RI 9303

RI 9303

REPORT OF INVESTIGATIONS/1990

PLEASE DO NOT REMOVE FROM LIBRARY

Electromagnetic Investigation of Abandoned Mines in the Galena, KS, Area

By Michael J. Friedel, James A. Jessop,
Richard E. Thill, and David L. Veith

1910 ★ 80 ★ 1990
YEARS

BUREAU OF MINES

March 3, 1849

UNITED STATES DEPARTMENT OF THE INTERIOR

U.S. Bureau of Mines
S[illegible] Center
E. [illegible] Ave.
Spokane, WA 99207
LIBRARY

Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

Report of Investigations 9303

Electromagnetic Investigation of Abandoned Mines in the Galena, KS, Area

By Michael J. Friedel, James A. Jessop,
Richard E. Thill, and David L. Veith

UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel Lujan, Jr., Secretary

BUREAU OF MINES
T S Ary, Director

Library of Congress Cataloging in Publication Data:

Electromagnetic investigation of abandoned mines in the Galena, KS, area / by Michael J. Friedel ... [et al.].

p. cm. – (Report of investigations; 9303)

Includes bibliographical references.

Supt. of Docs. no.: I 28.23:9303.

1. Mine subsidences–Kansas–Galena Region. 2. Ground penetrating radar. I. Friedel, Michael J. II. Series: Report of investigations (United States. Bureau of Mines); 9303.

TN23.U43 [TN319] 622 s–dc20 [622'.8] 89-600333
CIP

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel
dB/ft	decibel per foot
ft	foot
ft^2	square foot
ft/ns	foot per nanosecond
Hz	hertz
MHz	megahertz
min	minute
mmho/ft	millimho per foot
mph	mile per hour
ns	nanosecond
ohm-ft	ohm-foot
V	volt

ELECTROMAGNETIC INVESTIGATION OF ABANDONED MINES IN THE GALENA, KS, AREA

By Michael J. Friedel,[1] James A. Jessop,[1] Richard E. Thill,[2] and David L. Veith[3]

ABSTRACT

As part of an investigation aimed at mitigating the hazards caused by abandoned mine openings, the Bureau of Mines conducted a series of electromagnetic surveys in the Galena, KS, area of the Tri-State mining district. The application of monostatic ground-penetrating radar (GPR) and inductive electromagnetic methods for detecting and delineating hazardous mine openings and attendant features was demonstrated to be feasible for shallow mine workings (i.e., less than 35 ft) occurring below flat-lying areas. Accurate determinations of depth to a mine roof appeared to be limited to roughly 20 ft using the GPR method. Features such as mine voids, fractures, and zones of subsidence were located beneath the Mainstreet (State Highway 26) site using the GPR system. Both the GPR and inductive electromagnetic techniques satisfactorily located mine openings and pillars at the Hell's Half Acre site. Geophysical interpretations were supported by exploratory drilling and mine maps.

---

[1] Geophysicist.
[2] Supervisory geophysicist.
[3] Mining engineer.
Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.

INTRODUCTION

In accord with its mission to assist the mining industry in developing technology to deal with problems caused by abandoned mines, the Bureau of Mines is investigating the use of electromagnetic energy for assessing the hazards of abandoned underground mine openings. As part of this investigation, the Bureau used surface ground-penetrating (ground-probing) radar (GPR) and inductive electromagnetic methods to locate shallow mine voids near Galena, KS, in the Tri-State mining district. The objective of this study was to evaluate the applicability, effectiveness, and potential limitations of a lower frequency (80-MHz) GPR system and a variable intercoil inductive system.

Galena, KS, is located in the Ozark Plateau Province, which is characterized by cherty limestones of the Keokuk Formation, of Mississippian age. A generalized columnar section depicting the Kansas Mississippian age rocks is presented in table 1. At the Galena study site, the limestone occurs at or near the surface, is medium to coarsely crystalline and bluish-gray, and contains gray chert and commercial amounts of sphalerite and galena. Where soils exist, they are characterized by a residual cherty gravel ranging in thickness from 0 to 3 ft. The decomposition of iron and zinc imparts a reddish-brown color to the rocks. Both lead and zinc deposits were mined between 1870 and 1970. The primary ore body occurred as irregular runs, which were up to 3,000 ft long, less than 100 ft wide, and less than 100 ft deep (*1*).[4] The shallow nature of these lead-zinc deposits resulted in exploration by sinking a square shaft, 4 ft in width, until trace minerals were detected. At this point, the miners would drift outward searching for the main ore body. When the ore was encountered, extraction would proceed by the room-and-pillar method. If the ore was exhausted, pillars were typically robbed. Often there was a need for increased ventilation; consequently, additional shafts were sunk. It was not uncommon for a mining lot (200 ft^2) to have two or three shafts.

As a consequence of this mining activity, the city of Galena and the adjoining areas were extensively undermined. The approximate areal extent of mining is shown in figure 1. Hazards associated with the abandoned mine rooms preclude the implementation of any reclamation program employing heavy surface equipment. Features such as shafts, subsidence troughs, and refuse piles tend to exacerbate the present problem. As a first step toward reclaiming this area, a suitable method was sought for assessing the extent of underground mining. While a shaft can usually be located by inspection, i.e., by observing boulder piles or concrete foundations that supported hoisting apparatus, the presence of an underground opening can only be inferred. An obvious approach might be to correlate the observed shafts with mine maps indicating the extent of workings. However, records of mining activity in the Galena area generally were not kept. Although some mine maps were produced, many were lost over the years and others have often been found to be inaccurate. A common method employed to detect the abandoned mine workings is to drill throughout the area of interest, but the time, expense (roughly $4 to $10 per foot), and poor subsurface sampling obtained make this method cost ineffective. As an alternative approach, the Bureau investigated the use of GPR and inductive electromagnetic technology to detect the mine voids.

GPR has been successfully employed to resolve structural features in both soil and bedrock (*2-3*) and to locate buried pipes and cables (*4*). Related investigations have concentrated on assessing the feasibility of GPR for detecting coal (*5*), granular deposits, and sea ice thickness in permafrost regions (*6*). Recent studies have also confirmed the usefulness of GPR for delineating tunnels (*7-8*) and abandoned mines (*9*) in granitic and limestone rock masses. Application of the inductive electromagnetic technique to mapping geology was reviewed by Wait (*10*). Similarly, inductive electromagnetic measurements were useful in mapping contaminant migration (*11*), salt water intrusion (*12*), and permafrost (*13*).

Table 1.–Generalized columnar section for Mississippian age rocks in Galena area

Geologic unit	Av thickness, ft	Description[1]
Warsaw Shale or Limestone.	120	Limestone, crinoidal; contains gray chert. Base marked by glauconite-rich bed.
Keokuk Limestone . .	130	Limestone, medium to coarsely crystal-line, bluish-gray, and gray chert; contains oolitic limestone near top. Cherty parts weather to characteristic reddish-brown color.
Fern Glen Limestone . .	170	Limestone, finely crystalline, bluish-gray.

[1] All contain deposits of lead and zinc of commercial grade.

---

[4] Italic numbers in parentheses refer to items in the list of references at the end of this report.

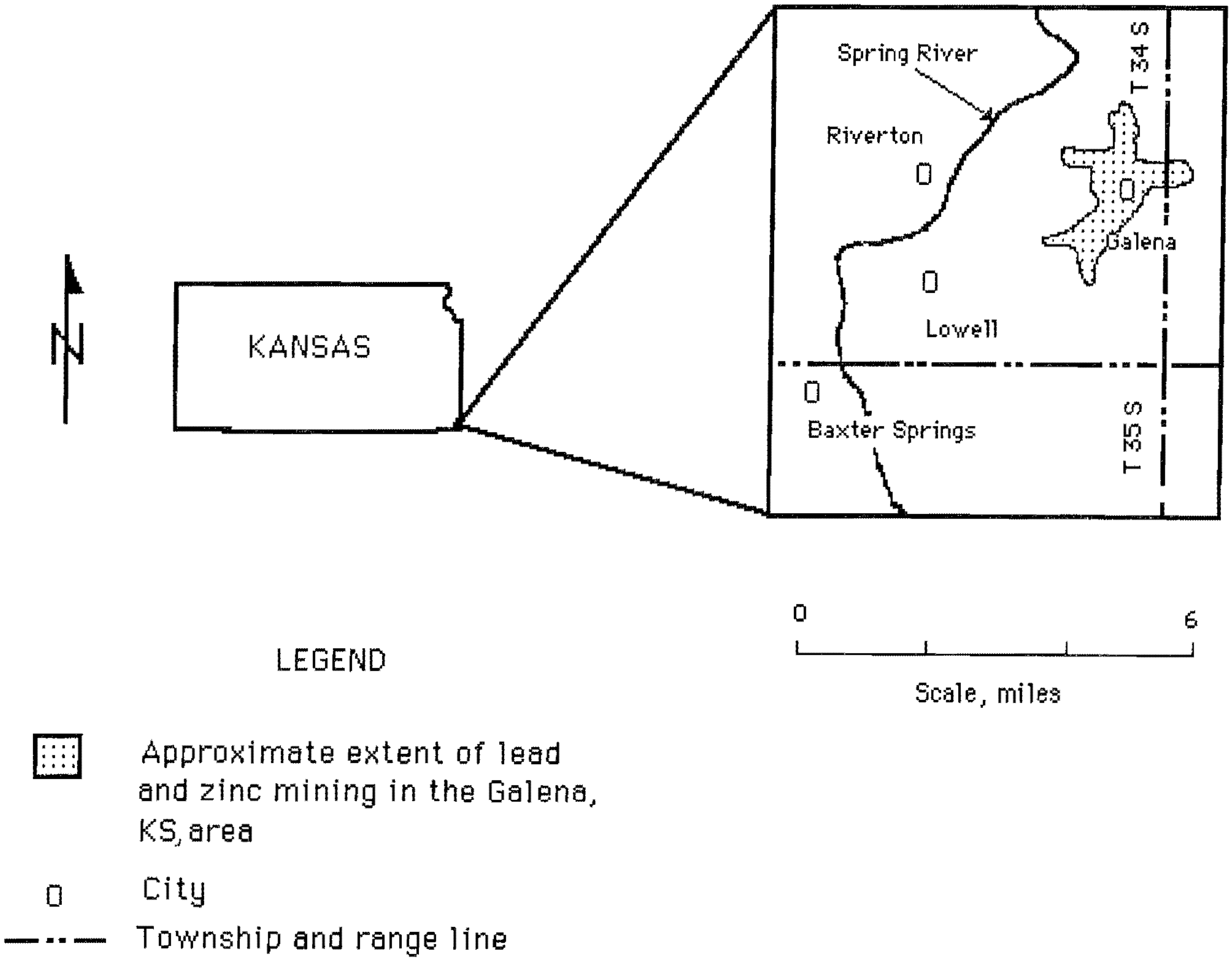

Figure 1.–Location map of electromagnetic investigation of abandoned mines in Galena area.

ELECTROMAGNETIC PRINCIPLES

GPR systems transmit a short-duration electromagnetic pulse (1 to 10 ns), which corresponds to relatively high frequencies (80 to 1,000 MHz). The distance-frequency relationships for typical limestones are given in figure 2. This diagram depicts the effect of attenuation on a transmitted electromagnetic wavelet with increasing distance.

Generally, as the distance increases, the radar wavelet experiences a loss of higher relative frequencies. Also, those materials characterized by higher relative conductivity, i.e., higher relative clay content and/or increasing water content, can be expected to attenuate electromagnetic energy more rapidly. Therefore, the energy loss (decibels per foot) depends on the effective saturation and relative thickness of the material through which the electromagnetic energy propagates. Based on the attenuation curve, the depth of radar penetration in limestone can be expected to be no greater than about 164 ft for the 80-MHz antenna used and 100-dB attenuation. To penetrate to these depths, the GPR transducer should have a central frequency equal to or less than 100 MHz. Since the mine problem at the Galena site was expected at depths no greater than 50 ft, void detection using GPR appeared viable.

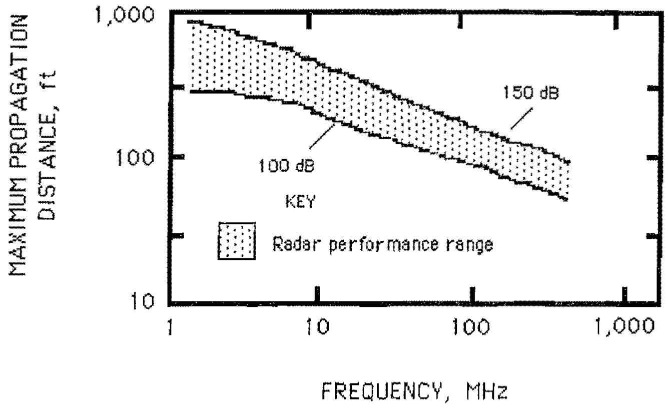

Figure 2.–Distance-frequency (attenuation) relationships for propagation of electromagnetic wavelet.

A radiated electromagnetic wavelet travels through a material at a velocity (V) proportional to the dielectric constant (K). Table 2 displays some common earth materials and associated dielectric constants. For Earth materials characteristic of low magnetic susceptibility, the expression for velocity is given by

$$V = c/(K)^{1/2} \quad (1)$$

where c = velocity of light, 0.984 ft/ns.

If the dielectric constant of the Galena limestone is 7, then from equation 1, the velocity is 0.372 ft/ns.

Table 2.–Typical dielectric constants for various Earth materials

Material	*Dielectric constant (K)*
Air	1
Clay (dry to saturated)	8-43
Fresh water	80
Granite	5- 8
Limestone	7
Sand (dry to saturated) ...	4-30
Sea water	81

The resolution of the GPR system can now be determined by forming the product of velocity and width of the electromagnetic pulse. A 1-ns pulse will result in resolution on the order of 0.372 ft, while a pulse of 10 ns will result in lower resolution, on the order of 3.72 ft. There exists a tradeoff between the resolution and maximum penetration of the transmitted radar energy. Bureau efforts were concerned with penetration of radar in limestone to depths of 15 to 50 ft to resolve mine pillars and voids greater than 6 ft. To detect these features, a portion of electromagnetic energy must be reflected back toward the surface. Reflection of a radar wavelet occurs when changes in the subsurface dielectric properties exist. As the contrast increases, so does the amount of reflected energy. The dielectric contrast between the limestone and air (in the unsaturated void) indicates a strong reflection, in comparison with the dielectric contrast between the limestone and water for a saturated void.

The GPR and inductive electromagnetic systems differ in their fundamental operation and mode of deployment. The inductive electromagnetic technique relies on energizing the transmitter coil with an alternating current at some audio frequency (fig. 3). With a receiver coil placed some distance from the transmitting coil, small currents introduced by the transmitter result in a secondary magnetic field. The measured quantity is the ratio of the secondary to primary magnetic field. The field ratios for vertical and horizontal dipole configurations are, in general, complex functions. However, when induction numbers (defined as the intercoil spacing divided by the distance a propagating electromagnetic plane wave has traveled when its amplitude has been attenuated to 1/exp of the amplitude at the surface) are much less than unity, the magnitude of the secondary magnetic field becomes directly proportional to the ground conductivity. The apparent conductivity is given by the following expression:

$$\sigma = \frac{4}{\omega\, u\, s}\ \frac{Hs}{Hp}, \quad (2)$$

where ω = angular frequency, $2\pi f$,

u = permeability of free space,

s = intercoil spacing,

Hs/Hp = ratio of secondary magnetic field to primary magnetic field,

and σ = apparent conductivity.

By varying the intercoil spacing and/or the dipole mode (fig. 4), the effective depth of exploration can be changed. As a rule of thumb, the effective depth of penetration for the horizontal dipole corresponds to about 3/4 of the intercoil spacing, while use of the vertical dipole translates to about 1-1/2 of the intercoil spacing. Therefore, an inductive electromagnetic system with either a 32.8- or 65.6-ft intercoil spacing should prove useful in probing to the depths associated with the abandoned mines.

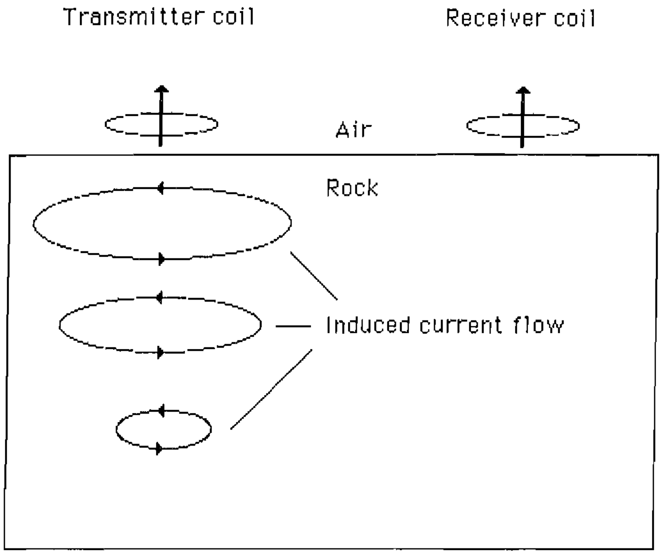

Figure 3.–Induced current flow in a homogeneous half-space.

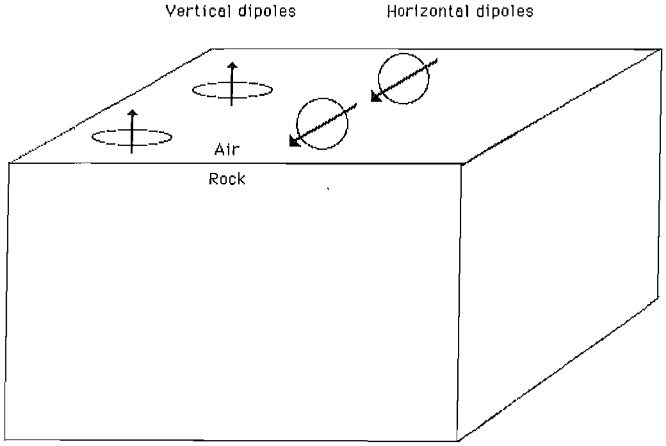

Figure 4.–Vertical and horizontal dipole field configurations for inductive electromagnetic technique.

EQUIPMENT

The GPR system used in this investigation was a GSSI SIR system-III.[5] The system includes a profiling recorder, transducer cable, power cable, and transducer. The broadband antenna is operated in a monostatic mode, and the reflected pulse is both transmitted and received by the same antenna. The time-frequency domain characteristics of the antenna are given in figure 5. The 6-ns pulse width characteristic of this transducer results in a spectrum with a center frequency of 80 MHz. Profiles displayed on the graphic recorder are typical of those used in marine subsurface profiling.

The inductive electromagnetic equipment used during this study was a Geonics EM34 system[5]. The system is composed of a transmitter and receiver coil, a transmitter and receiver meter, and three intercoil cables. Apparent conductivity measurements of 0 to 1,000 mmho/ft are read directly from the receiver, for either the vertical or horizontal dipole mode of operation.

FIELD PROCEDURE

For repeatability and uniformity in the field records, the GPR system was mounted on a trailer and towed behind a tractor at about 3 mph. This required a two-person team, one driving the tractor while the other operated the radar equipment. The polarity, gain, and scan rate settings were set while in calibration mode. Figure 6 depicts the effect of various polarities (i.e., positive, positive and negative chopped, positive and negative, negative and positive chopped) on the radar record at a scan rate of 16 scans per second. The positive polarity (fig. 6A) resulted in the cleanest and most interpretable record. The deep, intermediate, and surface gains also were set prior to profiling. The deep gain gives a linear increase across the time window; the middle gain is cosine shaped with a peak in the center of the time window; and the surface gain is constant. The relative response of each gain setting is shown in figure 7. Each gain, beginning with the deep, is increased until the recorded profile displays continuity in machine noise.

---

[5] Reference to specific products does not imply endorsement by the Bureau of Mines.

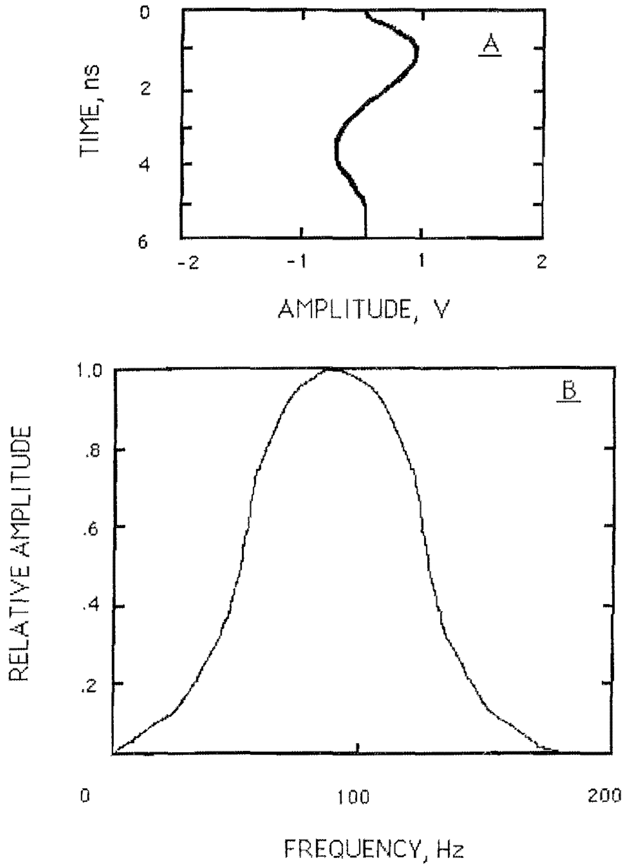

Figure 5.–Time (A) and frequency (B) domain characteristics of ground-penetrating radar transducer.

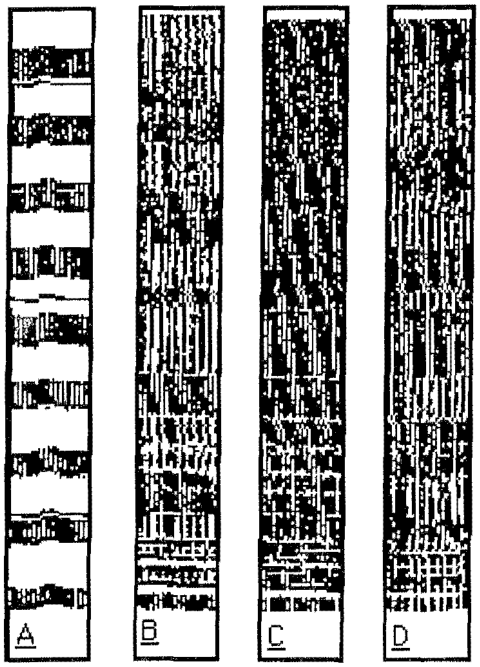

Figure 6.–Effect of polarity type variations on ground-penetrating radar calibration. A, Positive; B, positive chopped; C, positive and negative; D, negative and positive chopped.

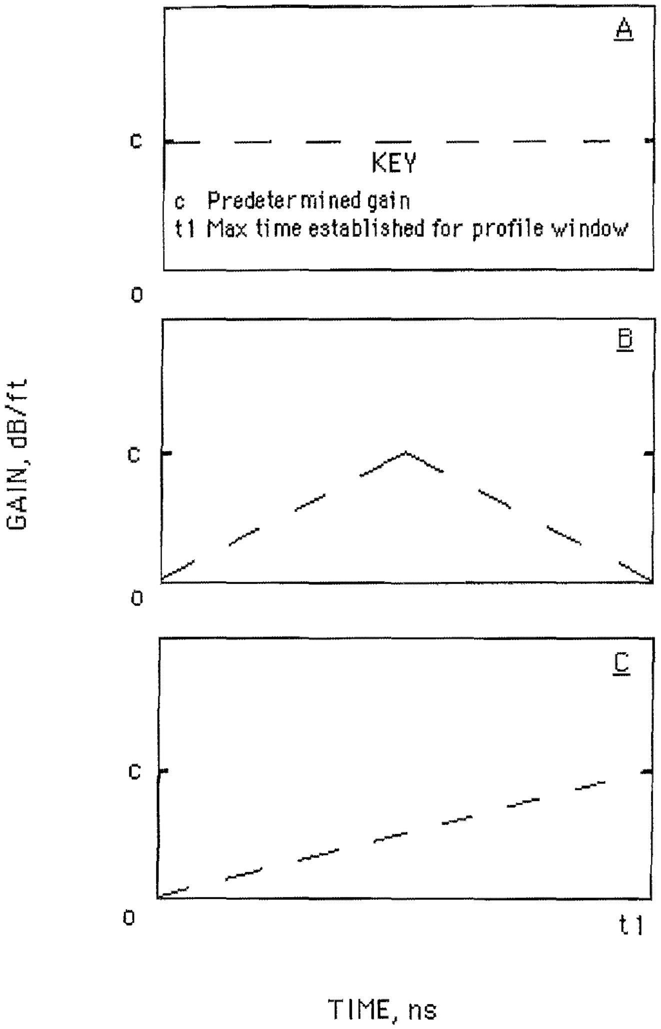

Figure 7.–Relative time response for surface (A), center (B), and deep (C) gain pots.

Additional calibration of the GPR system was necessary while recording at a field site. E.g., an estimate of the position of the surface reflection was necessary in order to determine the correct time to a reflector. The appearance of a surface reflection depends on the position of the antenna with respect to the ground surface. The relative position is then adjusted within the time window, such that the surface reflection appears at or near the top of the profile. Final gain, scale, and scan rate settings were also established at the field site prior to actual data collection. The effect of various time windows on graphic resolution is substantial.

The inductive electromagnetic system requires two operators but involves far less calibration. Calibration involves daily checks on possible drift and battery checks for the transmitter and receiver. While it is theoretically possible to use this system to make depth soundings, using a continuum of intercoil lengths, the primary mode of deployment is as a reconnaissance profiling tool. To measure the conductivity, the transmitter operator stops at the measurement station, while the receiver operator moves the receiver coil backward or forward until the meter indicates that the distance between coils is correct. Care must be exercised when aligning the coils, particularly when operating in the vertical dipole mode (coils in the horizontal plane). The sensitivity of coils to alignment is associated with the angle (Θ) between the secondary magnetic field and plane of the receiver-transmitter coils. Misalignment of the receiver-transmitter coils results in a cosine error in apparent conductivity. For the horizontal dipole (coils in the vertical plane), the magnetic field is orthogonal to the plane of the receiver coil. Misalignment of the coils in this case results in an error of cos Θ. For a vertical dipole, the magnetic field is approximately 45° to the horizontal. Hence, any misalignment of coils results in a larger error of magnitude cos(Θ + 45) (*10*).

INTERPRETATION

Surface GPR is somewhat limited in capability because of its site-specific performance. In previous attempts at detecting subsurface cavities (*2-3*), poor radar performance was attributed to (1) high water content in the soil and (2) the presence of significant amounts of clay in the overburden. Water and clay tend to increase the dielectric constant and overall conductivity. The effect of these two factors is to increase the attenuation of electromagnetic energy.

Another concern is that most broadband GPR antennas, such as the 80-MHz antenna used in this study, have little directionality. As a consequence, the graphic image represents a transient response averaged over an area larger than the antenna. Additionally, the lack of shielding in the 80-MHz antenna is expected to result in leakage of some electromagnetic energy. These problems tend to degrade the quality of the radar record. The most favorable conditions for good GPR response, in this mode of operation, occur when the radar antenna is towed at a uniform rate on a flat bedrock surface and where the water table is below the depth of electromagnetic penetration. The Galena site, with shallow workings and sparse vegetation on the surface, appeared to be a candidate for successful demonstration of the GPR method.

The inductive electromagnetic technology also has problems when highly conductive ground prevails. At high conductivity values (in excess of 3,000 mmho/ft) the quadrature component of the received magnetic field is no longer linearly proportional to the apparent conductivity; i.e., the induction number is not small. At low values of conductivity (less than 3 mmho/ft), it becomes difficult to magnetically induce current into the subsurface. Any difficulty at the Galena site would probably be attributed to the latter case. Providing that terrain conductivity can be measured, it is the lateral variations of these electrical properties that form the basis of interpretation.

In this investigation, GPR data were collected over both undisturbed and mined areas. Figure 8 depicts the locations of GPR surveys completed over suspected abandoned mine voids in the Galena area. The procedure involved recording a typical time-distance GPR field profile over an unmined area (fig. 9). Radar profiles were calibrated in nanoseconds (ordinate) as a function of increasing distance (abscissa). The horizontal scale depends on the towing speed. Since a constant towing speed over rough terrain can seldom be maintained, a series of vertical distance lines are established to locate anomalies. These vertical lines locate field station markers set 25 ft apart. The 10 uniformly spaced, horizontal black lines (from 0 to 180 ns) are time indicators. The time between intervals depends on the full time window setting.

In figure 9, the total distance spanned is about 125 ft, with a time window of 180 ns. The thick band crossing the record at the top indicates the surface reflection. The multiple succession of black bands indicates the presence of varying lithology, or structural change at depth. For this record, the formation consists of interbedded limestone strata. The general continuity of these bands suggests that the limestone strata are continuous and horizontal. This also was verified from inspections of outcrops in the area.

Figure 10 gives several examples of GPR profiling over known mine voids. Multiple reflections are common features in all of these records. In comparison with the primary reflection from other strata, multiple reflections are recognized by their lower amplitude and somewhat discontinuous nature. Multiple reflections are caused by the transmitted pulse being re-reflected from a surface. For air-filled voids, the relatively strong velocity contrast between the rock (about 0.4 ft/ns) and air (about 1.0 ft/ns) results in guiding a significant portion of the energy within the void. Leakage back to the surface produces a first-order multiple, termed a "peg leg" by seismologists (fig. 11). The discontinuous and nonhorizontal character associated with the multiple reflections probably occurs from reflections off roof or floor rock. The interaction of multiple reflections with the primary reflection produces a complex wave train composed of the linear superposition of both types of reflections. In general, multiple reflections have a characteristic amplitude that is less than the primary, owing to attenuation and scattering. The roof of a void space is considered to be located directly below the first continuous reflector having a succession of multiples.

To establish the depth to one or more mine voids using monostatic GPR, it is necessary to convert from the standard time-distance GPR measurement to a distance-depth measurement. This conversion is made by forming the product of the electromagnetic interval velocity (V) and differential two-way travel time to the feature of interest. Since the bulk dielectric properties are usually not known a priori, assuming normal incidence and isotropic conditions, the velocity for the interval between the surface and mine-related feature is calculated based on previous

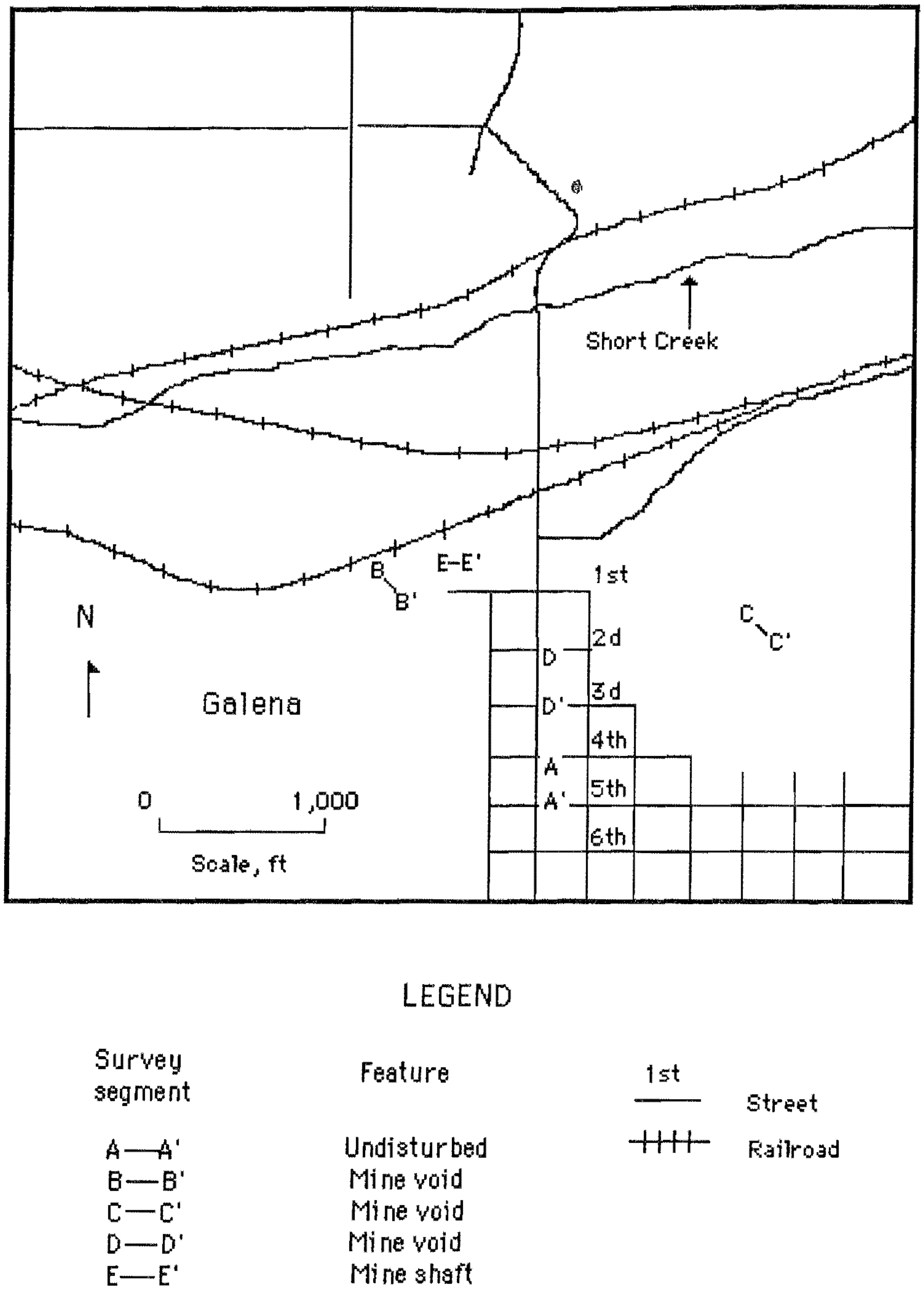

Figure 8.–Locations of ground-penetrating radar surveys conducted over mined and unmined areas in Galena area.

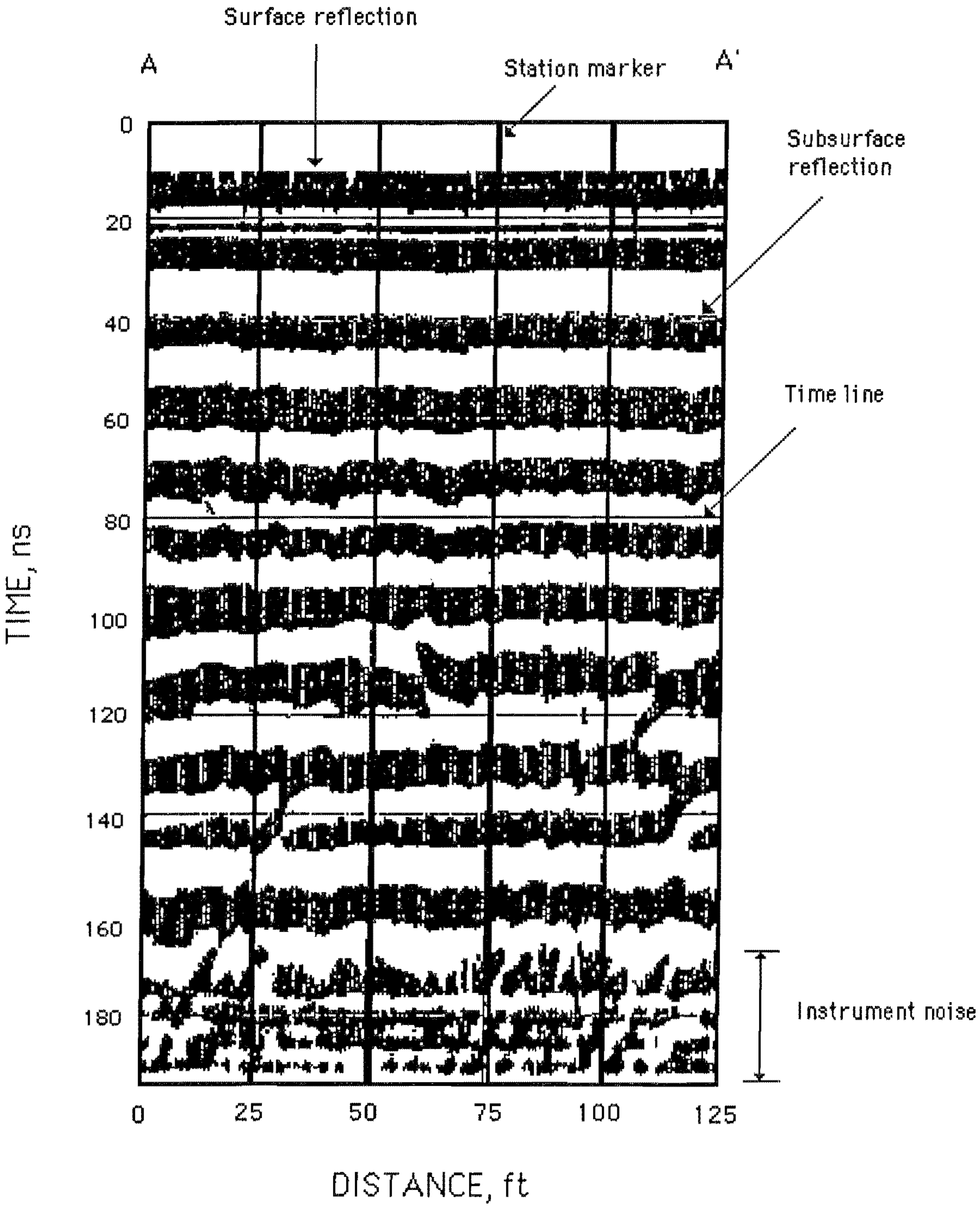

Figure 9.–Typical ground-penetrating profile recorded over undisturbed area. Horizontal continuity in reflection character is attributed to local horizontal stratification of Mississippian limestone. Acquisition parameters included an 80-MHz antenna, a 180-ns time window, positive polarity, 16 scans per second, and 100 lines per inch.

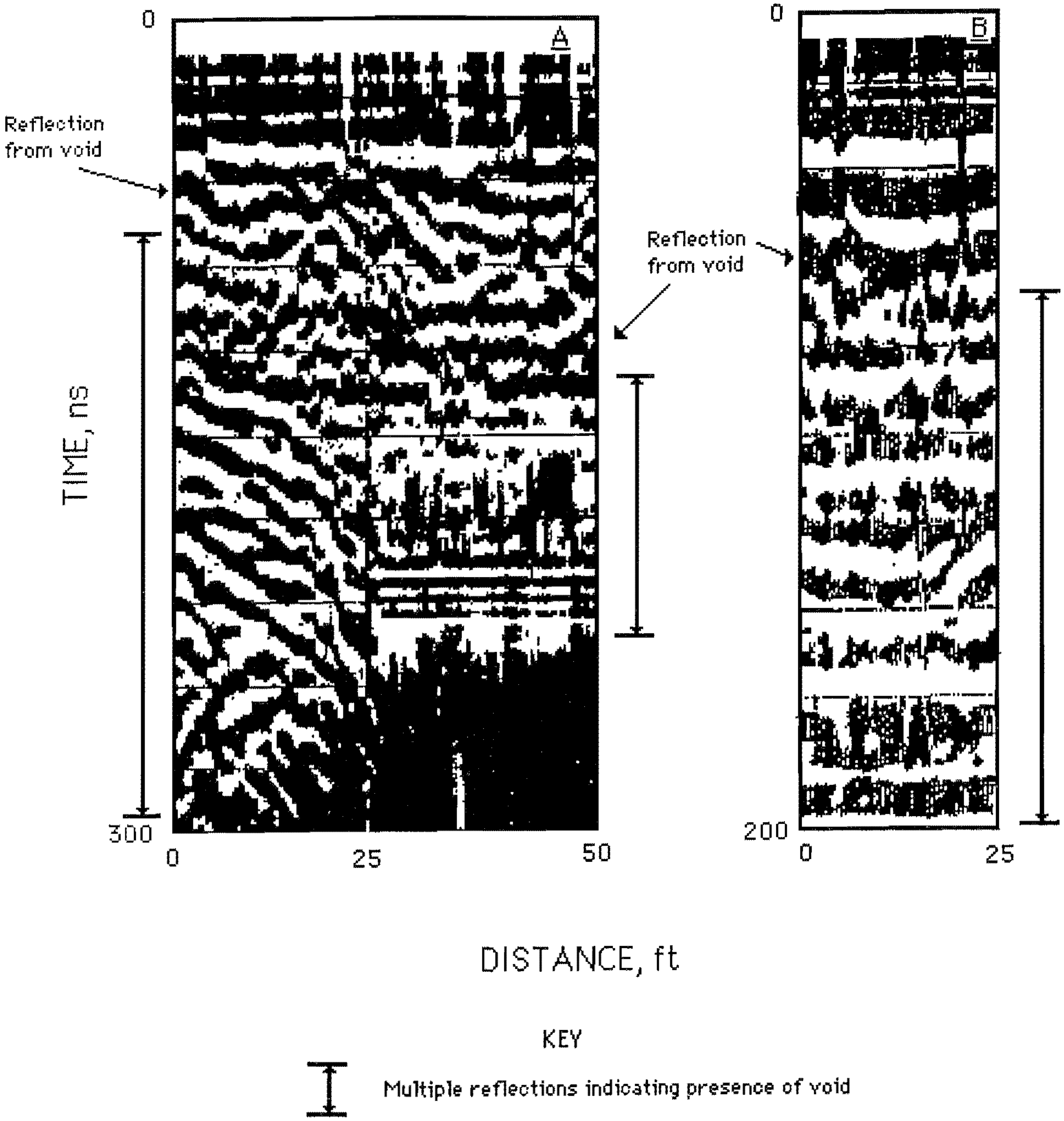

Figure 10.–Ground-penetrating response over known mine voids. Multiple reflections indicate relative position of mine opening for (A) profile segment B-B' and (B) profile segment C-C'.

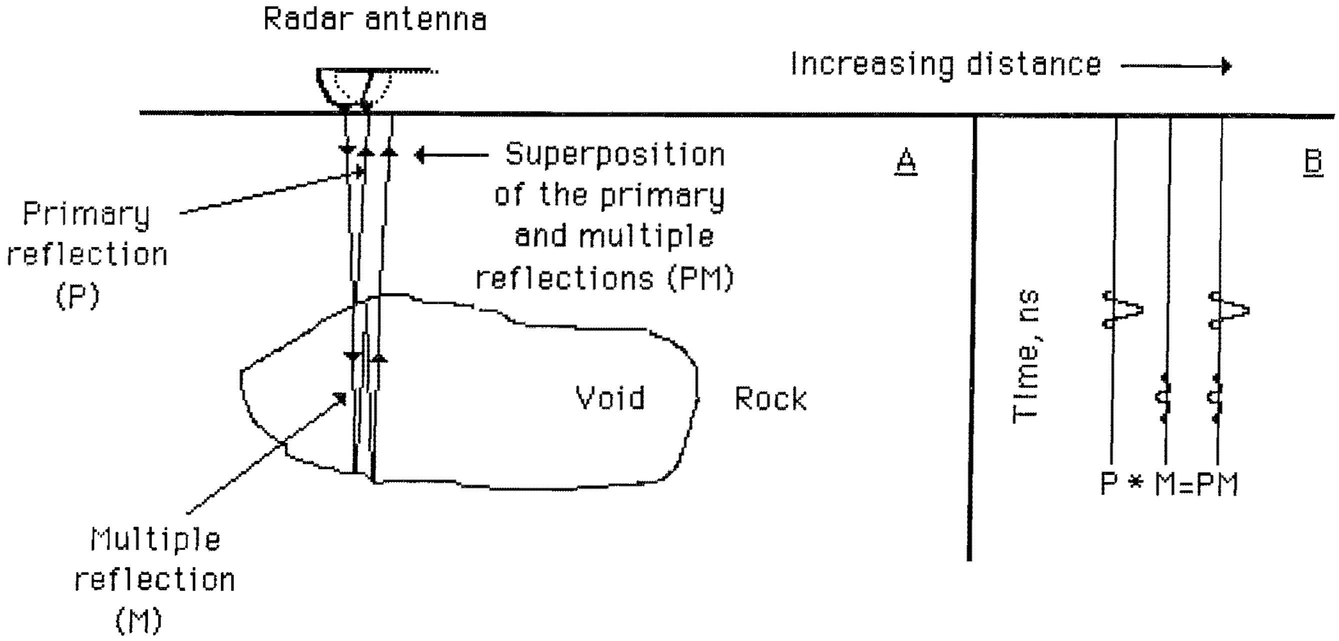

Figure 11.–Simplified propagation path of pulsed electromagnetic wavelet (A) and transient response of each propagation path segment (B). In P*M=PM, * denotes convolution operator.

knowledge of depth to a void in the study area and its associated travel time. This information is then combined with the two-way travel time determined from the GPR profile recorded while traversing over a void using the following formula:

$$V = 2h/t \tag{3}$$

where h = depth to void,

and t = differential time between surface reflection and reflection from void.

If the dielectric properties are known, then velocity of propagation can be calculated using equation 1. By rearranging equation 3 and substituting the apparent velocity and two-way travel time, the depth to the mine void can be determined.

The Bureau used an equally effective and less costly method by locating an exposed mine void and measuring its depth with a tape measure. This void was at a depth of about 15 ft and extended about 25 ft in plan view. An adjacent mine room opened at a depth of about 35 ft; the lateral extent could not be determined, since it was partially filled with water.

A 50-ft GPR traverse was initiated over both voids, resulting in the 300-ns full-scale record shown in figure 10A. While multiple reflections are evident throughout this GPR record, beyond 25 ft they appear only to a time of about 180 ns. The uppermost continuous band, occurring from 0 to 25 ft at about 75 ns, is interpreted as the mine roof reflection. Beyond 25 ft, it is not clear which reflection represents that from the void roof; however, the occurrence of multiple reflections clearly indicates the presence of a mine opening. While mine voids at depths as great as 35 ft can be detected, vertical resolution is seemingly lost as depth increases. It appears, however, that the GPR response may be used to indicate the relative depth of mine voids, one to another, based on the strength of multiple reflections. A reduction in the full-scale time window may enhance the GPR record, thus extending the interpretation to greater depths.

When the differential travel time from the surface to the void was combined with the measured depth using the expression given in equation 3, an interval velocity of about 0.5 ft/ns was calculated. This value is in general agreement with that given CH2M Hill report (0.55 ft/ns) (*9*). Combining this velocity value with the speed of light and rearranging equation 1 results in a dielectric constant of about 3.9. This value is somewhat lower, by about a factor of 1.8, than the published value given by Wait (*10*). It should be noted, however, that the dielectric constant given in the literature is not qualified by sample size, competency or the degree of relative saturation. A decrease in the dielectric constant could be expected, however, under highly weathered and unsaturated conditions, as characterized by the Galena study site. Other factors that could contribute to miscalculations are (1) selecting an incorrect travel time to a reflector and (2) incorrectly determining depth during the drilling operation.

Other features that could be interpreted from the radar profiling at the Galena site included a backfilled shaft, fractured zones, FM radio transmission, and overhead power lines. Each feature resulted in the characteristic GPR response depicted in figure 12. The responses associated with the backfilled shaft and fractures extend over

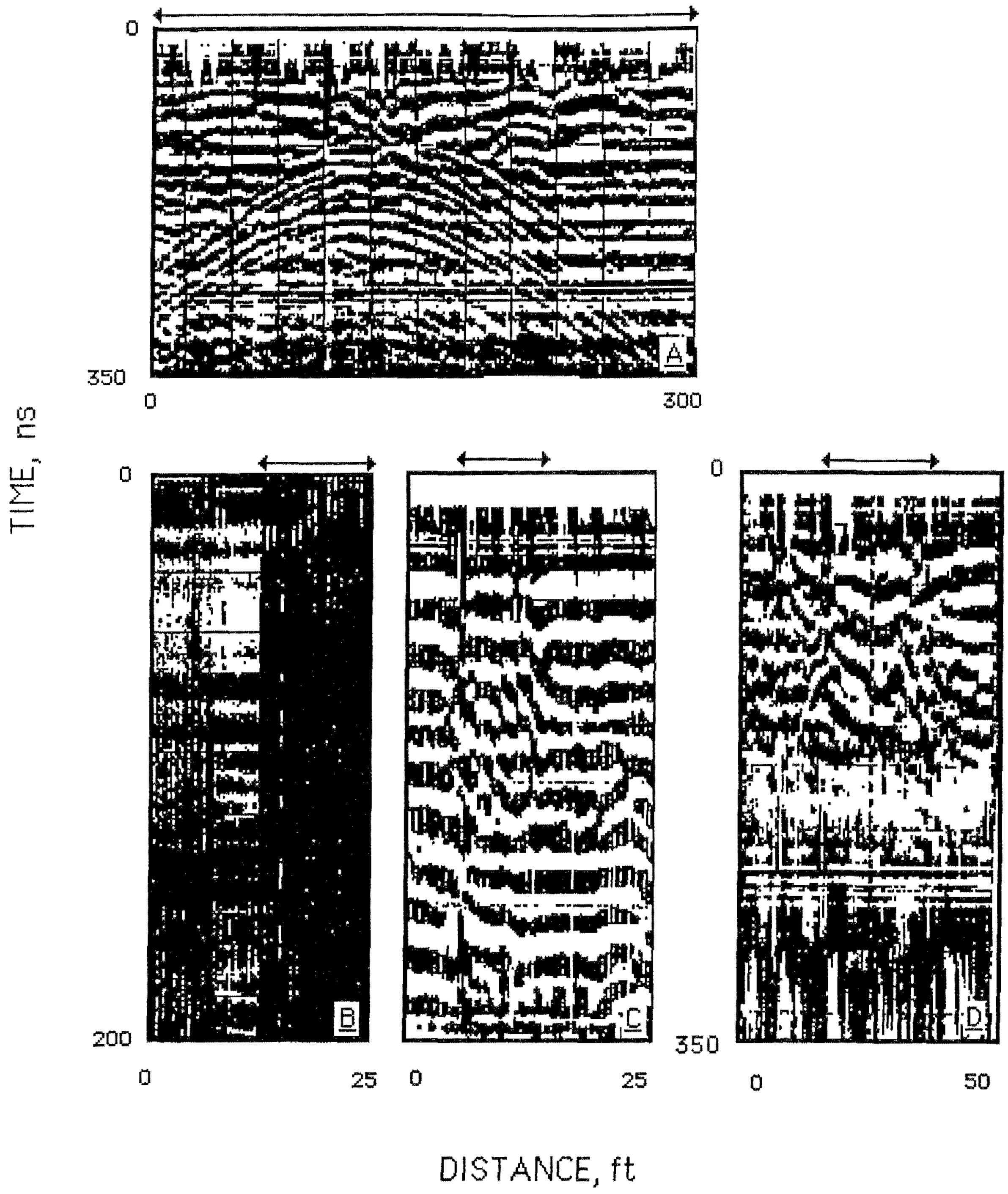

Figure 12.–Some cultural and structural ground-penetrating responses recorded while radar-profiling in the Galena, area. A, Overhead power line; B, FM transmission; C, fracture set; D, backfilled shaft. Arrows denote approximate extent of each feature.

distances of about 22 and 9 ft, respectively, while the horizontal extent of the FM carrier covers about 13 ft. Also, there appears to be limited information at or beyond a travel time of about 180 ns. The distance the FM carrier affects depends on the duration of transmission time. The effect from an overhead power line occurs at or below 200 ns, covering a distance of roughly 300 ft. The crest of the power-line response coincides with the passing of the radar antenna directly beneath it. Since the frequency response of the power line to the antenna represents roughly six orders of magnitude difference, the response is attributed to the induction of higher order harmonics.

FIELD RESULTS AND DISCUSSION

Locations of suspected mine openings were made using superimposed subsidence and subsurface mine maps (*1*). Since the GPR system was towed by a tractor, site selection was restricted to areas of existing roads or relatively flat terrain. The first site, within the Galena city limits, was selected because smooth road surfaces were indicated as traversing over a number of suspected mine openings, based on mine maps. These locations were also expected to be in an unsaturated state above the mine workings, but to a lesser degree, since the ground was covered by concrete, asphalt, and buildings. Figure 13 gives the relative position of survey line G-G' with respect to the position of abandoned voids existing below Mainstreet (State Highway 26). The first radar survey traversed Mainstreet in a north-south direction from the center of First to Fifth Streets. Since the city water main was located in the center and along the length of this road, care was exercised to survey between the centerline and curb. Field acquisition parameters included positive polarity, 100 lines per inch, 16 scans per second, and full scale of 200 ns. The complete length of this survey was about 1,200 ft, and it took less than 10 min. Cultural noise in the form of 60-Hz power lines rendered the inductive electromagnetic technique useless at this study site.

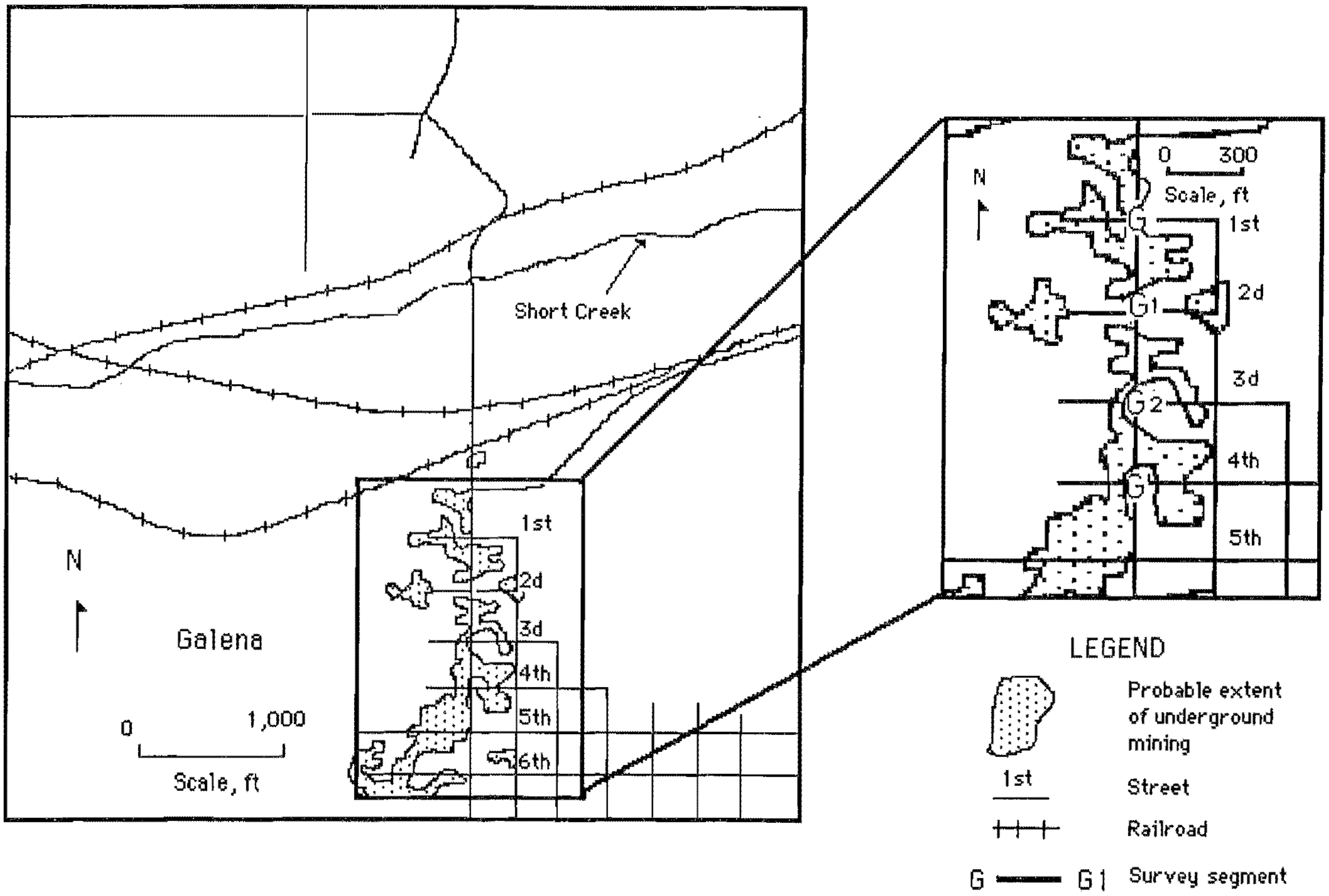

Figure 13.–Approximate extent of abandoned mine workings underlying Mainstreet (State Highway 26) study site.

Results given in figure 14 show that portion of the radar record collected between First and Second Streets. The full-scale time window was divided into 10 intervals of 20 ns. Noteworthy features in this profile include (1) horizontal limestone strata, (2) fractures, (3) a mine opening, and (4) subsiding strata. The interpretation of interbedded limestone is based on continuous horizontal reflections located at the north end between stations 3 and 4 (from 50 to 75 ft) and 10 and 12 (from 225 to 275 ft). Next, a series of nearly vertical fractures, positioned between stations 2 and 3 (from 25 to 50 ft), were detected. The first fracture crossed the complete time window. Two others terminated at about 120 ns. A feature of primary interest is suggested by the set of multiple reflections occurring below about 70 ns between stations 5 and 10 (from 100 to 225 ft). These multiple reflections indicate a mine void opening. The crest of the mine roof appears to be located below station 8 (175 ft) at 70 ns. If the estimated velocity of 0.5 ft/ns and the differential travel time are used, the depth to the void roof is about 20 ft. What appears to be a subsidence feature is indicated between 20 and 70 ns, between stations 6 and 10 (from 125 to 225 ft). It is characterized by a parabolic shape in an otherwise continuous horizontal reflector. This slumping of strata may be due in part to an adjustment of in situ stress or degradation of roof conditions. Another interpretation of this feature is that this represents a backfilled shaft, based on the response given in figure 12. The lateral extent over which this anomaly exists, however, favors the former interpretation.

Figure 15 depicts a portion of the next 300 ft of the complete GPR record of the survey along Mainstreet, survey segment G1-G2, between stations 14 and 24. This section shows no indication of faulting. There appears to be another void, however, indicated in the vertical record between 75 and 160 ns and horizontally between stations 15 and 21 (from 350 to 500 ft). The crest of this void also appears to be associated with subsiding strata or a backfilled shaft. Again, this is indicated by the parabolic reflecting horizon, between stations 19 and 21 between 30 and 50 ns. While no drilling information was available to verify these interpretations, the position of these voids agrees with mine void locations indicated by the mine map of this area (fig. 13).

Another survey site, known as Hell's Half Acre, is located just northeast of Galena (fig. 16). This study site was characterized by a relatively flat surface, approximately 50 to 100 ft wide, probably used as a haulage road in previous mining operations. The surface consisted of residual cherty gravel a few inches in thickness. Water measurements in adjacent mine shafts revealed that the water table occurred at a depth of roughly 50 ft. This also was confirmed in an earlier Bureau report (*1*) and later by drilling. Again, the survey trend was in a north-south direction. The resulting radar profile was about 750 ft in length, with a 25-ft spacing between station markers. The field acquisition parameters were the same as in the Galena survey except for the time window. In this case, a 350-ns window was employed.

The first segment, H-H1, of the GPR record is shown in figure 17. Station numbers begin at 2 and end at 12, covering approximately 250 ft. Perhaps the most outstanding feature in this profile is the horizontal continuity of reflections between stations 5 and 6 (from 100 to 125 ft), indicating the presence of a mine pillar. The horizontal reflections in this figure, however, are not as uniform as those at the Mainstreet study site, most likely because of the rough surface over which the antenna was towed. Also, areas to the south and north of this pillar are characterized by discontinuous reflections between a time of 0 and about 140 ns. This is presumably due to the highly fractured nature of the strata overlying the void. Utilizing a 300-ns time window resulted in compressing interpretable information; thus, it was not possible to determine the exact position of the void roof. A mine opening is inferred between stations 2 and 5 and to the south side of this pillar, based on a combination of multiple reflections from the void, reflections from the fractured roof, and the disturbed nature of the roof rock. The parabolic reflectors indicated below stations 4, 5, and 9 indicate either (1) a velocity pullup in response to changing dielectric properties by an increased stress gradient and crack closure or (2) a static problem associated with travel-time changes in response to fluctuations in topography. The latter is unlikely, however, since only minor topographic changes were observed along the survey line.

The GPR interpretations at the Hell's Half Acre field site were supported by exploratory drilling. The first test hole, drilled at station marker 4, confirmed the presence of a mine opening at a depth of about 30 ft. By combining the depth, velocity, and time to the surface reflection, and rearranging equation 3, the reflection time to the void was expected at about 140 s. Establishing which reflection shown in figure 17 corresponded to the void was not obvious. The second hole, spud about 10 ft north of station 6, was drilled to a depth of about 60 ft and gave no evidence of a void. This drill hole confirmed the interpretation of a pillar, and it was also useful in establishing the depth to the water table, about 50 ft. A third borehole drilled about 5 ft south of station marker 6 intersected a void at a depth of 35 ft. Although drill logs or mine maps were unavailable for the remaining 450 ft of record, a high degree of confidence in the geophysical interpretation was based on the previous drill records from this site and the confirmed results found at the first study site. Underground rooms were indicated beginning at station 7 and ending at station 22 (from 150 to 600 ft). Again, the lateral position of the mine voids was best located (fig. 18) by first noting the position of pillars.

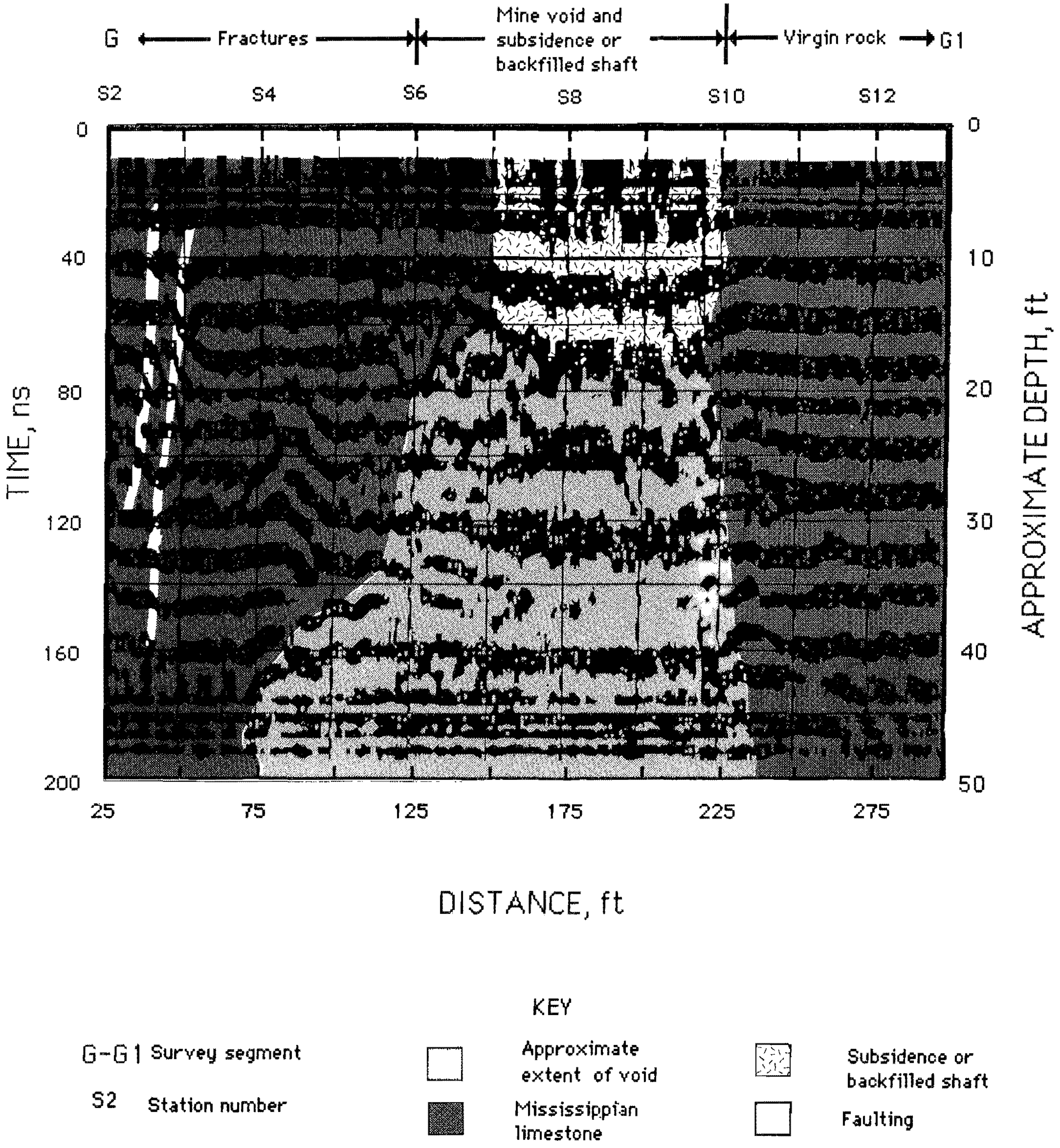

Figure 14.–Profile segment, G-G1, of north-south ground-penetrating radar record collected along Mainstreet (State Highway 26). Noteworthy features include a mine opening, a backfilled shaft (or subsidence feature), and fractures.

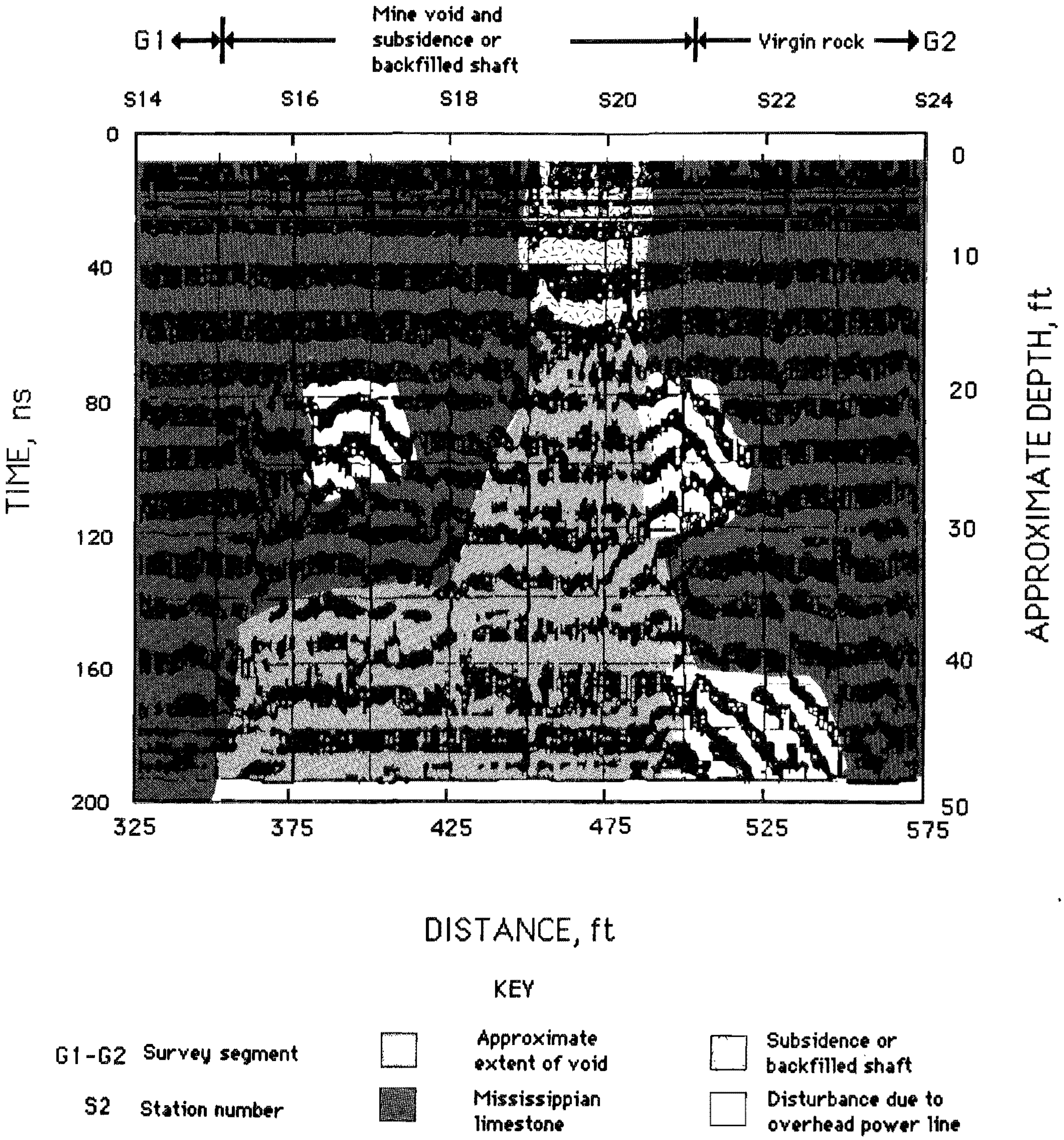

Figure 15.–Profile segment, G1-G2, of the north-south ground-penetrating radar record collected along Mainstreet (State Highway 26). Noteworthy features include a mine opening, a backfilled shaft (or subsidence feature), fractures, and electromagnetic disturbance.

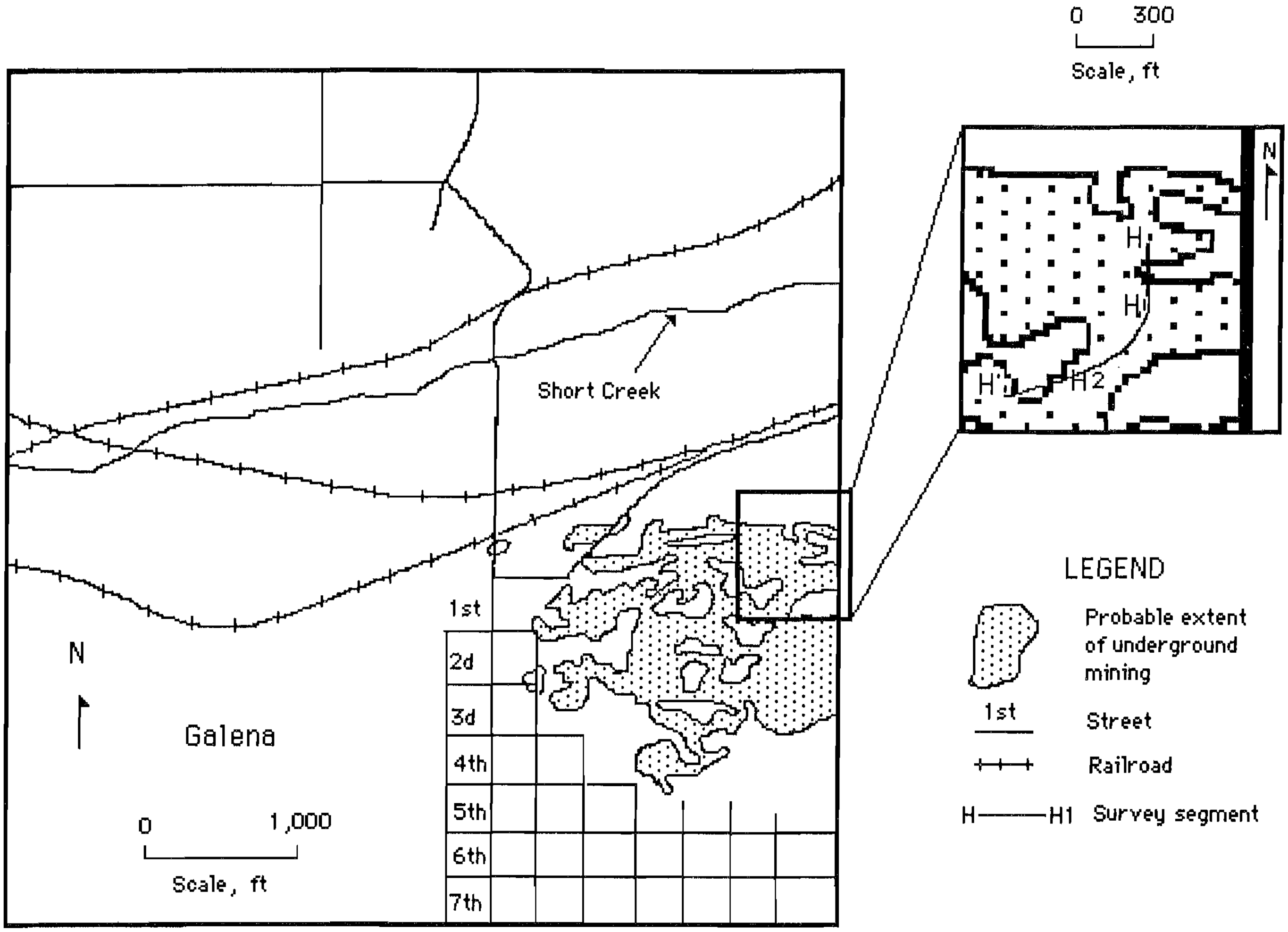

Figure 16.–Approximate extent of abandoned mine workings underlying Hell's Half Acre study site.

The inductive electromagnetic equipment was deployed along the same north-south traverse in the Hell's Half Acre area, but the survey included only a portion of the survey segment H-H1. Conductivity readings (millimho per foot) took about 1 min each and were observed at 5-ft increments, with a total of four between each station marker. The electromagnetic response for both horizontal and vertical dipole modes, with a 32.8-ft intercoil spacing, was plotted as a function of distance in figure 19. Conductivity values for the horizontal dipole were essentially constant and equal to roughly 1.67 mmho/ft (6,430 ohm-ft) between stations 2 and 5 (from 25 to 100 ft). The uniformity in measurements was attributed to background conductivity of the limestone. The slight decrease in conductivity, to 1.31 mmho/ft (8,203 ohm-ft), between stations 5 and 6 (from 100 to 125 ft) was due to the pillar. The effective exploration depth in the horizontal dipole mode was roughly 49 ft. For the vertical dipole mode, the electromagnetic energy penetrated beyond the mine void roof. Changes in thickness of the overlying rock should occur as fluctuations in conductivity, as was detected between stations 2 and 5. The general response of the vertical dipole survey is similar to a simple model where a traverse is conducted over a vertical dike. The symmetric nature of the negative anomaly suggests that the pillar is symmetric and vertically oriented. The negative response occurring over the pillar was due to current flow in the pillar, as if it were in free space. The anomaly, in this case, was large enough to result in apparently negative excursions. Since the inductive electromagnetic system used does not have a polarity reversal switch, these conductivity values appeared as zero conductivity.

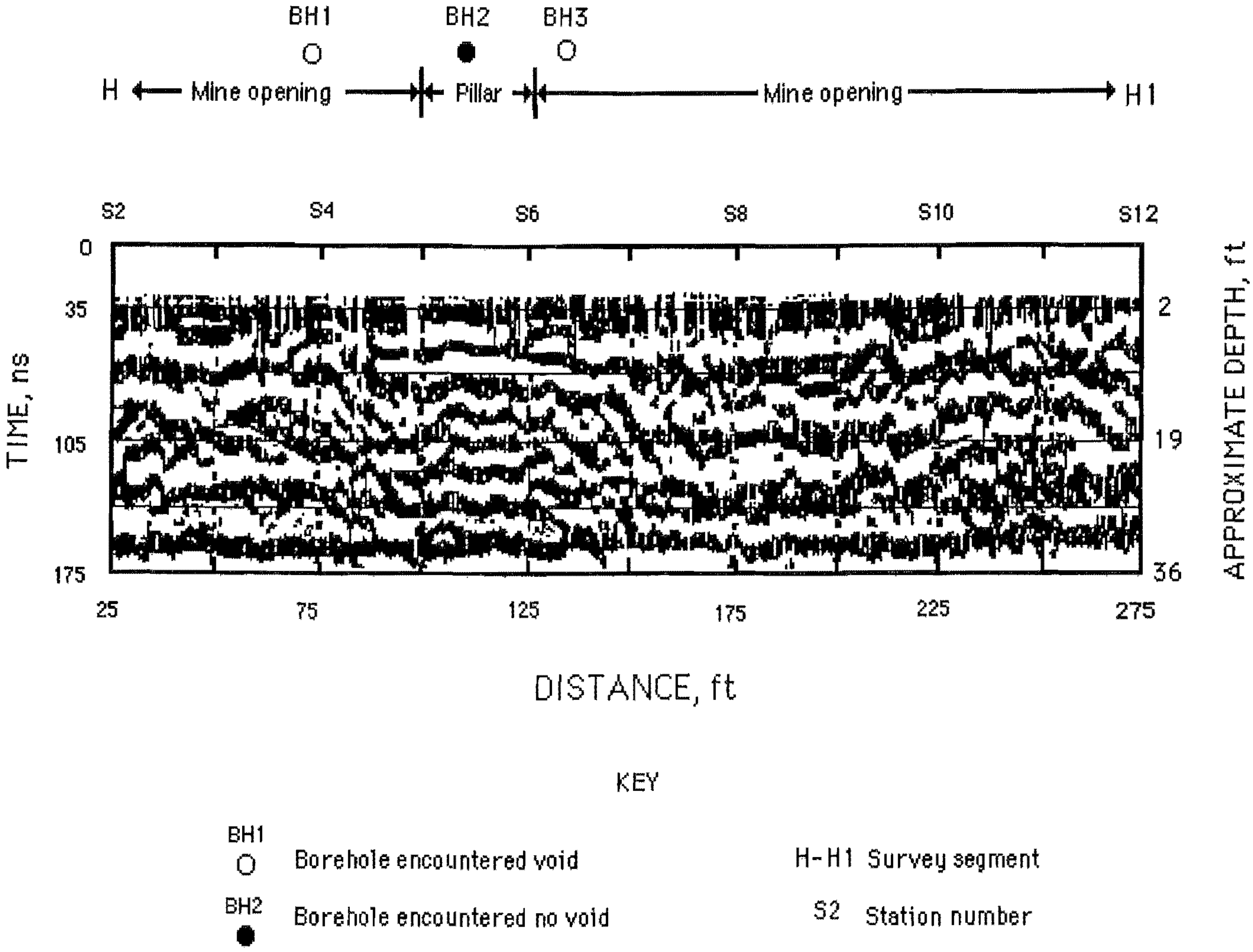

Figure 17.–Profile segment, H-H1, of ground-penetrating radar record collected at Hell's Half Acre study site. Noteworthy features include two mine voids and a pillar.

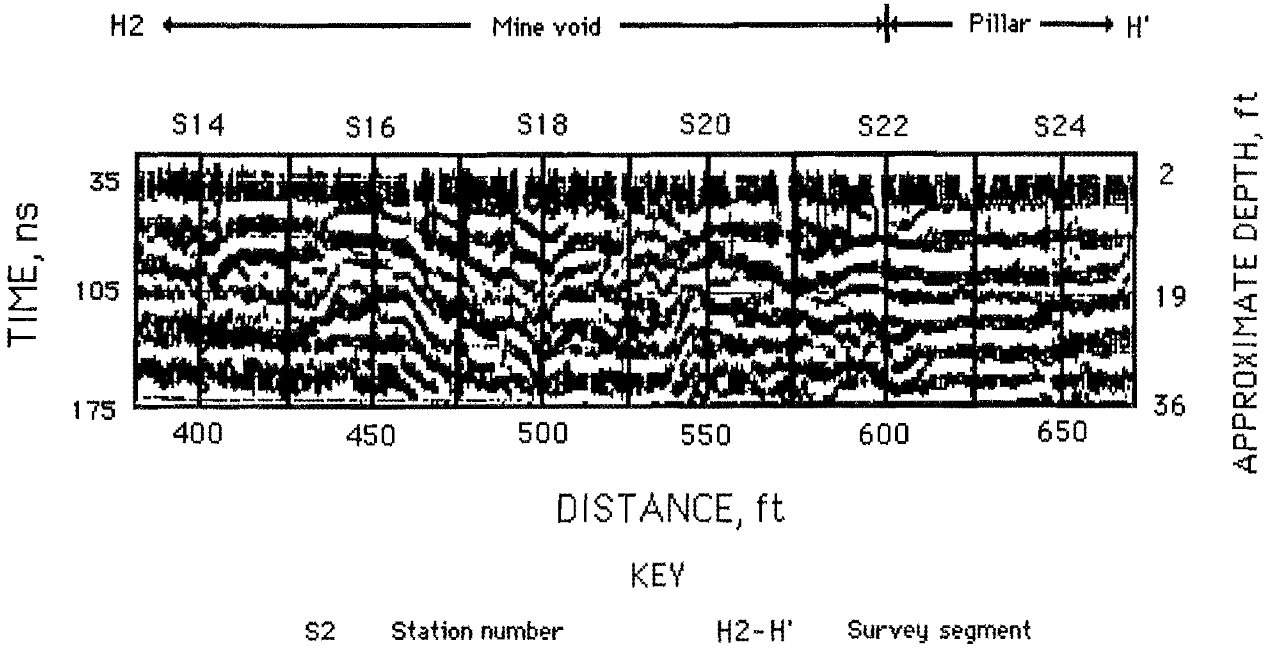

Figure 18.–Profile segment, H2-H', of ground-penetrating radar record collected at Hell's Half Acre study site. Noteworthy features include a mine void and a pillar.

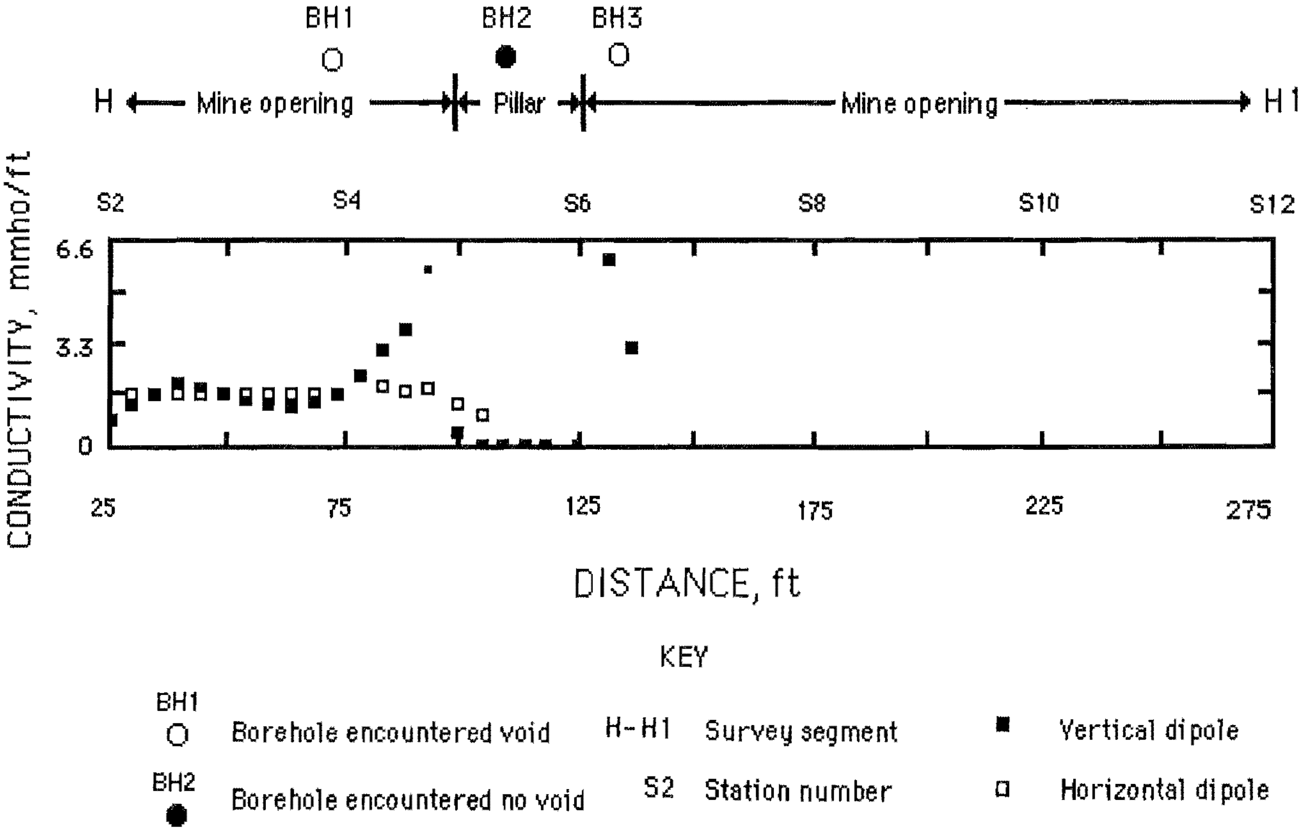

Figure 19.–Profile segment, H-H1, of inductive electromagnetic survey collected at Hell's Half Acre study site.

CONCLUSIONS

The application of GPR and inductive electromagnetics for delineating hazardous abandoned mine openings was demonstrated at the Galena, KS, area. The interpretation of subsurface mine features, such as voids and pillars, was confirmed by either mine maps or exploratory drill records at both study sites. While, in principle, the GPR method can be used to accurately determine the depth to an abandoned mine opening, the site-specific nature imposes constraints in field application. The following observations should be considered when planning future investigations in the Galena mining area.

1. The lateral extent of mined and unmined areas can be distinguished to depths of about 35 ft based on the continuity of reflections in the GPR records. Continuous reflections are useful as an indicator of an undisturbed zone, while multiple reflections signify a mine opening.
2. The shallower voids result in stronger and more multiple reflections, with time. The duration with time of multiple reflections can provide a qualitative indication as to the relative position of voids. The longer time duration of multiple reflections indicates relatively shallow voids. Conversely, multiples that occur over a shorter time period indicate a relatively deeper void.
3. There appears to be a limiting depth criteria for accurate depth determinations. In the Galena area, for workings at or beyond a depth of about 20 ft, it was difficult to determine the corresponding mine roof reflection. This precluded an accurate travel-time assessment and consequent depth determination. This may be in part attributed to the larger time-scale window used while radar-profiling over the deeper mine voids.
4. The transition from surveying on pavement to surveying on an essentially gravel road, despite the flat topographic expression, resulted in degrading the quality of the GPR record. Otherwise horizontal reflections from horizontal subsurface strata became hummocky, but remained continuous. It is expected that radar records recorded over rougher terrain, or where changes in local topography exist, would require extensive data processing, i.e., static corrections and migration, decreasing the simplicity of the overall GPR system employed during this study.
5. The inductive electromagnetic conductivity profiles provided corroborative information with respect to the lateral extent of mined and unmined areas. The penetration of electromagnetic energy to depths above a void can provide rapid reconnaissance for establishing background conductivity (or resistivity) information. In turn, this is useful for determining whether the GPR method can be expected to penetrate to a desired depth.
6. Both of the electromagnetic techniques were shown to be affected by cultural features such as an active FM transmission tower, overhead power lines, and buried utilities.

When the aforementioned effects are recognized and compensated for, the GPR and inductive electromagnetic results show feasibility for detecting and delineating mine voids and other structural features at shallow depths in media having contrast in electrical properties.

REFERENCES

1. McCauley, J. R., L. L Brady, and F. W. Wilson. A Study of Stability Problems and Hazard Evaluation of the Kansas Portion of the Tri-State Mining Area (contract J0100131, KS Geol. Surv.). BuMines OFR 75-83, 1983, 193 pp.
2. Annan, A. P. Radar Sounding in Potash Mines, Saskatchewan, Canada. Geophys., v. 53, No. 12, 1988, pp. 1556-1564.
3. Moffat, D. L., and R. J. Puskar. A Subsurface Electromagnetic Pulse Radar. Geophys., v. 41, No. 3, 1976, pp. 506-518.
4. Morey, R. M. Continuous Subsurface Pulse Radar. Paper in Proceedings of Conference on Subsurface Exploration for Underground Excavation and Heavy Construction. ASCE (Henniker, NH), 1974, pp. 83-99.
5. Cook, J. C. A Study of Radar Exploration of Coal Beds (Teledyne Geotech). BuMines OFR 5-72, 1971, pp. 5-72.
6. Pilon, J. A. Applications of Ground Probing Radar in Permafrost Regions to Granular Deposits, Pipeline Right-of-Way and Frozen Core Dams. Abstract in Expanded Abstracts. Soc. Explor. Geophys., 1987, pp. 73-75.
7. Butler, D. L. Evaluation of Geophysical Methods for Cavity Detection at the WES Cavity Test Facility. U.S. Army Eng. Waterways Exp. St., Tech. Rep. GL-804, 1980, 125 pp.
8. Rubin, L. A., J. C. Fowler, and W. L. Still. New Sensing System for Pre-excavation Subsurface Investigation for Tunnels in Rock Masses (final rep., contract DOT-FH-11-8602). U.S. Dep. Transp., 1976, 12 pp.
9. CH2M Hill (Chicago, IL). Ground Penetrating Radar and Spontaneous Potential Surveys, Technical Memorandum; Galena. Subsite, Cherokee County Site (final rep., U.S. EPA contract 68-01-7251). EPA, 1988, 45 pp.
10. Wait, J. R. Geo-Electromagnetism. Academic (New York), 1982, 485 pp.
11. Slain, D. D., and J. P. Greenhouse. Case Studies of Geophysical Contaminant Mapping at Several Waste Disposal Sites. Paper in Proceedings of the Second National Symposium on Aquifer Restoration and Ground Water Monitoring Columbus, OH, (May 26-28, 1982) Univ. Waterloo, Ontario, Canada, 1982, pp. 299-315.
12. Stewart, M. T. Evaluation of Electromagnetic Terrain Conductivity Measurements for Detection and Mapping of Salt Water Interfaces in Coastal Aquifers. FL Water Resour. Res. Cent., Project Rep. (grant A-043-FLA), 1981, 95 pp.
13. Sinha, A. K., and L. E. Stephens. Permafrost Mapping Over a Drained Lake by Electromagnetic Induction Methods. Paper 83-1A in Current Research, Part A. Geol. Sur. Can., 1983, pp. 213-220.

INT.BU.OF MINES,PGH.,PA 29106