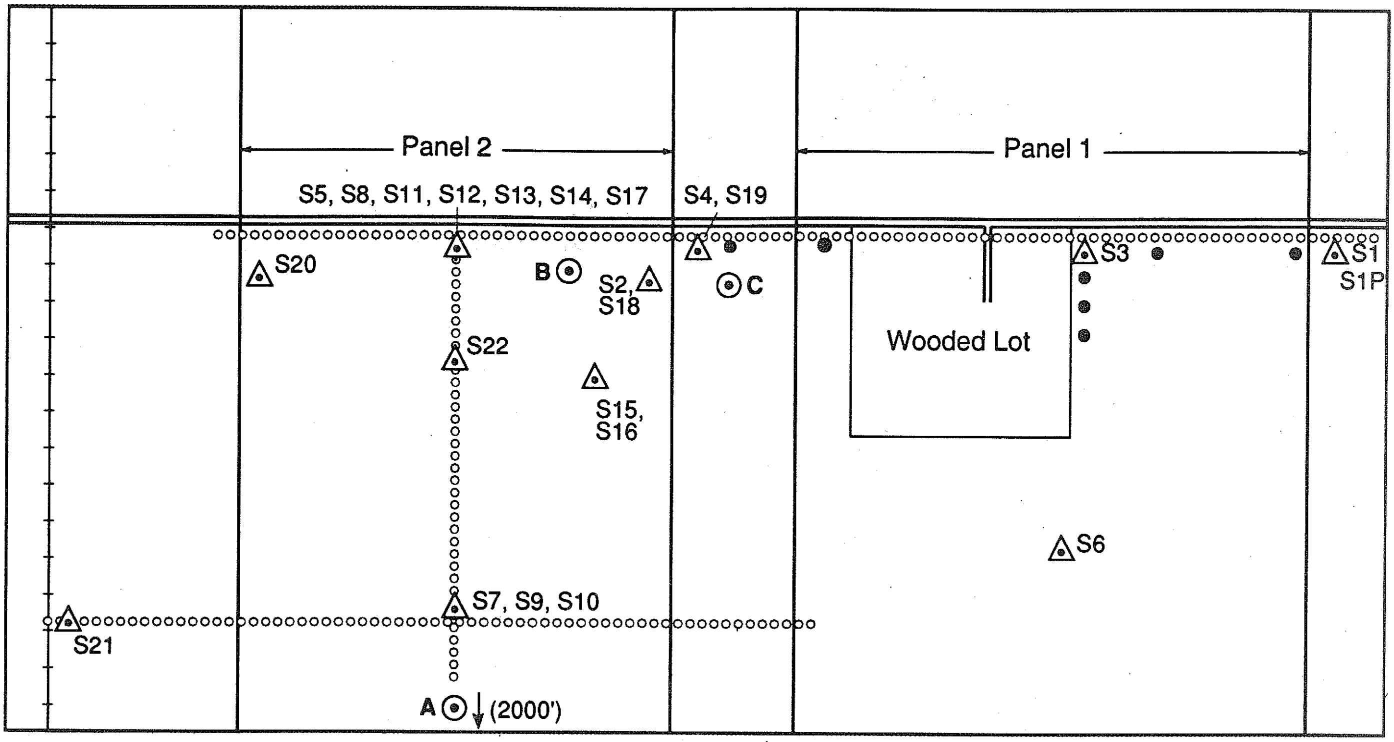

Figure 3 Saline County electrical survey lines. Soundings are prefixed by *S*. Soundings S23 and S24 are off the map, 2,000 ft east of S7. Some piezometers are not shown.

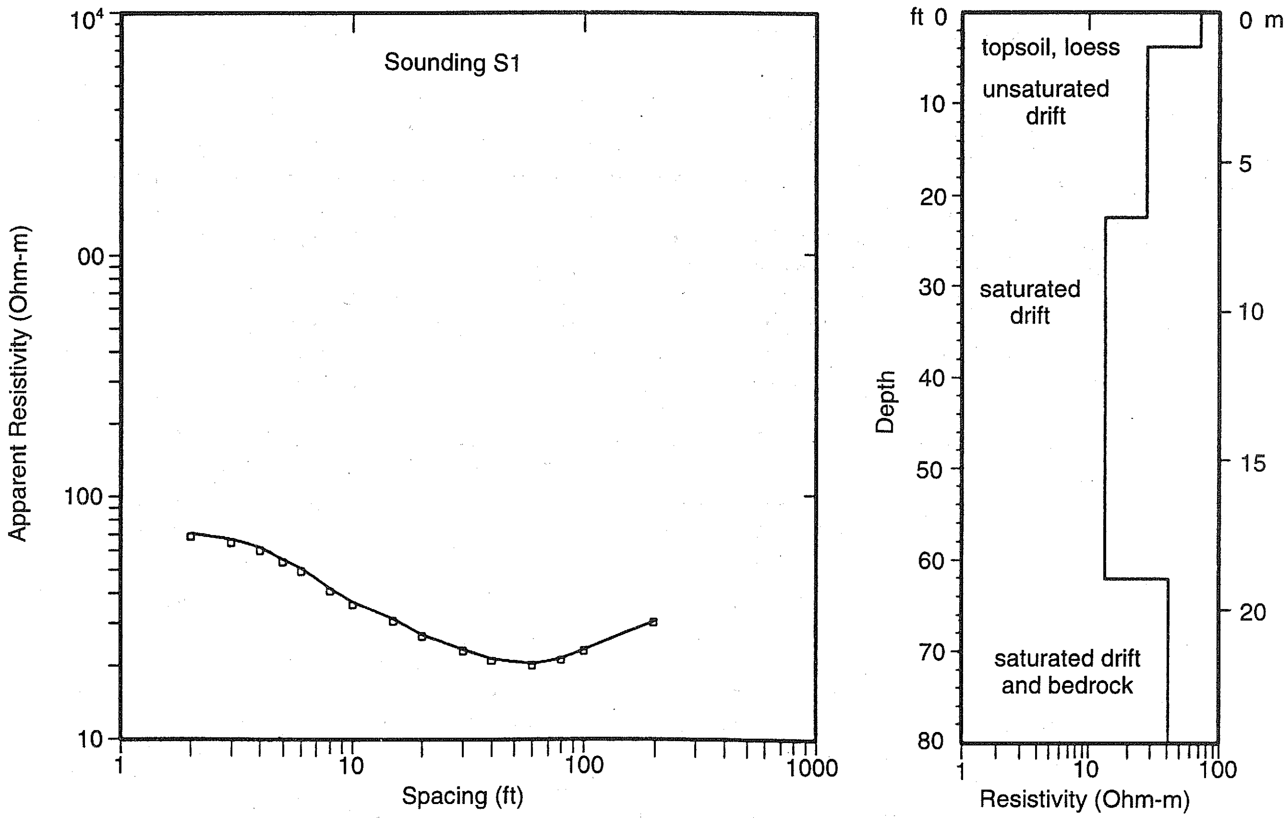

Figure 4 Vertical electrical sounding north of panel 1 and its layered model interpretation.

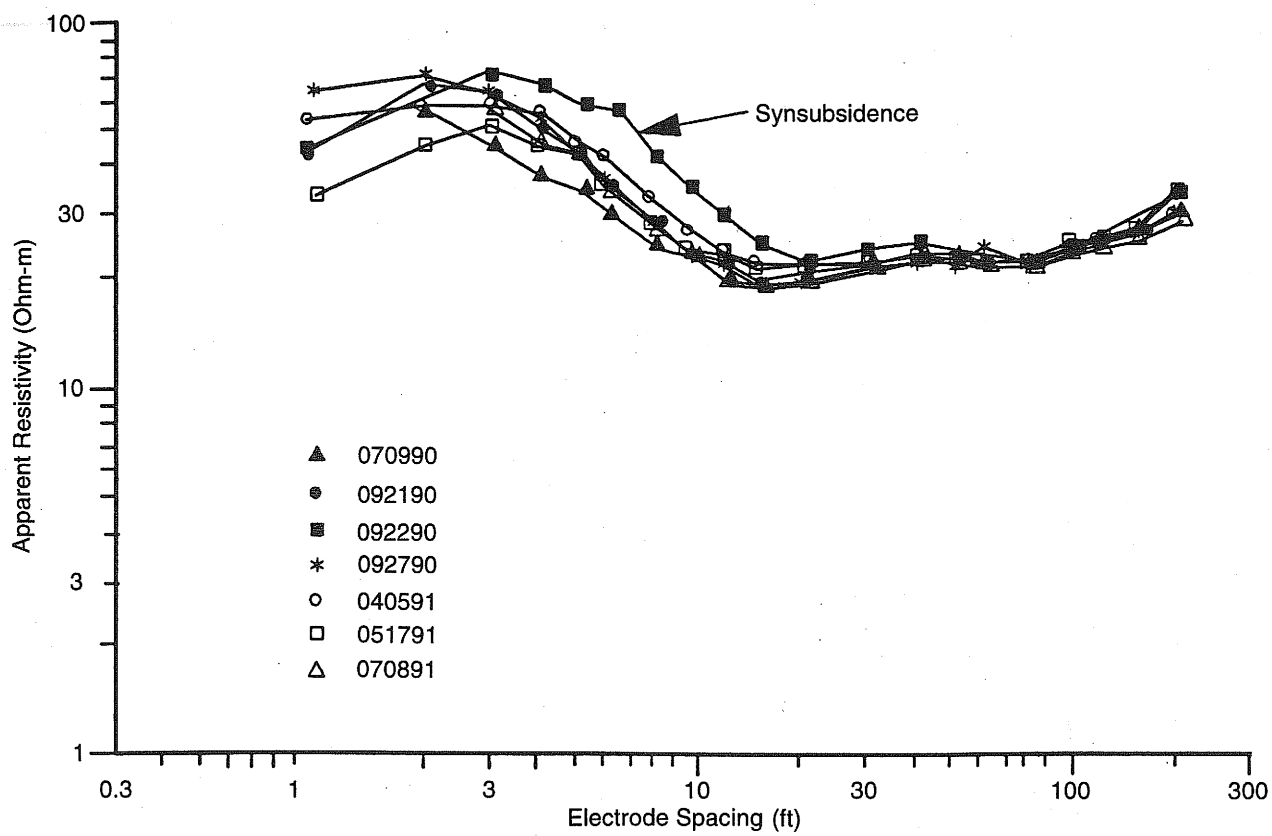

Figure 5 Repeated soundings at Monument 98 illustrating changes in apparent resistivity before, during, and after subsidence of panel 2.

that developed during passage of the dynamic tension zone. In the case of soundings S7 and S9 (made 490 ft east of the monument line near the end of the synsubsidence period), this high-resistivity zone appears to penetrate only about 2 ft (fig. 6b). Interestingly, the base of this high-resistivity layer corresponds exactly to the base of a preexisting layer. One possibility is that the air-filled fractures occur only in the loess, which is about 2 ft thick at this location. Another possibility is that closure of fractures was already underway at this location because the mine face had passed about 1 week earlier. At Monument 98, inversion of synsubsidence sounding S11 (September 22, 1990) revealed a similar shallow high-resistivity layer approximately 5 ft thick. This layer vanished 5 days later, presumably as fractures closed. Pre- and postsubsidence sounding models from surveys over the northern static tension zone and north barrier pillar, however, showed no significant resistivity changes, despite the development of major fractures along the tension zone (fig. 7). This lack of response may be due to the narrowness of the fractured zone or the orientation of the resistivity array with respect to the fractures (arrays were oriented north-south).

Resistivity pseudosections Lateral changes in apparent resistivity were mapped along profile lines by moving Wenner arrays at a constant spacing along the earth's surface. Profiles were made at different spacings, and pseudosections were generated by plotting apparent resistivity values as a function of spacing. Pre-, syn-, and postsubsidence Wenner array profiles at electrode spacings of 5, 10, 20, 40, 60, and 80 ft were used to generate the pseudosections.

Two profile lines crossed panel 2, one along the monument line and one 490 ft east of the monument line. The presubsidence pseudosection profiles were made during July and August 1990, and the postsubsidence profiles were made during October 1990, approximately 1 month after subsidence. A short profile segment was also made along the monument line during subsidence. Inversion of pseudosections for two-dimensional resistivity models was not attempted because of the large scatter in apparent resistivity values at short spacings and the existence of only 4 to 5 measurements at most profile points. The scatter may be a response to shallow fracturing. Profiles along the monument line were also disturbed by the presence of buried metal culverts and utilities.

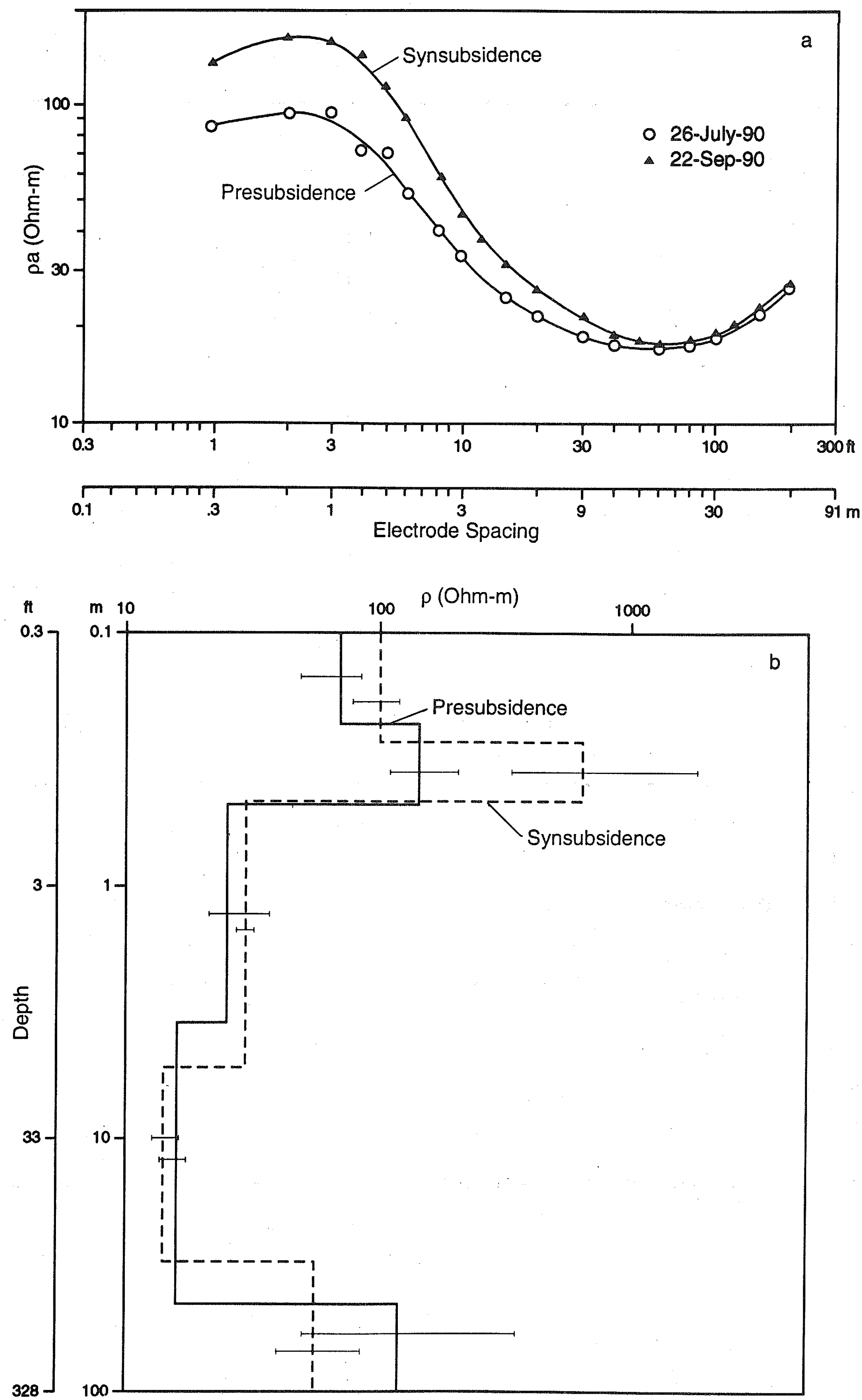

Figure 6 (a) Sounding curves (S7 and S9) made 490 ft east of the monument line, along the centerline of panel 2. (b) Five-layer models from inversion of sounding curves shown in figure 6a. Error bars indicate range of uncertainty (electrical equivalence) in the resistivities.

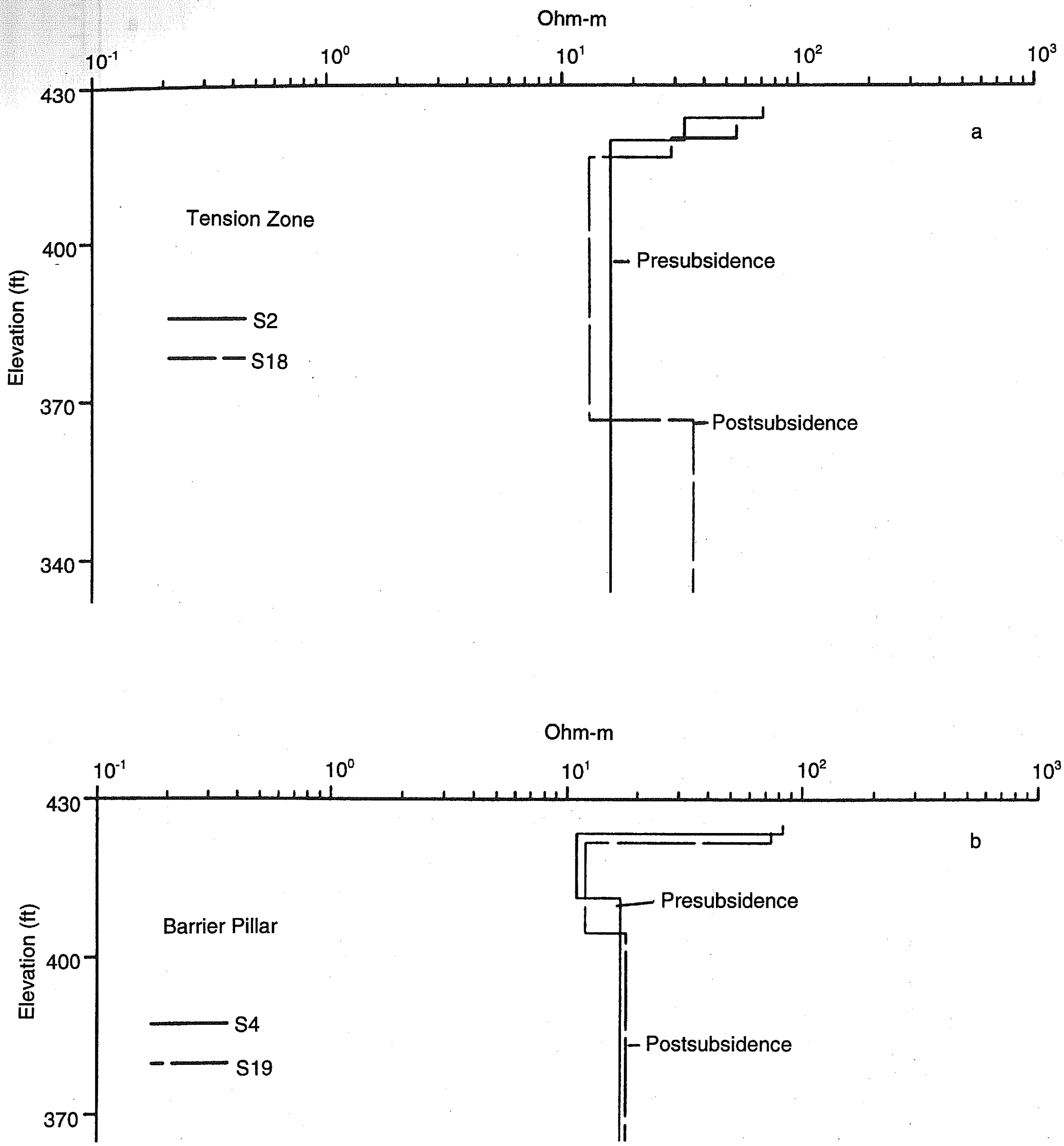

Figure 7 Geoelectrical models for pre- and postsubsidence soundings made over (a) the northern tension zone, and (b) the north barrier pillar of panel 2.

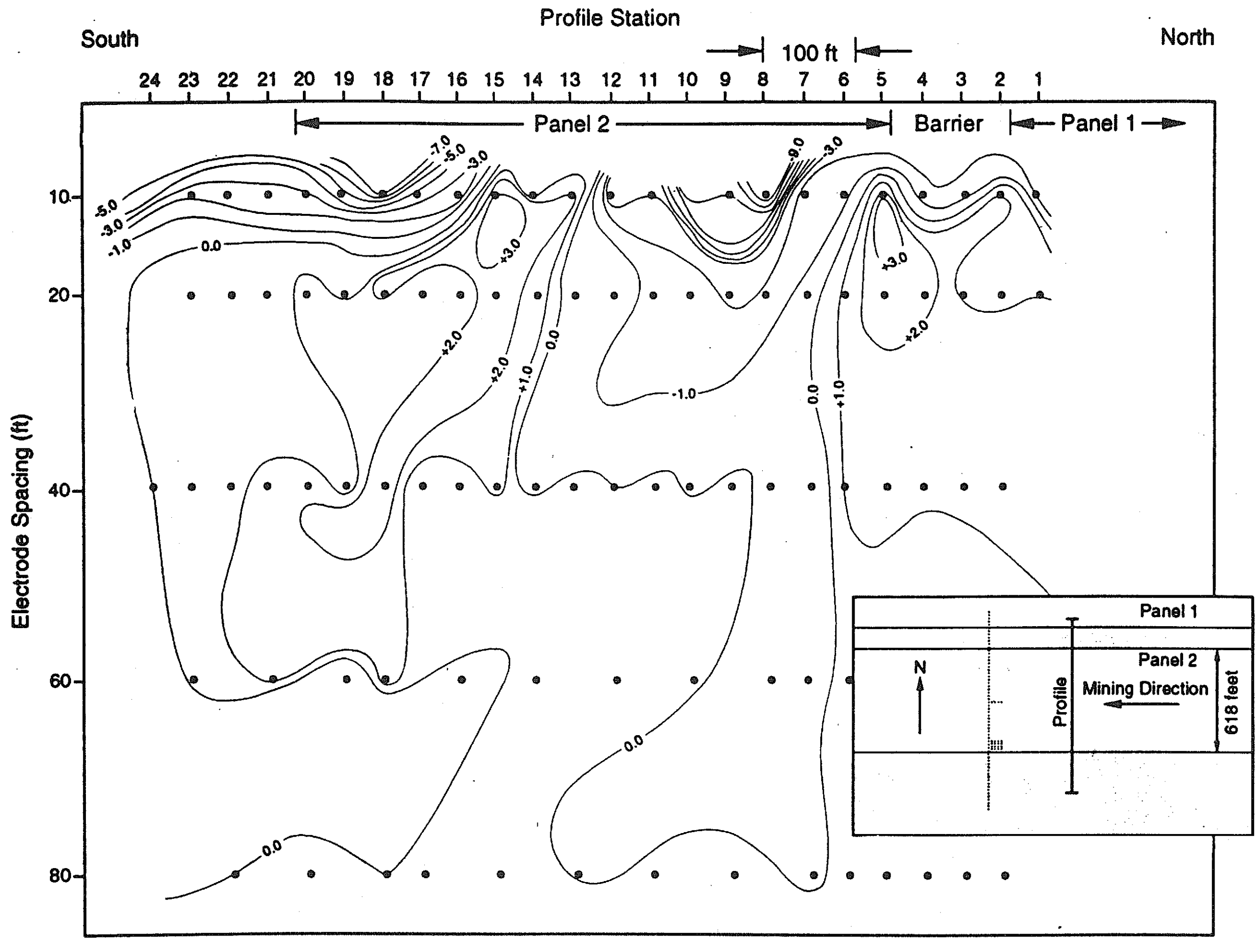

Figure 8 Apparent resistivity pseudosection 490 ft east of the monument line. Contoured values represent apparent resistivity differences (ohm-m) when postsubsidence apparent resistivities are subtracted from presubsidence resistivities.

Figure 8 shows a pseudosection of resistivity differences along the profile 490 ft east of the monument line. These differences were computed by subtracting postsubsidence apparent resistivities from presubsidence apparent resistivities. Positive values indicate a resistivity decrease during or after subsidence. Such decreases occur along the northern and southern margins of panel 2. The resistivity decrease along the southern margin may be deeper because readings were made at electrode spacings as large as 60 ft. It should be noted that pseudosections provide only a general qualitative indication of two-dimensional resistivity changes, and they may be deceiving. Pseudosections are not equivalent to geological cross sections because electrode spacing does not convert to a linear depth scale, "deeper" apparent resistivity anomalies can reflect shallow resistivity variations, offline anomalies can be projected onto the pseudosections, and resolution decreases with increasing spacing.

Azimuthal resistivity surveys Azimuthal resistivity surveys have proven effective in identifying fracture trends and predicting hydraulic conductivity, both in anisotropic consolidated and unconsolidated materials (Taylor and Fleming, 1988; Ritzi and Andolsek, 1992; Carpenter et al., 1994). In a conductive matrix with resistive fractures (such as a silty clay with air-filled fractures), apparent resistivity will be higher when the array is parallel to the fractures and lower when the array crosses the fractures (Keller and Frischknecht, 1966). Azimuthal resistivity surveys were made near the centerline and over the north barrier pillar of panel 2. Wenner arrays with electrode separations of 5 and 15 ft were rotated 360 degrees around their center points, and measurements were taken every 10 degrees. Apparent resistivities were then plotted on a polar diagram as a function of azimuth.

Permanent concentric electrode arrays consisting of 72 10-inch steel carriage bolts were used to ensure electrodes always occupied exactly the same position during measurements. Four

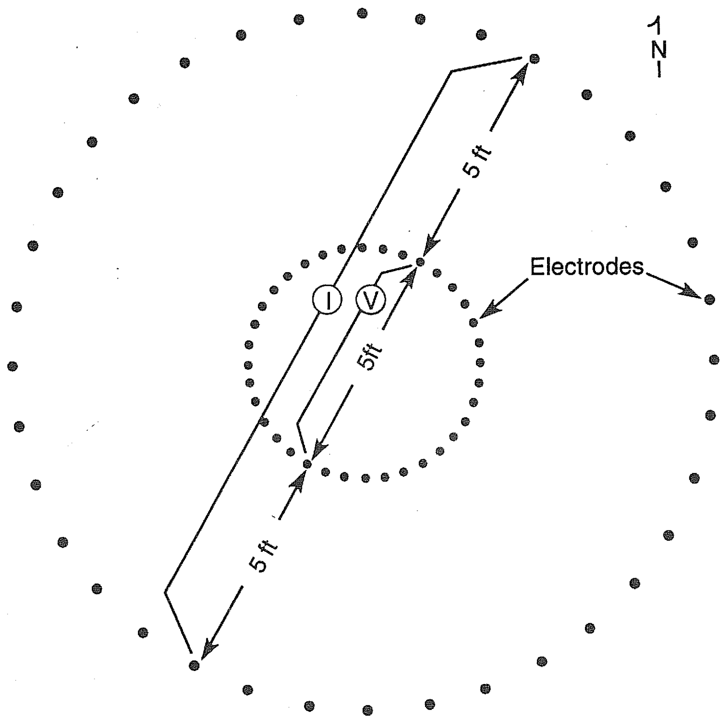

Figure 9 Azimuthal resistivity array consisting of permanent electrodes. Electrodes are hooked up in a Wenner configuration at various azimuths such as the one shown oriented N30E. Current electrodes are labeled *I*, potential electrodes are labeled *V*.

carriage bolts were hooked up at a time in a Wenner configuration along each azimuth (fig. 9). The degree of repeatability (or precision) in azimuthal resistivity measurements was about 1 ohm-m; azimuthal resistivity variations less than this are not significant. No azimuthal measurements were made before subsidence because of thick vegetation covering the site.

Two azimuthal arrays were placed in the dynamic compression zone of panel 2 to monitor fracture development during and after subsidence. Array A was located along the centerline approximately 2,500 ft south of the monument line, and array B was located near the monument line 165 ft north of the panel 2 centerline. As syn- and postsubsidence measurements from arrays A and B were similar, only array B data will be presented below. In this area a nearly isotropic resistivity distribution became strongly anisotropic during subsidence at both 5 and 15 ft electrode spacings (figs. 10 and 11). The maximum apparent resistivity was recorded at a 5-ft spacing on September 25, 1990, when electrodes were oriented N10E. Apparent resistivities measured with the 15 ft array were generally higher when the array was oriented north-south (33 ohm-m), which is the predicted orientation of fractures at the centerline. Increased resistivity was also observed along N60W and N40E trends with the 15 ft array, possibly reflecting arcuate (fig. 1) or conjugate fractures. During subsidence a fissure with a N30E trend opened beneath array B and then closed (its trend is marked by an *F* on figures 10 and 11). Resistivity minima were recorded at this azimuth by the 5 ft array but not by the 15 ft array. Azimuthal surveys made in May 1991 produced a roughly isotropic resistivity plot at a 5-ft spacing (fig. 10d), suggesting most shallow fractures had closed or been filled within 8 months after subsidence. The plot for the 15 ft array (fig. 11d) exhibits a completely different anisotropic pattern, possibly reflecting seasonal earth resistivity variations.

Syn- and postsubsidence azimuthal resistivity variations were also monitored at array C, over the north barrier pillar of panel 2. A complex pattern of northeast- and northwest-trending apparent resistivity increases were recorded at a 5 ft electrode spacing. However, little resistivity variation was recorded at a 15-ft spacing, aside from a slight overall resistivity increase during the postsubsidence period.

Seismic Methods

Seismic refraction Seismic refraction surveys (figs. 2b and 12) were made over panels 1 and 2 in Saline County to map fractures (areas with reduced P-wave velocity) and to monitor water table changes during subsidence. An overview of the seismic refraction method can be found in Dobrin (1976). The energy source for the refraction surveys was an 8-lb sledgehammer striking a metal plate. Twelve geophones (Mark Products vertical component, 8-3/4 Hz natural frequency)

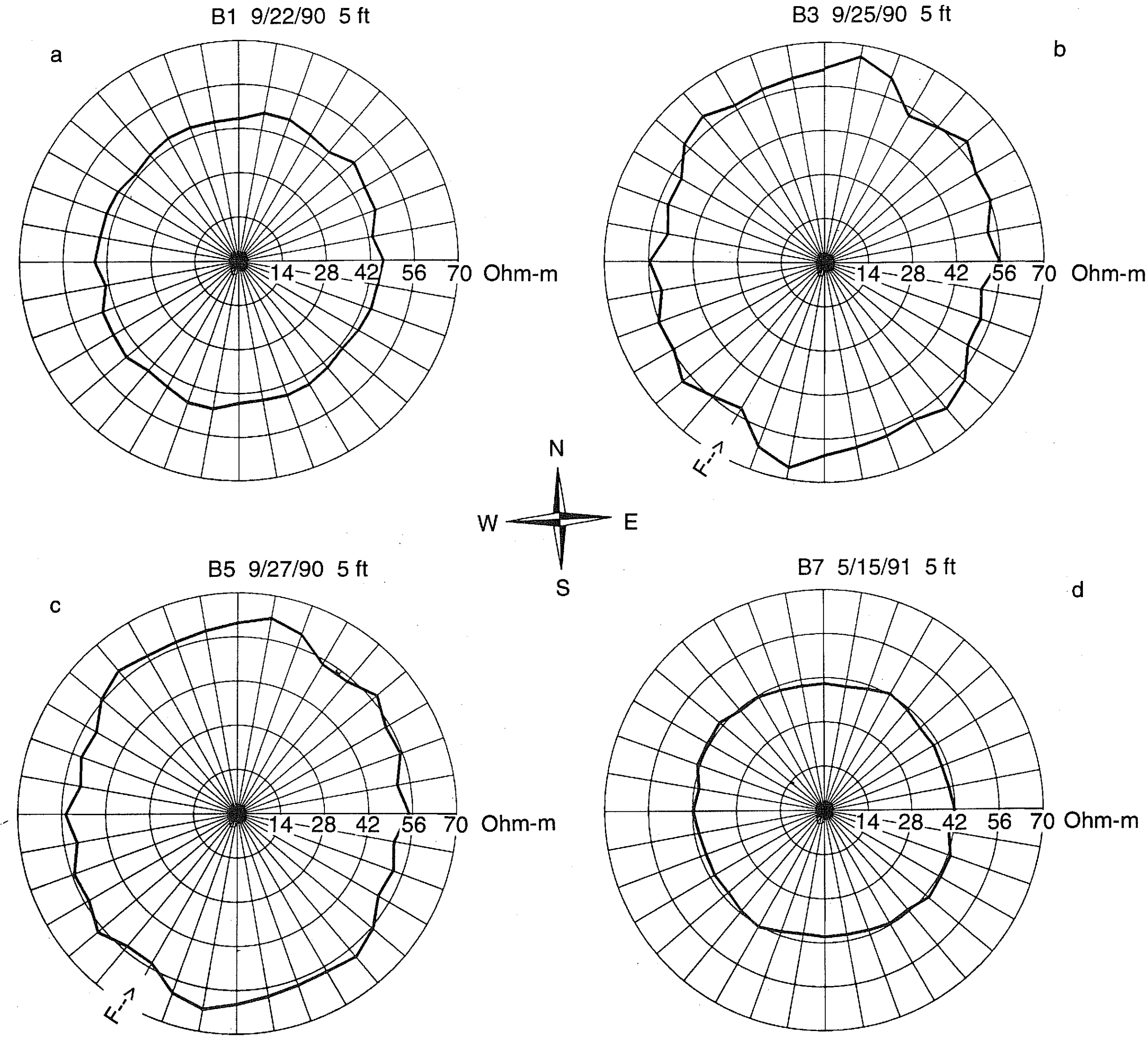

Figure 10 Azimuthal resistivity plots at array B for an electrode spacing of 5 ft. Plots (a), (b), and (c) represent synsubsidence measurements; plot (d) represents postsubsidence measurements. *F* denotes surface fracture trends.

were placed along the survey lines with spacings of 5, 10, or 20 ft. The 10-ft spacing was used most often, with a source offset 10 ft from the nearest geophone. Lines were reversed to identify dipping layers. Geophone outputs were recorded by an EG&G ES-1225 12-channel digital seismograph, and records were stored in the field on digital cassette tape. The data were later transferred to a personal computer on which arrival times were measured, plotted on time-distance graphs (fig. 13), and analyzed using the program SEISVIEW (EG&G, 1987). This routine uses the intercept-time method to compute dipping multilayer models from the arrival times.

Fifty seismic refraction lines (including repeated lines) were completed over various portions of panels 1 and 2 during panel 2 subsidence. Most of these lines were concentrated along the centerline of panel 2 and over the northern tension zone of panel 2, areas where fracturing and water table changes were expected. Most refraction data were modeled with three layers. Borings and water levels from shallow drift piezometers (R.G. Darmody, personal communication, 1992) were used to interpret the refraction models. The top layer in the models is usually 3 to 4 ft thick with a P-wave velocity generally less than 1,000 ft/s. This unit represents loess and topsoil. The second layer consists of a more consolidated clay exhibiting velocities between 1,000 and 2,000 ft/s. This layer extends to the water table at a depth of 13 to 20 ft. Layer 3 represents saturated clayey and sandy drift with a velocity from 4,400 to 5,800 ft/s. This rather wide velocity range incorporates the uncertainty of picking weak first arrivals at long offsets and the effects of lateral

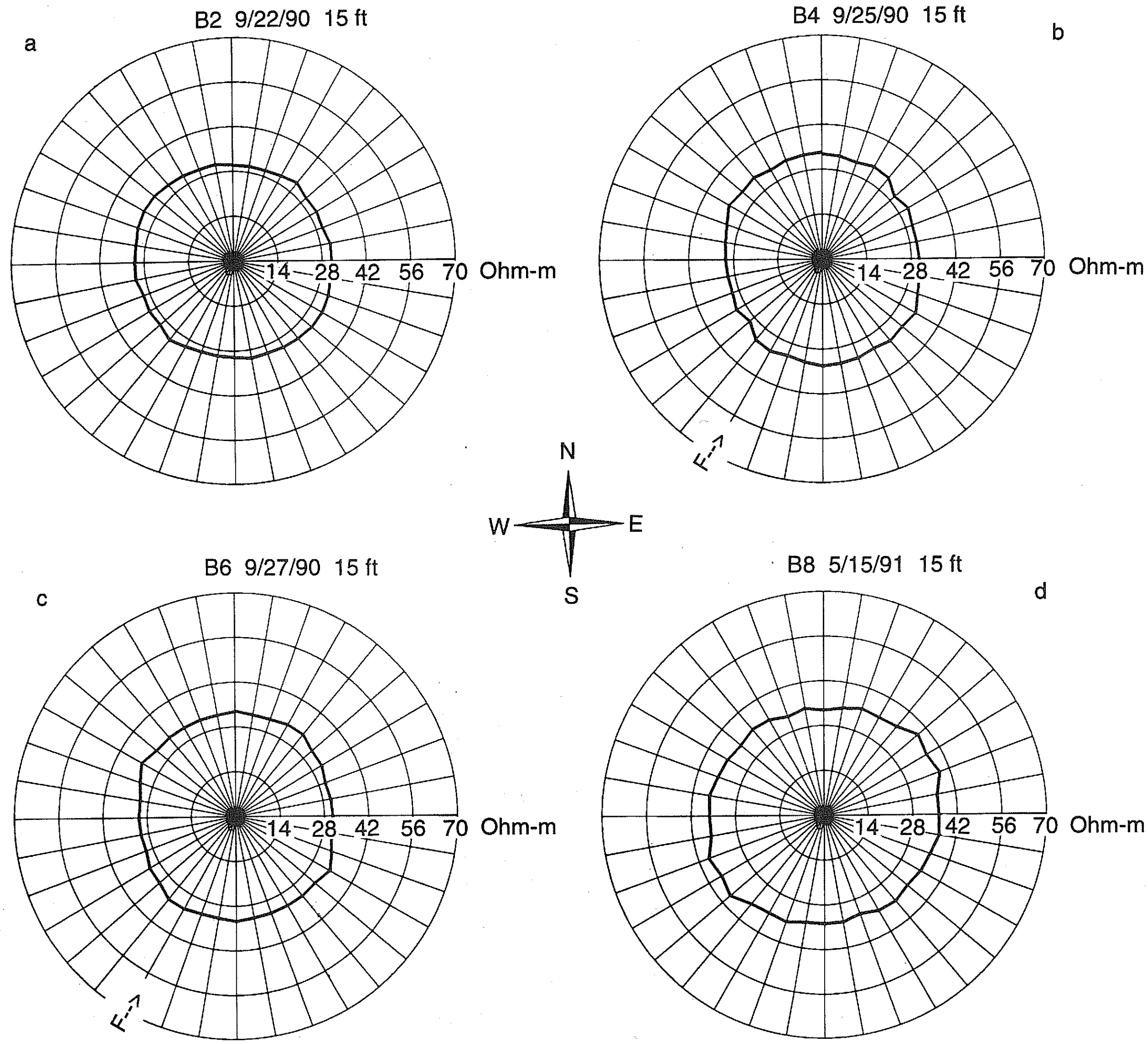

Figure 11 Azimuthal resistivity plots at array B for an electrode spacing of 15 ft. Plots (a), (b), and (c) represent synsubsidence measurements, plot (d) represents postsubsidence measurements. *F* denotes surface fracture trends.

velocity heterogeneity. Some of the saturated low-rigidity clay-rich materials exhibited velocities less than that of sound in water (i.e., less than about 5,000 ft/s).

Uncertainty in these velocity estimates arises from errors in reading arrival times and from the use of a layered model that is an oversimplification of actual field conditions. Uncertainties were quantified by comparing multiple interpretations of the same line and by examining velocity variations between adjacent lines. The velocity uncertainty is approximately 200 ft/s for the top layer, 400 ft/s for the second layer, and about 600 ft/s for the bottom (saturated) layer. Errors in depth (estimated from errors in picking intercept times and depth discrepancies between adjacent lines) were 1 ft for top of the drift beneath the loess and about 2 ft for the water table. No major hidden low-velocity layers were encountered when refraction models were compared to borings and inverted resistivity soundings.

Effects of subsidence on P-wave velocity and water level Figure 14 shows a series of cross sections from combined pre-, syn-, and postsubsidence refraction surveys along the centerline of panel 2. Presubsidence surveys were made between July and September 1990, synsubsidence surveys were made September 25–26, 1990, and postsubsidence surveys were made April 5, 1991. Presubsidence refraction data were not collected more than 300 ft east of the monument line because of extremely thick vegetation. Two-layer models were used where three layers could

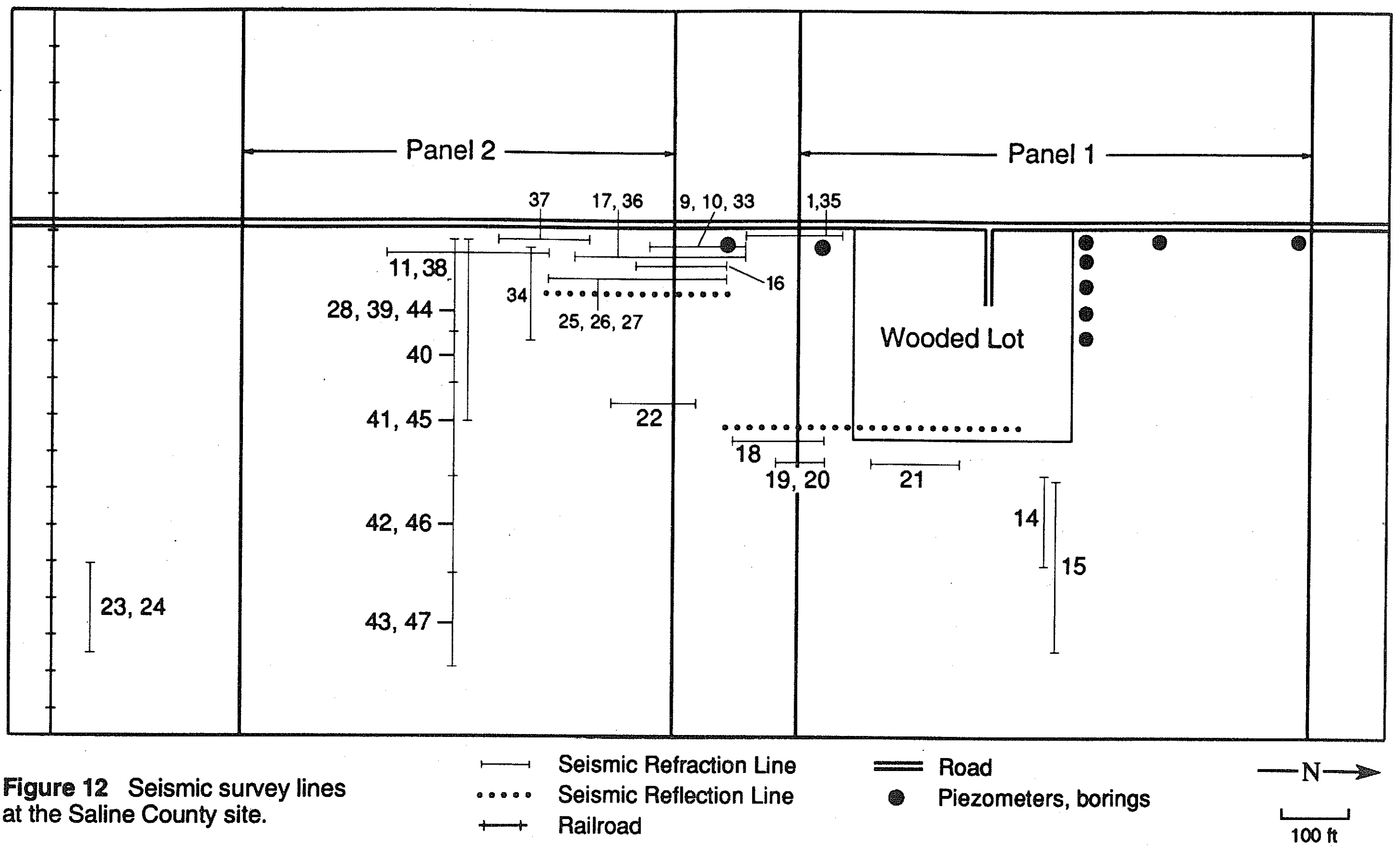

Figure 12 Seismic survey lines at the Saline County site.

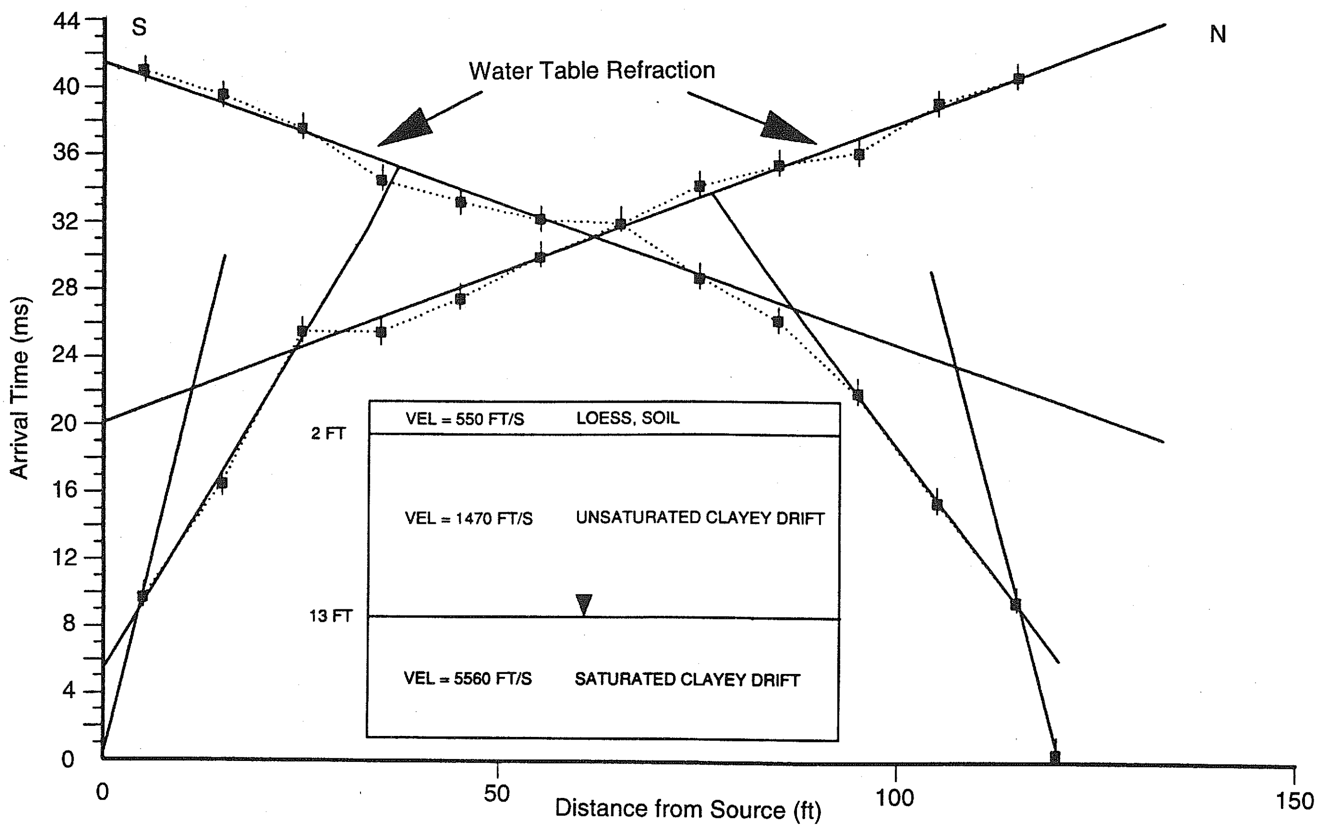

Figure 13 Typical refraction arrival time data (lines 23 and 24) and layered model. The upper interface dips slightly to the north, whereas the water table exhibits no significant dip. Velocities (V) are in ft/s.

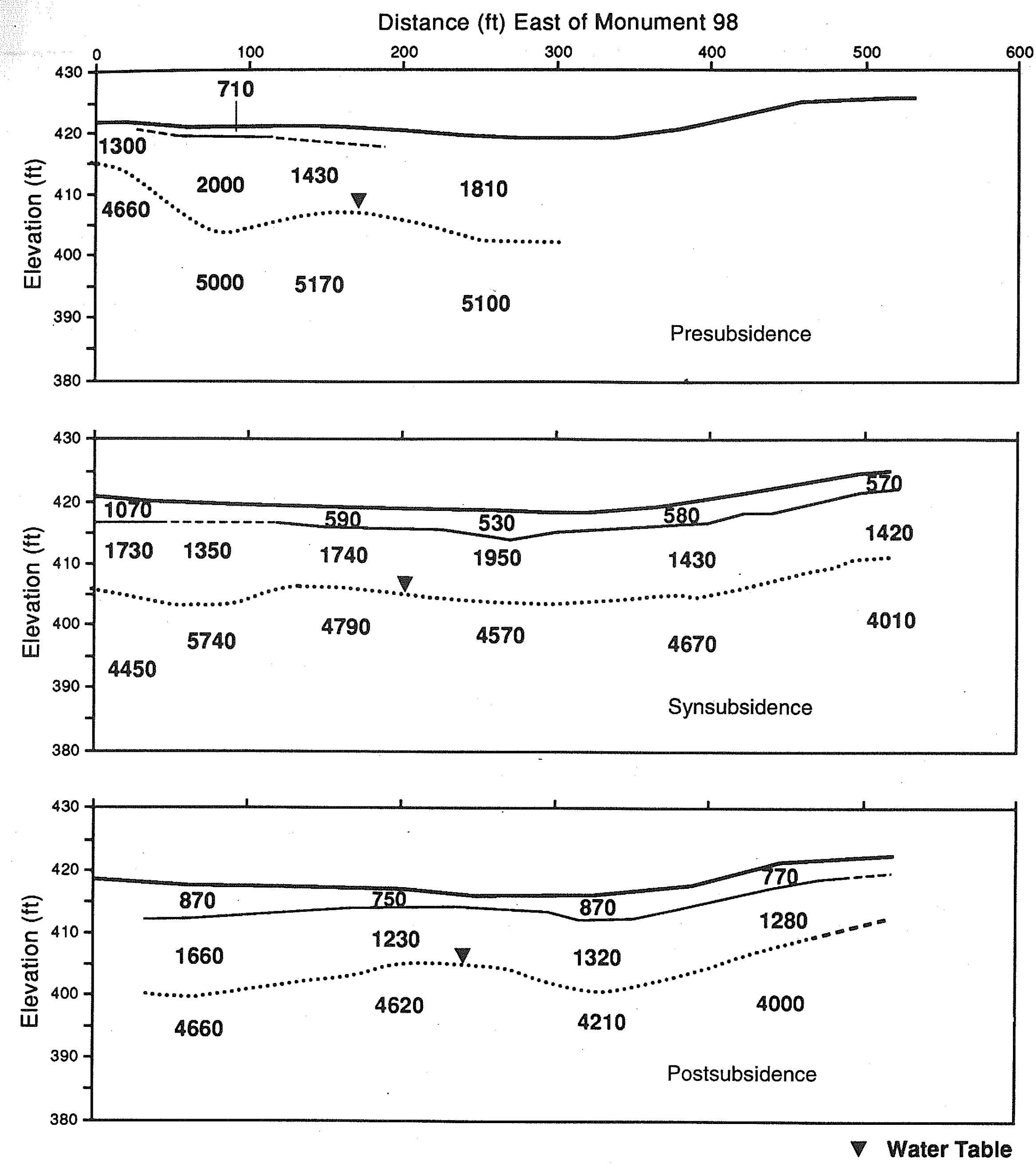

Figure 14 Centerline velocity models from (a) pre-, (b) syn-, and (c) postsubsidence refraction surveys. Velocities (bold) are rounded to nearest 10 ft/s.

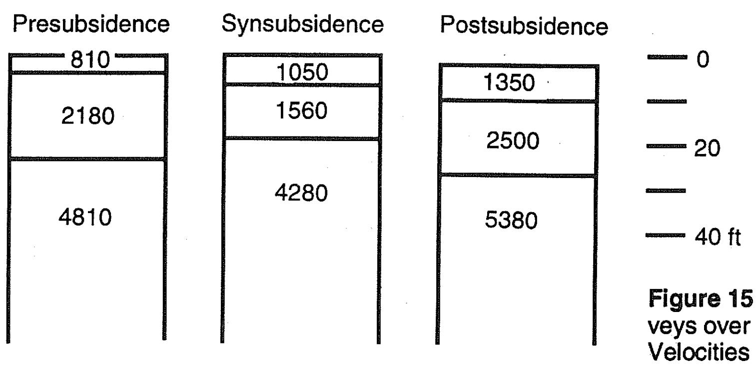

Figure 15 Velocity models from refraction surveys over the northern tension zone of panel 2. Velocities are rounded to the nearest 10 ft/s.

not be resolved on refraction time-distance graphs. Given the uncertainties in velocities as discussed above, no significant changes in velocity were recorded during subsidence, either above or below the water table. An 8 ft drop in the water table was recorded next to the monument line. This could not be confirmed, however, by other synsubsidence refraction profiles along the monument line. Otherwise, water levels remained remarkably uniform throughout subsidence, although some local changes in the water table appeared after subsidence.

Figure 15 shows three velocity-depth profiles computed from refraction lines made across the north tension zone of panel 2 (near the monument line). The presubsidence survey was made July 10, 1990, the synsubsidence survey September 25, 1990, and the postsubsidence survey July 9, 1991. The pre- and postsubsidence velocity models are essentially identical, except there is a slightly thicker low-velocity upper layer in the postsubsidence case. The synsubsidence refraction lines exhibited substantial lateral velocity variations in the top layer, which made interpretation of underlying thicknesses and velocities difficult. If an average velocity of 1,050 ft/s is used for the upper layer (whose actual velocity varied from 750 to 1,350 ft/s), the unsaturated clayey drift exhibits a synsubsidence velocity decrease of approximately 700 to 1,000 ft/s, between 6 and 20 ft. A similar velocity reduction to a depth of 16 ft was observed when two layers were used to model the synsubsidence data. The lowermost saturated drift also exhibits a slightly (although not significantly) lower synsubsidence velocity. The synsubsidence water table was not significantly different from the presubsidence water table. The water table, however, dropped several feet during the postsubsidence period.

Seismic reflection surveys The common-offset (CO), or optimum-offset, seismic reflection method (Pullan and Hunter, 1985) was used to investigate the extent of fracturing at, and immediately below, the bedrock surface at the Saline County site. Common-offset consists of a source (a sledgehammer striking a metal plate several times) and a geophone, which are moved along the profile line at a fixed separation, or offset (fig. 2c). Reflections from several hammer blows recorded by the geophone are combined and plotted on a time section at the source-geophone midpoint.

One 540-ft-long CO seismic reflection line was made in two segments 70 to 240 ft east of the monument line (fig. 16). Reflection points were separated by 10 ft, and the shot-receiver offset was 180 ft. This offset allowed the bedrock surface and shallow bedrock reflectors to be imaged while minimizing amplitudes of earlier refracted, direct, and surface waves. The CO reflection survey was made in August 1990, approximately 8 months after subsidence of panel 1 and shortly before subsidence of panel 2. Instrumental static time shifts were minimized by aligning the ground-coupled sound wave on all traces. Static corrections have not been made for elevation variations or lateral velocity changes.

Figure 16 shows a strong reflection representing the bedrock surface at a two-way travel time of about 70 to 80 ms. A strong pair of reflections with travel times of 100 to 130 ms lose their coherency across the margin of subsided panel 1. Geophysical logs over the center of panel 1 suggest the uppermost (100 ms) of these deeper reflections represents a thin (1 to 2 ft thick) limestone at a depth of about 125 ft. Fracturing of this limestone may cause the disruption in these reflections. Since reflections from the bedrock surface are not strongly disrupted, the limestone, which is more competent than the surrounding shales, may have fractured more extensively in response to subsidence. Packer tests conducted on this limestone interval at the center of panel 1 showed

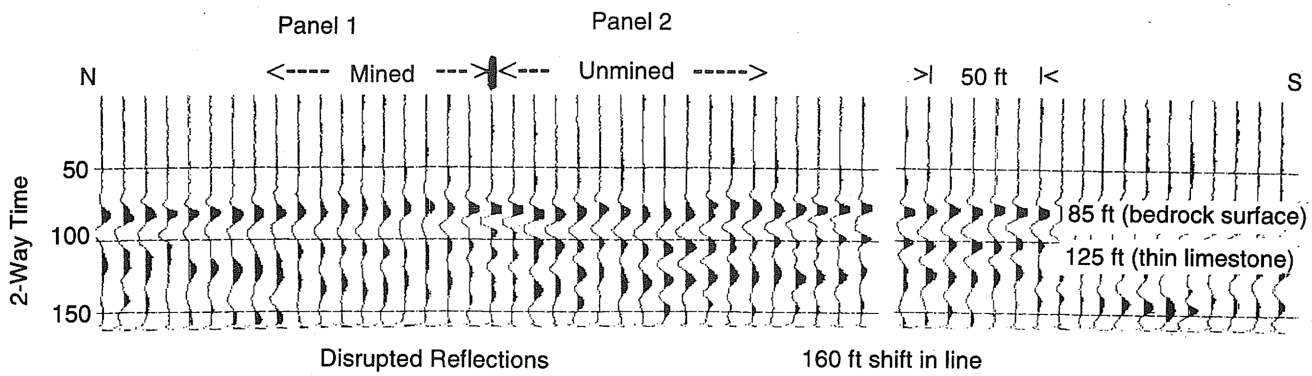

Figure 16 Common-offset seismic reflection section across panels 1 (postsubsidence) and 2 (presubsidence).

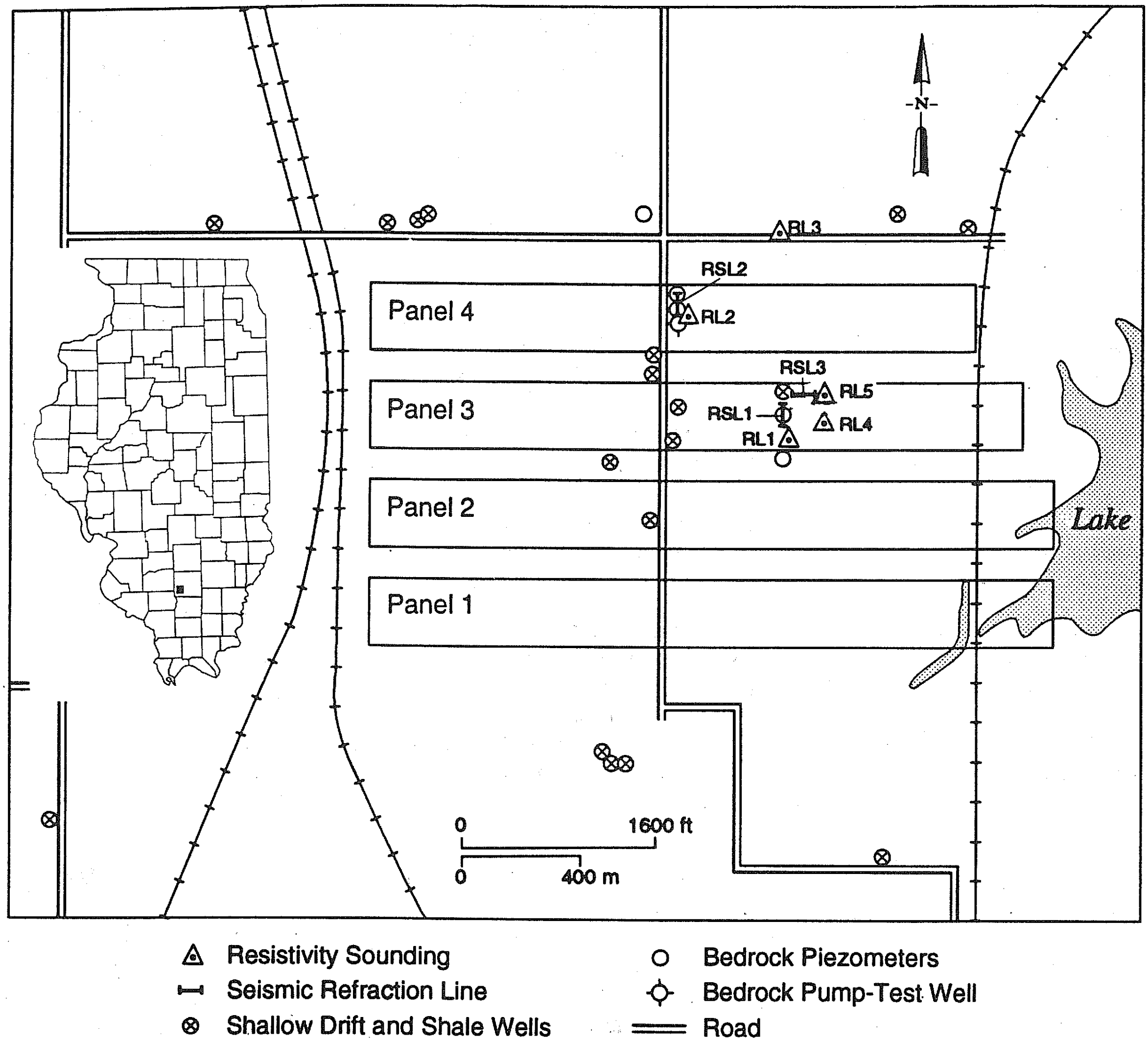

Figure 17 Jefferson County study site showing panel outlines, geophysical lines, wells, and borings.

an increase in hydraulic conductivity from less than 10^{-8} cm/s before subsidence to approximately 10^{-7} cm/s after subsidence (Booth and Spande, 1991).

Some measure of the extent of disruption may be estimated from the horizontal resolution of the seismic reflection "footprint." The horizontal resolution is commonly estimated as the radius of the 1st Fresnel zone, which, in this case, is 65 to 100 ft. Thus, the fracturing of the limestone unit probably extends over a lateral distance of at least 65 ft to significantly degrade the reflections. This is consistent with the general character of the CO section, which shows at least a 90-ft-wide zone of incoherent reflections beneath the bedrock surface.

This interpretation is not unique. The CO profile shown in figure 16 represents a series of wide-angle reflections with incidence angles of approximately 45 degrees. Reflection amplitudes at these wide incidence angles can be highly variable due to slight changes in velocity and density along interfaces and different stacking/source characteristics for different traces (Pullan and Hunter, 1985). S-waves can also be produced at these interfaces and interfere with the P-wave reflections.

JEFFERSON COUNTY GEOPHYSICAL SURVEYS

Geophysical surveys were made over two previously subsided longwall panels in Jefferson County, Illinois, to test at a different location the results of geophysical surveys made over panels 1 and 2, and to identify major long-term changes that might occur 2 years after subsidence (fig. 17).

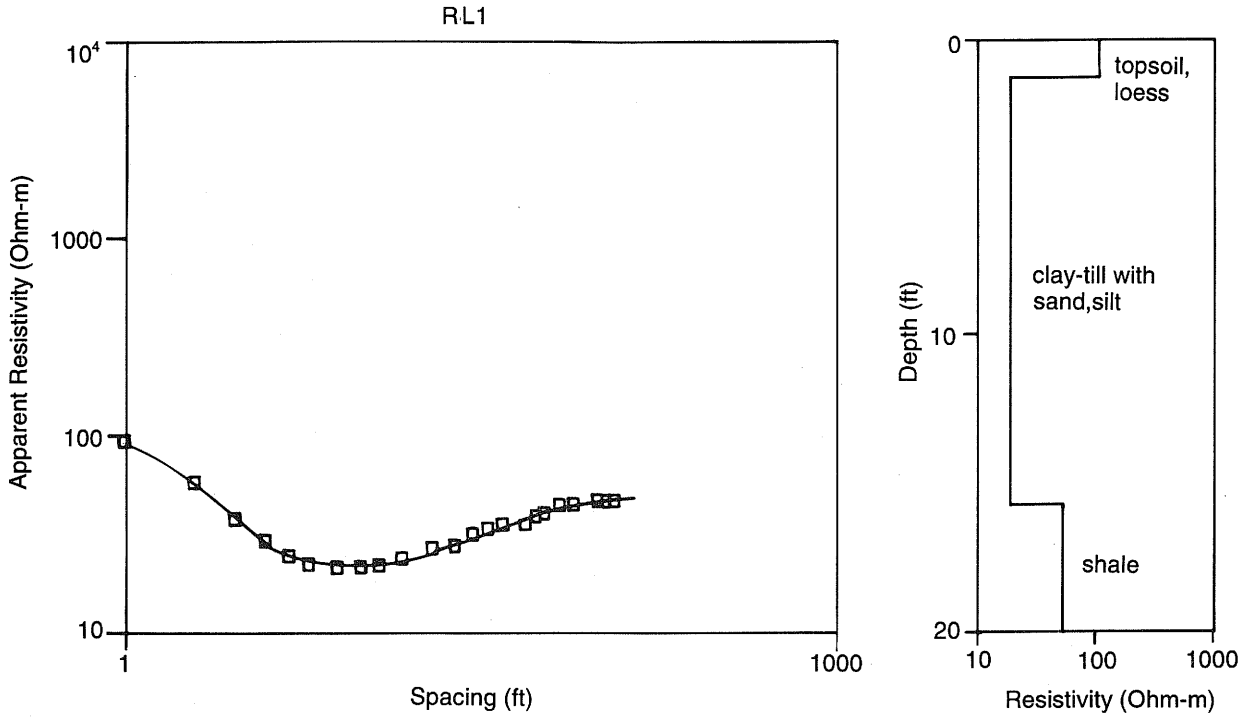

Figure 18 Typical vertical electrical sounding from the Jefferson County site with a layered model interpretation based on well logs and borings.

Site stratigraphy is similar to Saline County, although drift thickness is 8 to 28 ft and the drift consists primarily of silty Illinoian till (Spande, 1990). At the base of the till, sand, pebbles, and gravels commonly occur, which overlie shales and sandstones of the Pennsylvanian Bond Formation. Bedrock units are essentially horizontal in the study area. Four longwall panels removed about 10 ft of Herrin (No. 6) coal from the Carbondale Formation, approximately 725 ft beneath the surface. The panels averaged 600 ft wide, were over 5,000 ft long, and were separated by 200-ft-wide double-pillar barriers. A detailed analysis of the hydrogeologic impact of subsidence of panels 3 and 4 may be found in Spande (1990) and Booth and Spande (1992).

Five resistivity soundings and three seismic refraction surveys were made over panels 3 and 4 between May and July 1991. Panel 3 was mined in May 1988, and panel 4 was mined in early 1989. These geophysical measurements were thus made at least 2 years after subsidence.

Resistivity Soundings

The primary objective of the resistivity soundings was to identify resistivity changes between the edge and center of panel 3 that might reflect earth resistivity changes associated with drift and bedrock fracturing. To establish the degree of natural resistivity variation, additional soundings were made over panel 4 and in an unmined area to the north. All soundings were inverted for layered resistivity models, and equivalence (uncertainty) was computed using procedures and software described above.

Interpretation of resistivity soundings was based on nearby boring and piezometer logs. A generalized geoelectrical section for the Jefferson County site (e.g., figure 18) includes 1 to 5 ft of loess and topsoil (40 to 110 ohm-m), overlying 4 to 15 ft of red, brown, or blue clay (15 to 30 ohm-m), which rests on Pennsylvanian shale bedrock (50 to 90 ohm-m). The water table ranges from 7 to 13 ft and cannot be identified from the soundings. Comparisons between individual soundings and nearby well logs indicate the depth to the loess-clay interface may be estimated to within 1 ft and the bedrock surface to within 6 to 7 ft of its true depth. Soundings RL2 and RL3 were similar to soundings made over panel 3, with some variation in loess/topsoil and bedrock resistivities.

Effect of fracturing on resistivity East-west oriented soundings made over the center (RL4) and northern tension zone of panel 3 (RL5) show a thicker low-resistivity zone over the tension zone between a depth of 14 and 20 ft (fig. 19). Seismic surveys (discussed below) indicate this resistivity decrease occurs in the lowermost till. Equivalence analysis suggests this low resistivity

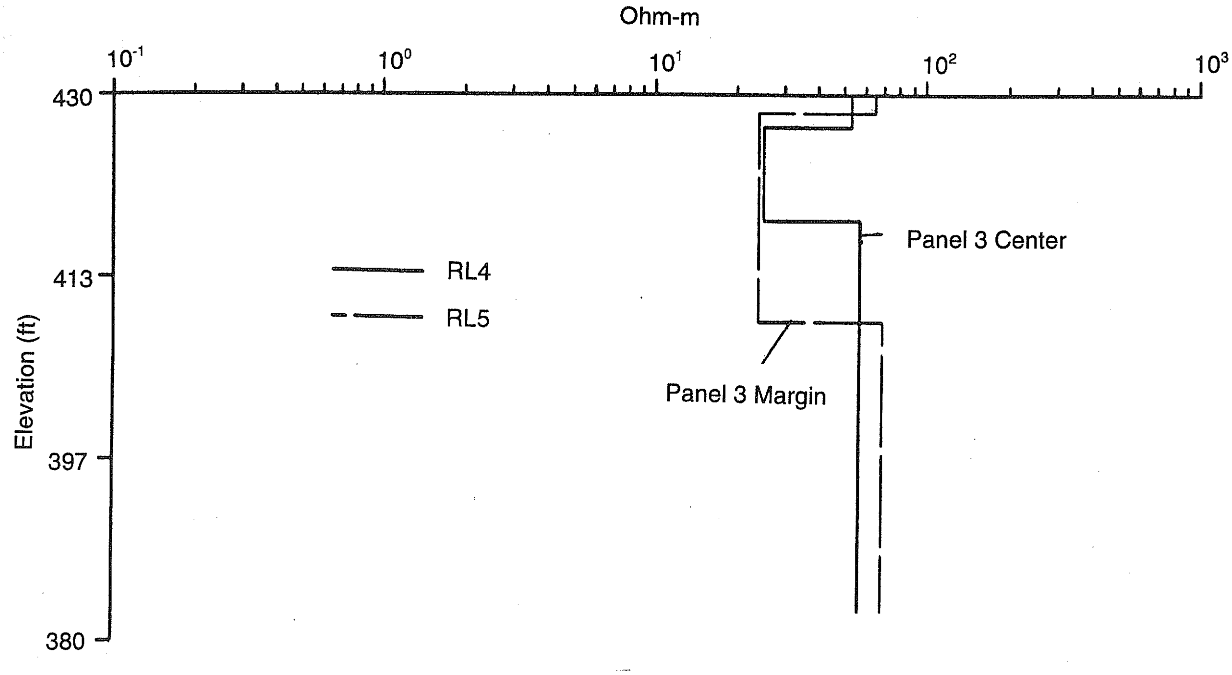

Figure 19 Layered resistivity models from soundings made over the center and edge of panel 3 in Jefferson County.

zone is real, although it is not known whether it represents a long-term fracture effect (such as percolating moisture) or a preexisting lithologic variation.

Seismic Refraction Surveys

Three seismic refraction surveys were made to test the hypothesis that velocity reductions (as seen in the synsubsidence profile over panel 2) persist over the static tension zones. Line RSL1 was located along the centerline of panel 3, and lines RSL2 and RSL3 were located over the tension zones of panels 4 and 3, respectively. An 8-lb sledgehammer was used as the seismic source with 12 vertical-component 8-3/4 Hz geophones and an EG&G ES-1225 recorder. Source offset from the nearest geophone and geophone spacing was 10 ft on all lines.

A two-layer model provided the best fit to traveltimes measured along RSL1; three-layer models were used to interpret refraction data from RSL2 and RSL3 (fig. 20). The uppermost layer in all models corresponds to unsaturated topsoil, loess, and clayey drift. The velocity of this layer at the center of panel 3 (RSL1) is significantly lower than along the northern margin of panel 3 (RSL3). This velocity reduction may reflect lithologic variations in the upper layer since it is opposite to what would be expected from tension zone fracturing. The velocity of saturated drift below 6 to 7 ft at RSL1 and RSL3 does not vary significantly between the panel center and margin. The second layer at RSL2 exhibits a low velocity because of its unsaturated condition, and direct velocity comparisons cannot be made with the second layer at RSL1 or RSL3. Shale bedrock is indicated at a depth of 15 ft along RSL2 and 24 ft along RSL3. No bedrock head-waves were observed along RSL1 at the panel centerline.

DISCUSSION OF RESULTS

Electrical resistivity soundings, profiles, azimuthal surveys, and seismic refraction and reflection surveys were evaluated as tools for characterizing fracturing and water table changes in bedrock and glacial drift above longwall coal mines in Saline and Jefferson counties, Illinois. Most of these surveys were made over the centerline, northern static tension zone, and north barrier pillar of panel 2 in Saline County.

The results can be summarized as follows:

1. Resistivity soundings suggest fractures in the dynamic tension zone along the centerline of panel 2 extend at least 5 ft deep. The resistivity sounding method could not resolve fractures

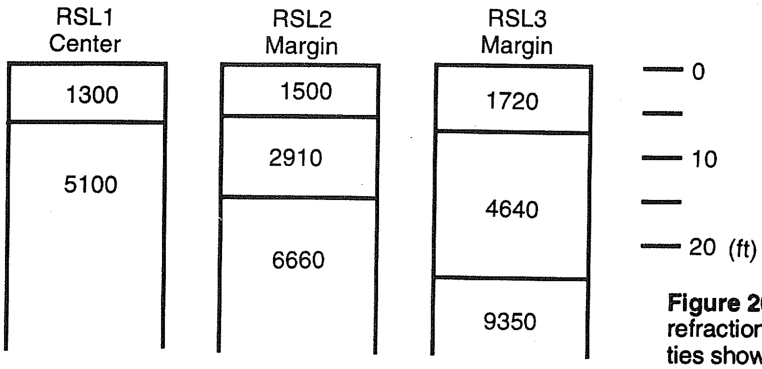

Figure 20 Layered models from seismic refraction surveys over panels 3 and 4. Velocities shown are rounded to the nearest 10 ft/s.

deeper than this, nor could it provide constraints on the lateral extent of drift fracturing. Resistivity soundings could not delineate bedrock fracturing.

2. Areas of reduced apparent resistivity were identified along margins of panel 2 on resistivity pseudosections. These resistivity reductions, however, could not be confirmed through soundings. An area of reduced resistivity was also identified 14 to 20 ft along the northern tension zone of panel 3 in Jefferson County. These resistivity reductions, if real, may indicate water percolation downward along tension zone fractures penetrating much of the drift.

3. Azimuthal resistivity variations were consistent with predicted fracture directions in the drift along the centerline and dynamic compression zone of panel 2 in Saline County. Repeated azimuthal surveys suggest shallow fractures had closed within 8 months of subsidence. Superficial fissures, small-scale heterogeneity, and seasonal resistivity changes add complexity to azimuthal resistivity plots, which may impede interpretation.

4. Pre-, syn- and postsubsidence seismic refraction surveys along the centerline of panel 2 in Saline County revealed no major changes in P-wave velocity or widespread changes in the configuration of the water table. Synsubsidence fracturing, however, introduced severe lateral velocity heterogeneity, which hampered interpretation. Synsubsidence P-wave velocity reductions were observed along the northern tension zone of panel 2, possibly in response to fracturing above a depth of 16 ft. Seismic refraction surveys in Jefferson County showed no velocity differences between panel centerlines and margins that could be attributed to fracturing.

5. Areas of possible bedrock fracturing over the southern margin of panel 1 in Saline County were identified using common-offset reflection surveys 8 months after subsidence. Packer tests confirmed increased permeability in a thin limestone layer exhibiting disrupted reflections at a depth of 125 ft over the panel margin. Seismic reflection surveys identified no fractures in the subcropping bedrock surface.

Probably the most useful information provided by the geophysical surveys were the minimum estimates of fracture depth derived from the repeated resistivity soundings, and the identification of a fractured bedrock unit through the common-offset seismic reflection surveys. Depth and lateral resolution were generally poorer with the resistivity methods than with the seismic methods. The resistivity methods, however, were less affected by lateral heterogeneity introduced by fractures. Resistivity profiles (pseudosections) and azimuthal resistivity surveys showed interesting changes with subsidence, but were far too labor intensive in the field and difficult to interpret quantitatively. Subsidence-induced changes in the bedrock were only monitored through a single common-offset reflection survey, made after the subsidence of panel 1. Results of this survey are encouraging, and this technique may be more widely applied in ongoing investigations of panels 4 and 5 in Saline County. Refraction surveys could also be used to obtain information from the bedrock surface; they were not used in this investigation because of the long line lengths required.

ACKNOWLEDGMENTS

We would like to thank Billy Anne Trent and Lisa Paulson for their assistance in preparing this manuscript and illustrations, and two anonymous reviewers for comments and suggestions. This research was supported by a grant from the Illinois Mine Subsidence Research Program and the Department of Geology, Northern Illinois University.

REFERENCES

Booth, C.J., and E.D. Spande, 1991, Changes in hydraulic properties of strata over active longwall mining, Illinois, USA, 4th Inter. Mine Water Assoc. Cong., Ljubljana, Slovenia, Yugoslavia, pp. 163-174.

Booth, C.J., and E.D. Spande, 1992, Potentiometric and aquifer property changes above subsiding longwall mine panels, Illinois basin coalfield, Ground Water, v. 30, pp. 362-368.

Burdick, R.G., L.E. Snyder, and W.F. Kimbrough, 1986, A Method of Locating Abandoned Mines, U.S. Bur. of Mines, Rep. Inv. 9050, 27 pp.

Carpenter, P.J., M.C. Keeley, and R.S. Kaufmann, 1994, Azimuthal resistivity surveys over a fractured landfill cover, Bull. Assoc. Eng. Geol., v. 31 (in press).

Darmody, R.G., 1990, Quarterly Progress Report, Jan. 1-Mar. 31, 1990, Illinois Mine Subsidence Research Program, June 19, 1990, Univ. of Illinois, Urbana, pp. 8-12.

Darmody, R.G., 1992, personal communication.

Dobrin, M.B., 1976, Introduction to Geophysical Prospecting, 3rd. Ed., McGraw-Hill,New York, 630 pp.

EG&G, 1987, User manual for SEISVIEW, EG&G Geometrics, Palo Alto, CA.

Fehrenbacher, J.B., J.D. Alexander, I.J. Jansen, R.G. Darmody, R.A. Pope, and M.A. Flock, 1984, Soils of Illinois, Illinois Agric. Exp. Stn. Bull. 778.

Frye, J.C., A. B. Leonard, H.B. Willman, and H.D. Glass, 1972, Geology and paleontology of Late Pleistocene Lake Saline, southeastern Illinois, Ill. State Geol. Surv. Circ. 471, 44 pp.

He, G., and T.H. Wilson, 1989, Longwall mine subsidence and its effect on seismic properties of the overburden, Soc. Explor. Geophys. 49th Inter. Meeting and Expos., Extended Abstr., pp. 368-371.

Henson, H. Jr., J.L. Sexton, and J.L. Jobling, 1989, High-resolution seismic reflection study of shallow coal seams near Harco, Illinois, Soc. Explor. Geophys. 49th Inter. Meeting and Expos., Extended Abstr., pp. 372-374.

Interpex, 1988, ResixPlus: DC Resistivity Data Interpretation Software, Interpex, Ltd., Golden, CO, diskette and user's manual.

ISGS, 1991, Illinois Mine Subsidence Research Program Field Trip, July 10, 1991, Ill. State. Geol. Surv., 50 pp.

Kelleher, J.T., D.J. Van Roosendaal, B.B. Mehnert, D.F. Brutcher, and R.A. Bauer, 1991, Overburden deformation and hydrologic changes due to longwall coal mine subsidence in the Illinois basin, Proc. of the 4th Inter. Symp. on Land Subsidence, pp. 195-204.

Keller, G.V., and F.C. Frischknecht, 1966, Electrical Methods in Geophysical Prospecting: Pergamon Press, Oxford, 517 pp.

Kratzsch, H.,1983, Mining Subsidence Engineering: Springer-Verlag, New York, 543 pp.

Pullan, S.E., and J.A. Hunter, 1985, Seismic model studies of the overburden-bedrock reflection, Geophysics, v. 50, pp. 1684-1688.

Ritzi, R.W. Jr., and R.H. Andolsek, 1992, Relation between anisotropic transmissivity and azimuthal resistivity surveys in shallow, fractured, carbonate flow systems, Ground Water, vol. 30, no. 5, pp. 774-780.

Rudenko, D., J.S. Walker, A.M. Richardson, H.D. Ackerman, and J.W. Reil, 1989, P-Wave and S-Wave velocity measurements related to subsidence over a longwall mine. Soc. Explor. Geophys. 49th Inter, Meeting and Expos., Extended Abstr., pp. 363-367.

Seils, D.E., R.G. Darmody, and F.W. Simmons, 1992, The effects of coal mine subsidence on soil macroporosity and water flow, 1992 Nat. Symp. on Prime Farmland Reclamation, Dunker, R.E., R.I. Barnhisel, and R.G. Darmody (Eds.), Dept. of Agronomy, Univ. of Illinois, Urbana, pp. 137-145.

Spande, E.D., 1990, Effects of Longwall-induced Subsidence on Hydraulic Properties at a Site in Jefferson County, Illinois, M.S. Thesis, Northern Illinois Univ., Dept. of Geology, 128 pp.

Taylor, R.W., and A.H. Fleming, 1988, Characterizing jointed systems by azimuthal resistivity surveys, Ground Water, v. 26, pp. 464-474.

Telford, W.M., L.P. Geldart, R.E. Sheriff, and D.A. Keys, 1976, Applied Geophysics, Cambridge Univ. Press, New York, 860 pp.

Van Roosendaal, D.J., P.J. Carpenter, B.B. Mehnert, M.A. Johnston, and J.T. Kelleher, 1992, Longwall mine subsidence of farmland in southern Illinois: near-surface fracturing and associated hydrogeological effects, 1992 Nat. Symp. on Prime Farmland Reclamation, Dunker, R.E., R.I. Barnhisel, and R.G. Darmody (Eds.), Dept. of Agronomy, Univ. of Illinois, Urbana, pp. 147-158.

Wilson, T.H., G. He, and B. Haslebacher, 1988, Seismic studies over active longwall mines, Proc. 7th Inter. Conf. on Ground Control in Mining, pp. 289-302.