

# Differentiating Rooms and Pillars on Reflection Seismic Profiles: A Seismic Investigation of Two Abandoned Coal Mines

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## ABSTRACT

High-resolution compression-wave (p-wave) reflection seismic profiles were acquired across and in proximity to two abandoned underground coal mines in southern Illinois. One abandoned mine is in the O'Fallon area; the other is in Steelville area.

Reflection seismic data were acquired at the O'Fallon site as part of a geotechnical investigation prior to construction. The primary objective was to establish that the construction site had indeed been undermined. A secondary objective was to differentiate and map underground rooms and pillars if present, so that a mined-out void could be tested with an exploratory boring. This would enable geotechnical engineers to determine the exact depth to the coal seam and the current condition of the underground rooms. The exploratory boring confirmed the reasonableness of the seismic interpretations. It also established that the mined-out void (6 ft high at a depth of 185 ft at the site of the exploratory boring) was still essentially intact.

Reflection seismic data were acquired at the Steelville site in an effort to confirm the accuracy of existing abandoned mine maps. One long reflection seismic profile was acquired parallel to and approximately 150 feet from the edge of the abandoned underground coal mine (as per abandoned mine maps); seismic data were also acquired perpendicular to the edge of the abandoned mine, extending from what was mapped as previously mined ground onto what was denoted as non-mined. Previously mined ground (rooms and pillars) was readily differentiated from non-mined ground on the acquired compression-wave reflection seismic data. The interpretation of these data confirmed the reasonableness of the existing abandoned mine maps.

## INTRODUCTION

Abandoned underground coal mines can cause major problems for overlying infrastructure because of their propensity to collapse over time. They also affect, because of regulatory statutes and safety considerations, the design of proximal underground and open pit mine workings.

The most common hazard associated with abandoned underground coal mines is subsidence, which can impact surficial infrastructure. Such subsidence can be defined as the vertical displacement of a point on the ground surface.

Subsidence occurs not only directly above the excavated openings but also on the ground surface beyond the boundaries of the excavation. This zone of subsidence outside the area of excavation can be defined using the *angle of draw* which is defined as the angle between vertical line and the line drawn from the edge of the excavation to the point of zero surface subsidence (Figures 1 and 2). In most instances, the angle of draw is between 25 and 35 degrees, depending upon the strength of the overburden. The angle is lower for rigid overburden and higher for less rigid overburden. Abandoned underground mines also pose a hazard to new proximal underground and open pit mines, as illustrated by the Quecreek mine accident which occurred in southwestern Pennsylvania on June 24, 2002. In this incident, nine miners were trapped 250 feet below ground surface in a flooded underground coal mine in southwestern Pennsylvania. Flooding occurred when a flooded abandoned mine was

breached by new mine workings. Fortunately, the nine miners were able to seek shelter in an air pocket, and were rescued (through drilled vertical raisebore) after spending 3 days underground. The subsequent Mine Safety and Health Administration (MSHA) investigation concluded that flooding occurred because the old abandoned mine plans, used as a basis for development plans by the Quecreek Mining Company, were grossly inaccurate.

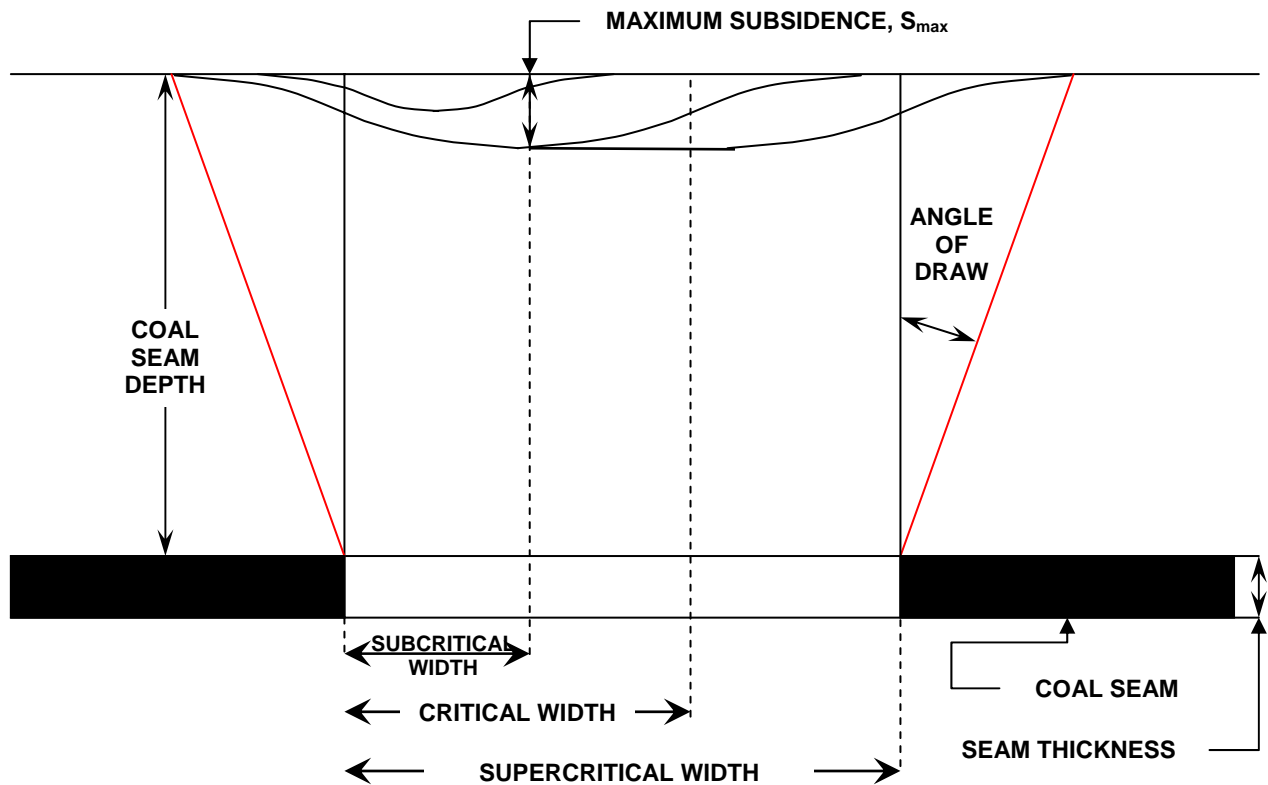


Figure 1. Subsidence above a coal seam. The maximum subsidence which can occur above an extracted coal seam is typically 50 to 60% of the original coal seam thickness. In order for the maximum subsidence  $S_{max}$  to occur, the extracted opening has to achieve its critical width and area.

Current federal regulations provide only a partial solution to the problem of how to avoid breaching old mine works. Regulations require that mining companies drill exploratory boreholes ahead of new development when approaching abandoned underground mines. The boreholes should be placed within 50 ft of abandoned mine workings based on existing abandoned mine maps, when such maps are certified by a registered engineer or registered surveyor, and within 200 feet of abandoned mines if the associated mine maps have not been certified. The problem is compounded because many abandoned mine plans are not only inaccurate but in many cases incomplete or nonexistent.

The following two case studies illustrate how reflection seismic data can be used to delineate from the surface the workings of old abandoned underground coal mines.

Reflection seismic data were acquired at two abandoned underground coal mines in southern Illinois (Figure 3). Abandoned Coal Mine #1 is located near O'Fallon Illinois; abandoned Coal Mine #2 is located near Steelville Illinois. The primary objective at the Coal Mine #1 site was to establish that the site had indeed been undermined. The secondary objective was to differentiate and map rooms and pillars, so that an exploratory boring could be drilled into a mined-out void. Seismic and boring control would enable geotechnical engineers to assess the integrity of the site and develop remediation plans prior to planned

construction. The objective at the Coal Mine #2 site was to confirm the reasonableness of existing abandoned mine maps by differentiating previously mined and non-mined areas on acquired seismic profiles, and comparing the interpretations to the existing mine maps. The confirmation of location of old mine openings would allow the new open pit mine for safe expansion of their pit boundaries.

High-resolution reflection seismic profiling has been previously used to identify and map abandoned underground mines (Gochioco, 2005). The technique is well-established, but not as commonly employed as its utility might suggest, because data acquisition, processing and interpretation require considerable expertise, and because the technique is expensive (per lineal foot) relative to other geophysical technologies. However, it is the only geophysical tool that can be used to differentiate rooms and pillars at depths in excess of 100 ft.

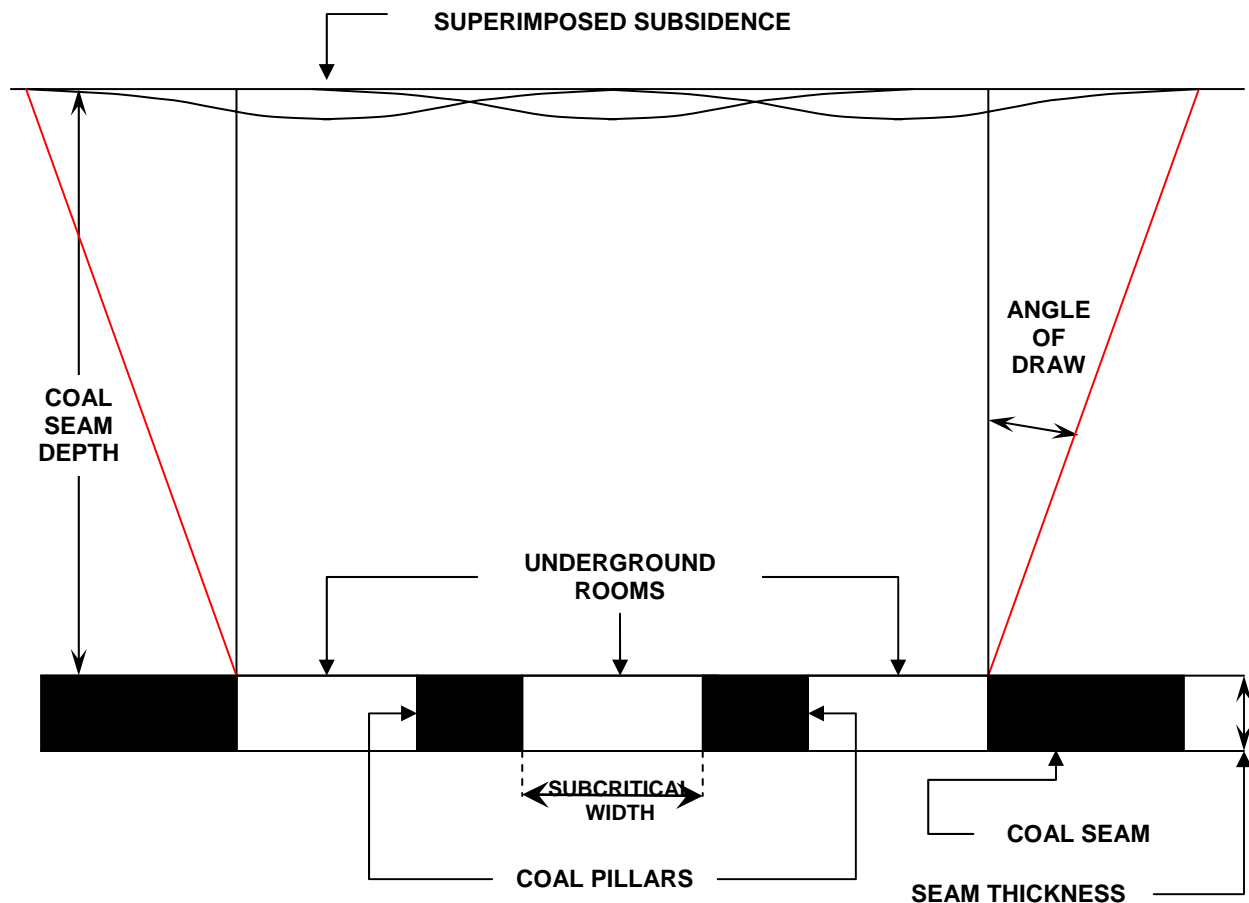


Figure 2. Superimposed subsidence above room and pillar coal mine. Total net subsidence caused by room and pillar mining methods is the combined effect of the superposition of individual subsidence troughs above each excavated rooms. An factor which decreases net subsidence above room and pillar mines related to the extensive use of rock supports such as rock bolts or rock dowels which are designed to prevent the excavations from collapsing while the mine is operative.

#### O'FALLON ILLINOIS SITE #1

Existing abandoned coal mine maps indicated the O'Fallon Illinois Site #1 had been undermined, and that the sizes and orientations of the rooms were somewhat irregular (Figure 4). Available historical data indicated the coal seam of interest was approximately 6 ft thick and at a depth of approximately 200 ft. It was anticipated that the mined-out voids were water-filled.

The current owners of the O'Fallon Site #1 wanted to develop the property. However, because there is no evidence or record of subsidence and because there were some concerns about the accuracy of the abandoned mine maps, the owners requested a reflection seismic investigation. The acquisition of seismic data seemed like a reasonable option because the mined-out rooms were water-filled, relatively shallow, and sufficiently high and wide to be imaged on compression-wave seismic data with a dominant frequency of 100 Hz.

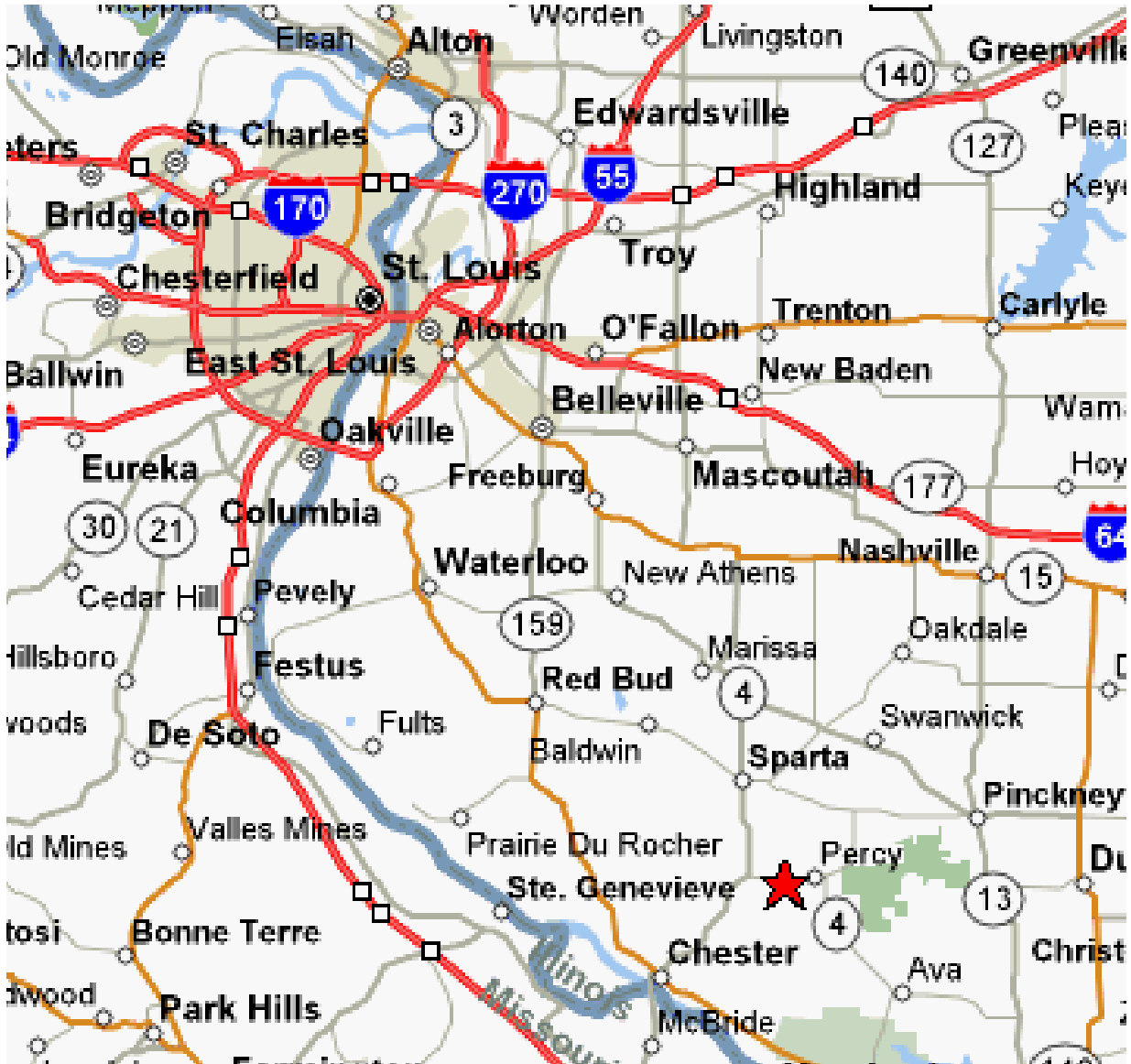


Figure 3: Map showing the locations of O'Fallon (Site #1; east of St. Louis on I-64) and Steelville (site #2; denoted by red star) study areas.

The primary objective of the O'Fallon seismic survey was to determine if the site had indeed been undermined. A secondary objective was to differentiate underground rooms and pillars (if present) so that a boring could be drilled into a mined-out room. The expectation was that accurate information about the coal seam (depth and thickness) and the underground voids (aerial extent and condition) would enable geotechnical engineers to design an appropriate foundation for planned structures.

The O'Fallon property is approximately 400 ft x 800 ft (Figure 4). In order to assess the site, eight parallel high-resolution reflection seismic profiles, spaced at 100 ft intervals, were acquired along 460 ft traverses that extended 30 ft on either side of the property (Figure 4). The seismic data were recorded using a 24-channel engineering seismograph. A source (sledge hammer and aluminum plate) and receiver (100 Hz vertically-polarized geophones) interval of 20 ft was used. The first and last source locations were 60 ft beyond the closest geophone; hence the reflection seismic profiles are slightly more than 460 in length.

The compression-wave seismic data were processed using a sequence consisting of:

1. Data conversion SEG2 to KGS-SGY
2. Geometry edit
3. Band pass filter 90-350 Hz
4. Mute air wave
5. First arrival mute
6. Mute ground roll energy
7. AGC scaling 50 ms window
8. CMP sort
9. Velocity analysis (via constant velocity stack)
10. NMO correction
11. Stretch mute
12. Stack (divided by the square root of fold)

Representative example seismic profile 11 is presented as Figure 6. Areas interpreted as rooms and pillars have been highlighted. The interpreted mined-out voids are characterized by a prominent event that represents the superposition (constructive interference) of the reflections from the top and base of the rooms. (The presence of such "bright spots" on 100+ Hz reflection seismic data was anticipated because the water-filled mined-out voids are slightly more than 1/8 of a wavelength thick.) The mined-out voids are also characterized by weak to prominent diffractions and velocity "pushdown" on the order of 5 ms. The magnitude of "velocity pushdown" is several ms greater than expected given the 6 ft thickness of the voids, and is attributed to minor stress fracturing of the rock overlying the voids and the attendant decrease in the compressional-wave velocity of the overburden.

A 200 ft boring was drilled on the basis of the interpretation of seismic profiles 11 (Figures 4, 5 and 6). The boring was located immediately to the east of trace # 225 on profile 11, and encountered a mined-out void as anticipated. The void was 6 ft in height and at a depth of 185 ft.

The borehole confirmed the accuracy of the seismic interpretation, and also provided the geotechnical engineers with the information they required in order to design an appropriate foundation. The reflection seismic study proved to be of significant utility to the property owners because it established that the area had been undermined and also enabled the engineers to place a borehole in a mined-out void. In the absence of seismic control, exploratory borings would probably have been sited on the basis of existing mine maps, which proved to be slightly inaccurate. If all exploratory borings had encountered intact coal, the engineers and property owners would have been placed in an uncomfortable situation. They would have had to make design choices without knowing with certainty whether the site had been undermined.

## **STEELVILLE SITE #2**

Knight Hawk Coal Company operates an open pit coal mine at Steelville Site #2. The coal seam is typically 8 ft thick and in the area of interest is at a depth of approximately 100 ft. The Knight Hawk open pit mine is expanding eastward toward an area shown as previously mined on abandoned mine maps (Figure 7 and 8). The abandoned mine reportedly employed room and pillar mining method. The mined out voids were below the static water table and were assumed to be water filled.

In an effort to validate the abandoned mine maps and ensure their open pit mine does not encroach within 200 ft of the abandoned underground mine, Knight Hawk Coal Company acquired a total of about 3800 lineal feet of high-resolution reflection seismic data along two traverses (Figure 7 and 8). The acquisition of seismic data at the Steelville site also seemed like a reasonable option because the mined-out rooms were water-filled, relatively shallow, and sufficiently high and wide to be imaged on compression-wave seismic data with a dominant frequency of 100 Hz.

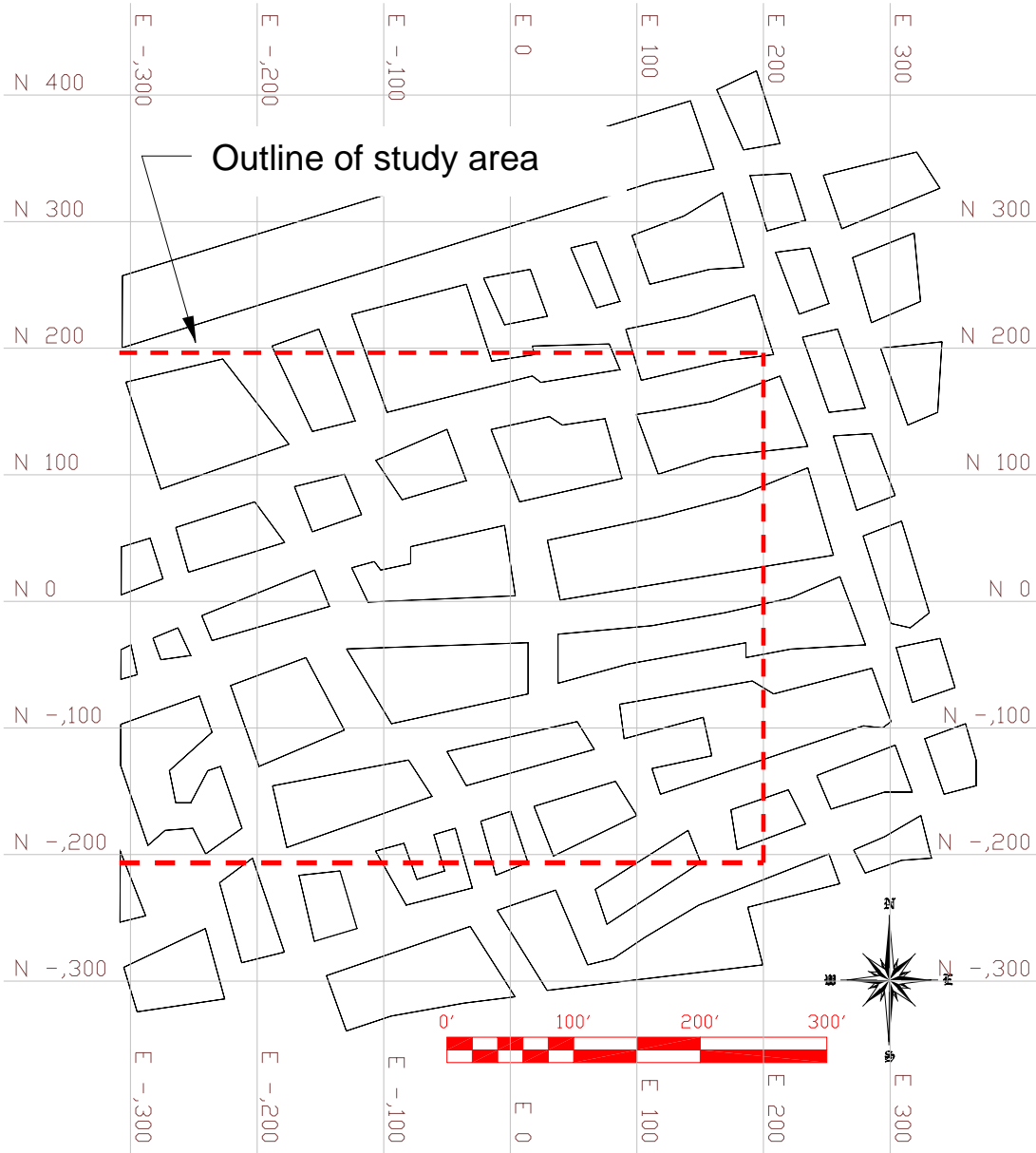
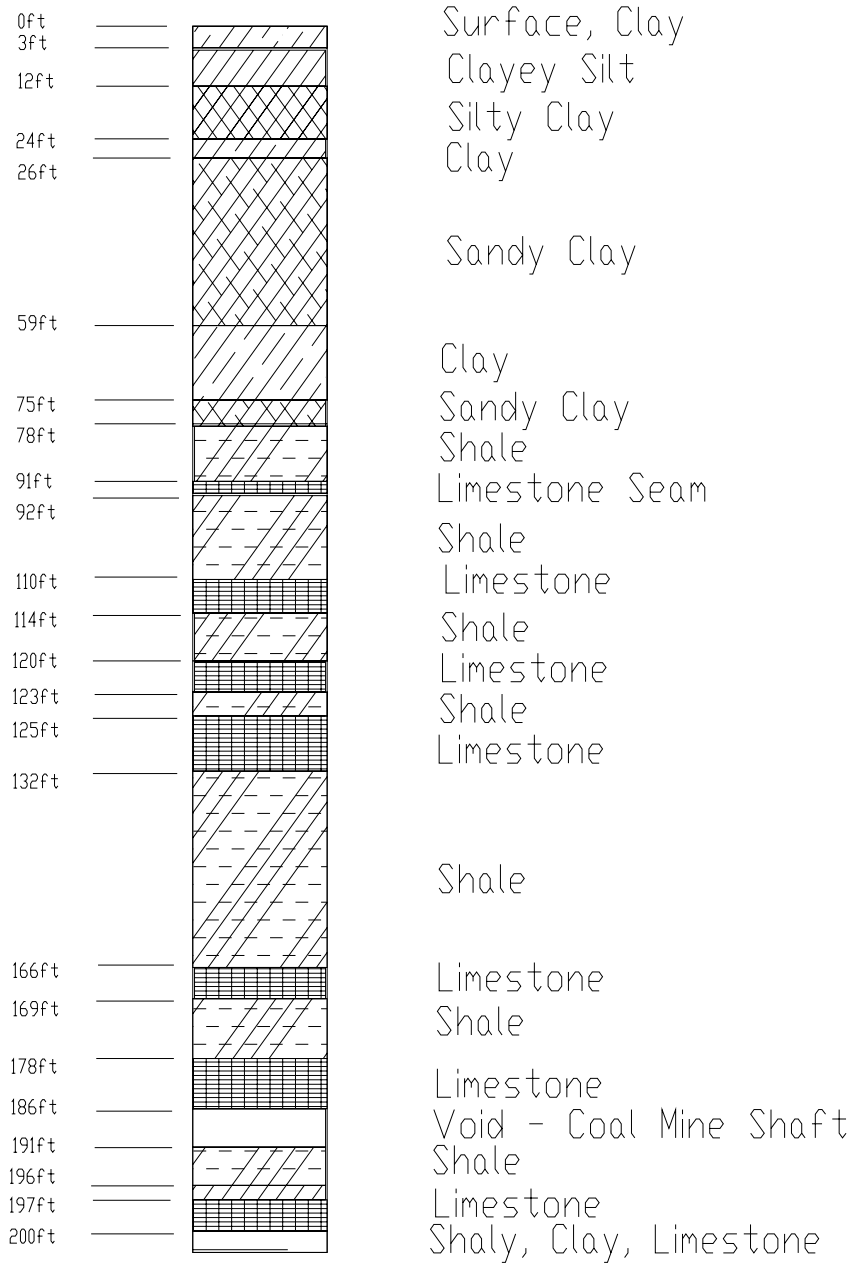


Figure 4. Outline of O'Fallon study area showing location of rooms and pillars as per abandoned coal mine map. Reflection seismic data were acquired to confirm that the site had been undermined and in an effort to select a suitable borehole location. Geotechnical engineers wanted to ensure the borehole encountered a mined-out void.

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Boring terminates at 202.2ft

Figure 5. Columnar section of the borehole at the O'Fallon Illinois Site #1.

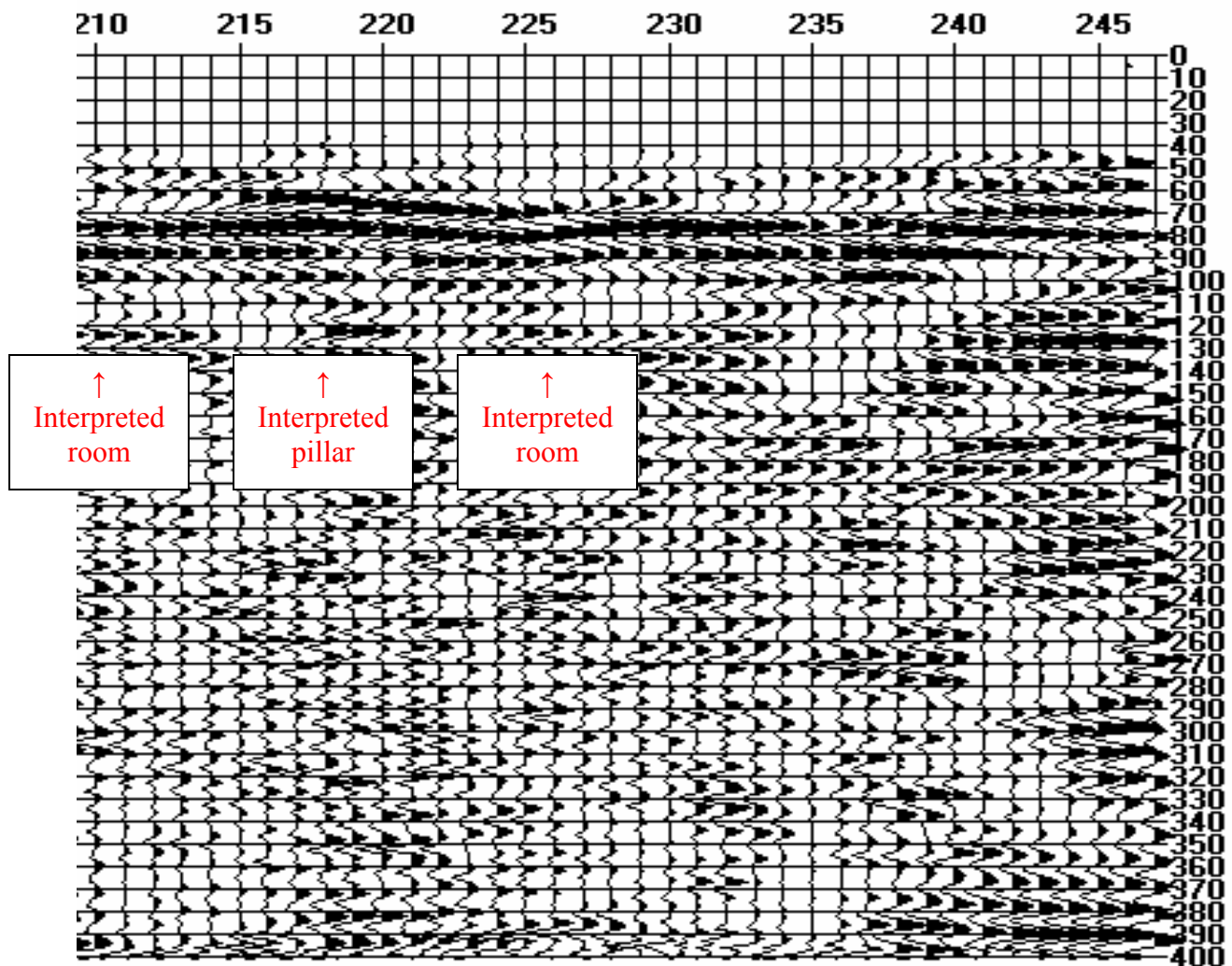


Figure 6: Example Reflection Profile #11, O'Fallon study site #1 (Figures 3 and 4). The horizontal axis denotes surficial station locations (at 10 ft intervals); the vertical axis is in milliseconds and denotes two-way travel time.

Traverse #1 was linear, approximately 600 ft in length, and extended westward from an area denoted as previously mined on abandoned mine maps to an area denoted as non-mined (Figure 7). Reflection seismic data were acquired along this traverse in an effort to assess the accuracy of the abandoned mine map and to establish criterion for differentiating the images of mined and non-mined ground on reflection seismic data.

Traverse #2 was non-linear, about 3200 ft in length, and approximately parallel to but at least 200 from the western edge of the abandoned mine (as per abandoned mine maps; Figure 8). This traverse also represented the planned eastern boundary of the open pit mine. Seismic data were acquired along this traverse because Knight Hawk Coal Company wanted to ensure their open pit mine does not encroach on previously mined ground.

The Steelville Site #2 high-resolution reflection seismic data were acquired and processed using the same equipment and parameters employed at O'Fallon Site #1. The seismic profile acquired along traverse # 1 is presented as Figure 9; a representative section of the seismic profile acquired along traverse #2 is presented as Figure 10. As anticipated, images of mined-out voids were identified on the eastern 400+ ft of profile #1, but not on seismic profile #2.

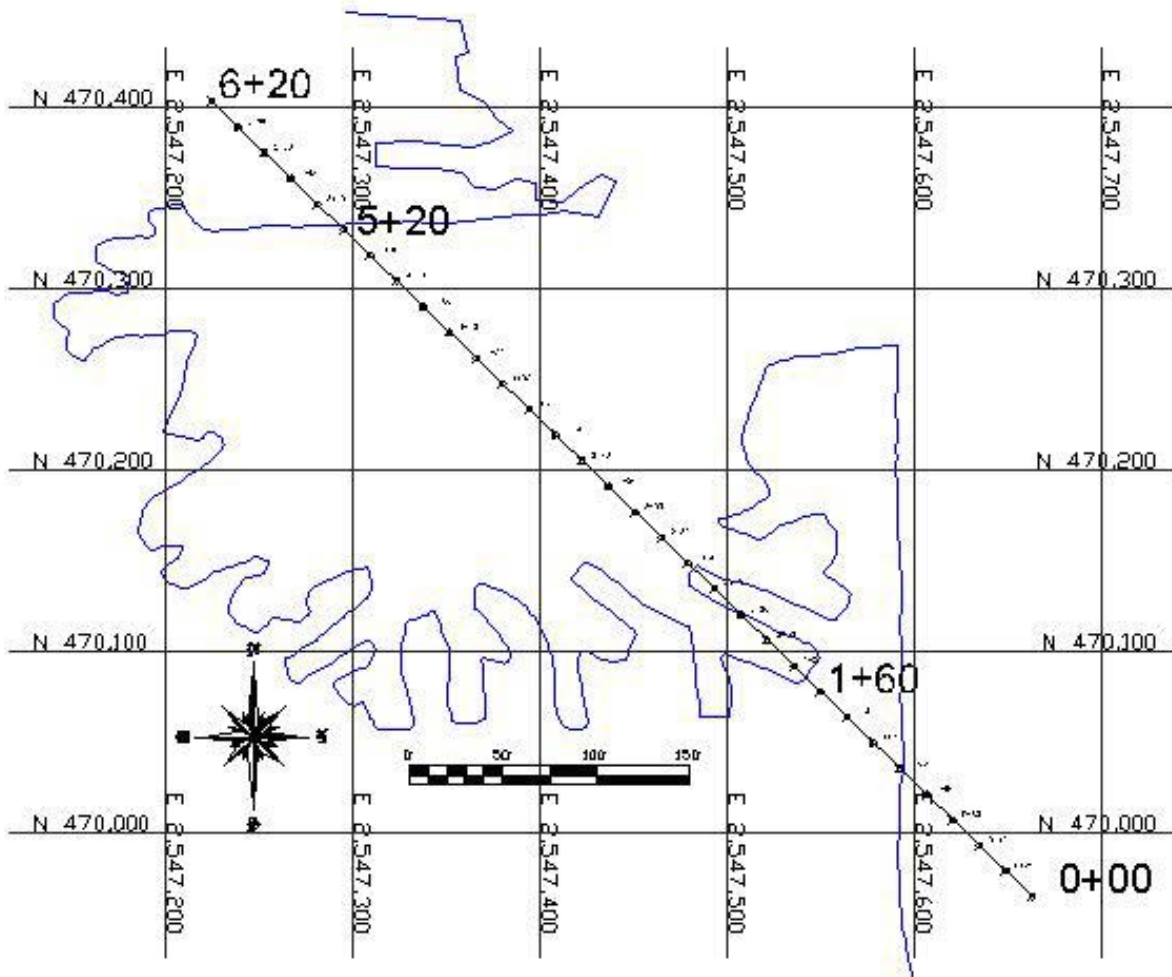


Figure 7. Map showing location of seismic traverse #1, Steelville Site #2 (Figure 3).

Areas interpreted as rooms and pillars have been highlighted on seismic profile #1. The westernmost void interpreted on the seismic profile is roughly coincident (within 20 ft) of the edge of the mined out area as denoted on the abandoned mine map (Figure 7). The interpreted mined-out voids are characterized by a prominent event that represents the superposition (constructive interference) of the reflections from the top and base of the rooms. The presence of such “bright spots” on 100+ Hz reflection seismic data was anticipated because the water-filled mined-out voids are slightly more than 1/8 wavelength in thickness. The mined-out voids are also characterized by weak to prominent diffractions and velocity “pushdown” on the order of 5 ms. The magnitude of “velocity pushdown” was several ms greater than expected given the 8 ft thickness of the voids, and is attributed to minor stress fracturing of the rock overlying the voids (and the attendant velocity decrease).

Reflection profile #2, in contrast to reflection profile #1, does not appear to image any mined-out voids. The high-amplitude event resulting from the constructive interference of the reflections from the top and base of water-filled rooms are not observed anywhere on this seismic profile. Similarly, “push-down” effects and chaotic reflection patterns, so characteristic of previously mined ground, are also noticeably absent on profile #2 supporting the interpretation that traverse #2 does not cross previously mined ground.

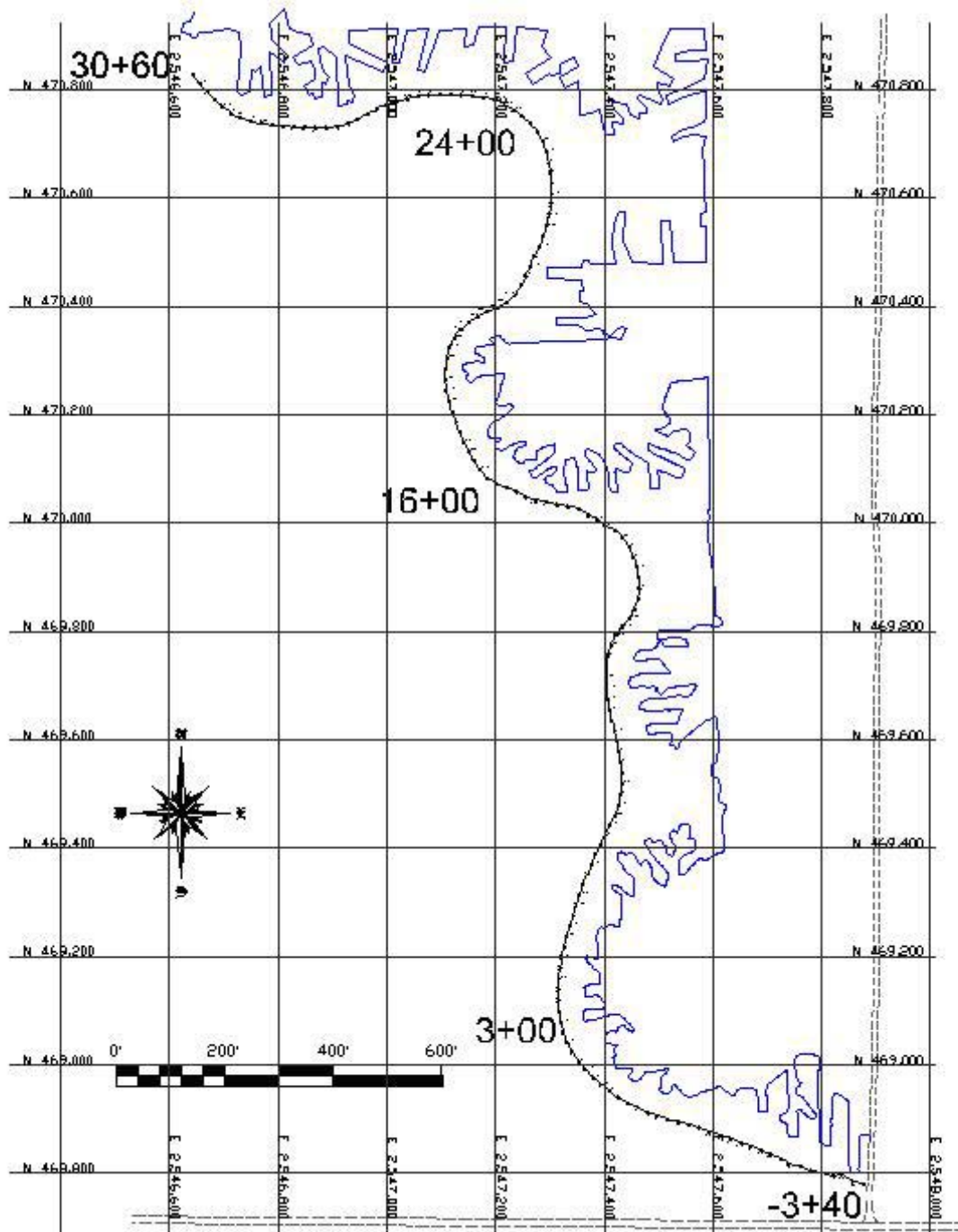


Figure 8. Map showing location of seismic traverse #2, Steelville Site #2 (Figure 3).

The reflection seismic study at the Steelville #2 site proved to be of significant utility to the Knight Hawk Coal Company because it supported the reliability of the abandoned mine maps (in terms of establishing the approximate boundary of the previously mined ground). More specifically, it gave the coal company increased confidence that the western margin of the open pit mine will not intersect the abandoned underground mine.

non-mined ← | → previously mined

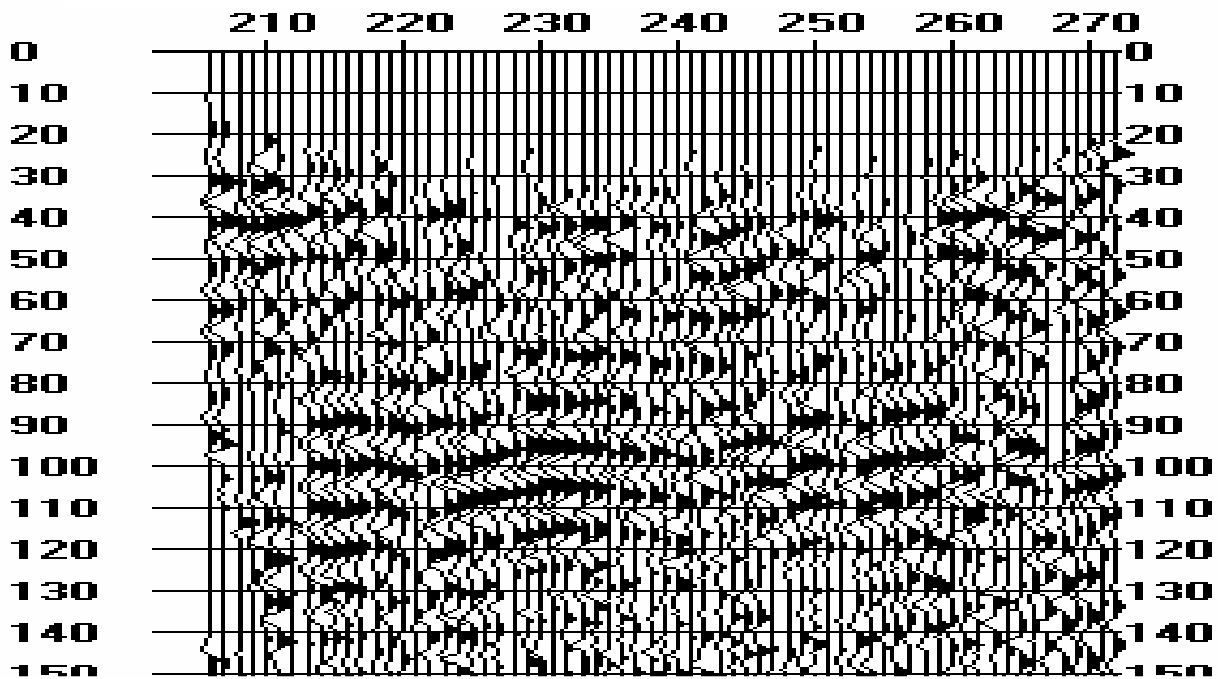


Figure 9: Interpreted version of seismic profile 1 (Figure 7). The trace interval (horizontal axis) is 10 ft. The vertical axis is in milliseconds and denotes two-way travel time. Trace 216 corresponds to surface station 5+00 (Figure 7). Evidence of underground mining activity is observed on seismic profile 1 on traces greater than 216. Previously mined ground is characterized by prominent diffractions, discontinuous reflections, variable reflection amplitudes and velocity pull-up.

## CONCLUSIONS

The O'Fallon and Steelville studies demonstrate that pillars and rooms can be differentiated on high-resolution compression-wave reflection seismic data under certain conditions. Mined-out voids at the O'Fallon and Steelville sites were characterized on 100Hz reflection seismic profiles by high-amplitude events that represent the constructive interference of the reflections from the top and base of the water-filled rooms. The voids were also characterized by weak-to-high amplitude diffractions and velocity "pushdown" on the order of 5 ms.

Although the mined-out voids on the O'Fallon and Steelville reflection seismic data sets are fairly conspicuous on the compression-wave data, it is important to recognize that they were "identifiable" only because conditions were appropriate. More specifically: 1) The rooms were water-filled; 2) The acquired seismic data had a dominant frequency on the order of 100 Hz; 3) Room heights were slightly in excess of 1/8 wavelength; and 4) Room widths were on the order of 1 Fresnel zone. The fact that the rooms were water-filled is extremely important in terms of resolution because compressional waves cannot be transmitted through air. Hence, if the rooms had been air-filled, the prominent interference even would not have been observed because a reflection from the base of the void would not have been generated. The frequency of the recorded seismic data is also critically important. For example, if the dominant frequency of the seismic data had been significantly less than 100 Hz, 50 Hz for example, appreciable tuning of the reflections from the top and base of the void would not have occurred. Similarly, if the room heights had been significantly less than 6 ft, 3 ft for example, appreciable tuning would not have occurred even on 100Hz data. Lastly, the voids were "interpretable" because their irregular widths were on the order of one Fresnel zone (60 ft at O'Fallon site; 45 ft at Steelville site). If room widths had been half their actual width, they probably could not have been confidently identified on the reflection seismic profiles.

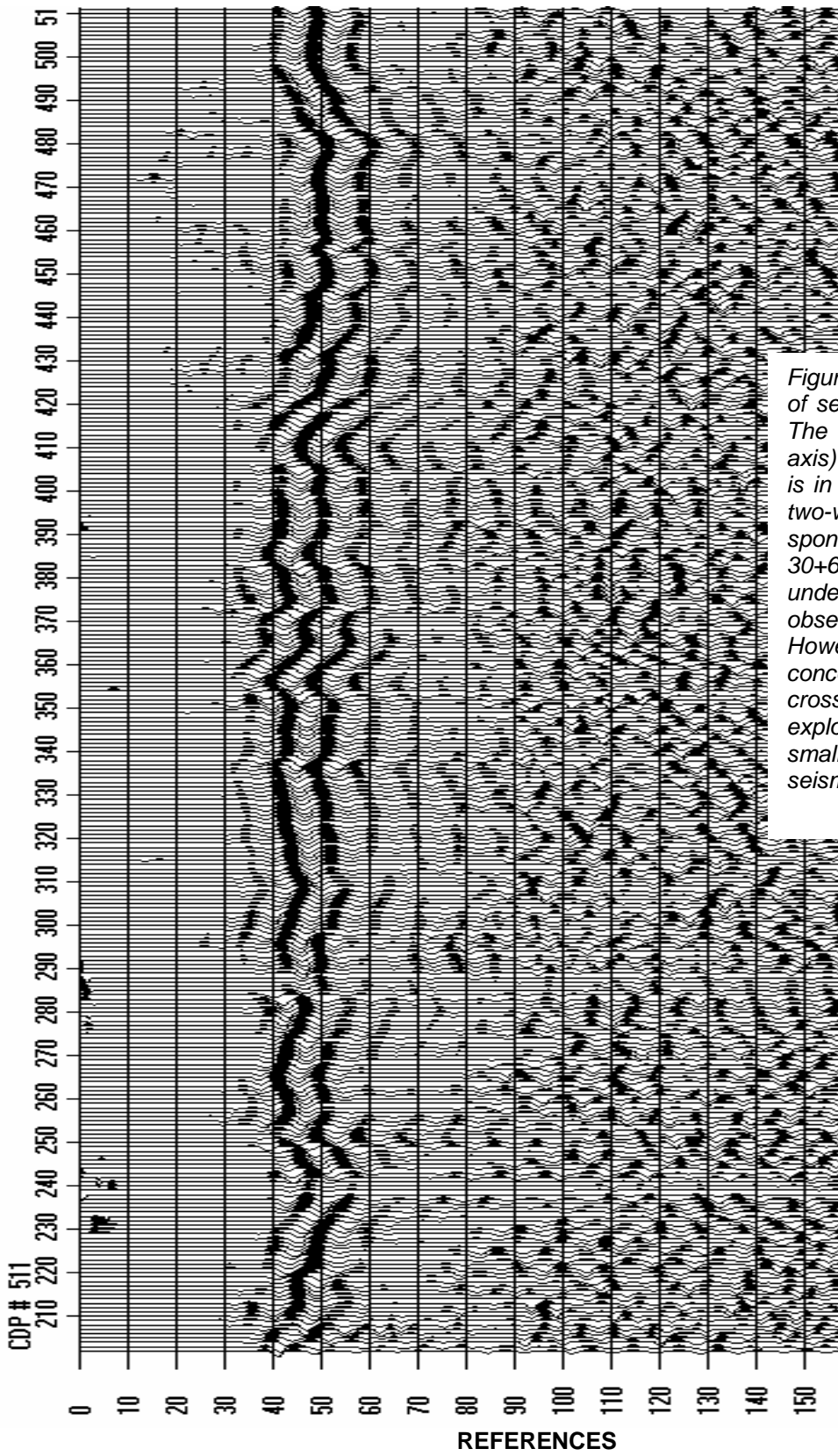


Figure 10: Interpreted version of seismic profile 2 (Figure 8). The trace interval (horizontal axis) is 10 ft. The vertical axis is in milliseconds and denotes two-way Time. Trace 202 corresponds to surface station 30+60. No visual evidence of underground mining activity is observed on seismic profile 2. However, it is certainly conceivable that the profile crosses one or more isolated exploratory shafts that are too small to be imaged on the seismic profile.

Gochioco, L.M., 2006, SME Journal vol. 60, No. 7, pp. 27-33 and Proceedings of 2004 SME Annual Meeting, Denver, Colorado.  
Mineral Resources Department of Labor Mine Safety and Health Administrations, Code of Federal Regulations - Boreholes in Advance of Mining, 30 CFR § 75.388