High-resolution SH-wave seismic reflection investigations near a coal mine-related roadway collapse feature

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Abstract

We acquired crossline–crossline (SH–SH) shear-wave reflection data along a heavily trafficked section of Interstate highway 70 in eastern Ohio where the roadway had collapsed into underground coal-mine workings. We acquired these data to determine whether subsurface subsidence processes had continued at the collapse location after remediation, and to identify additional areas of potential collapse along this section of the roadway. A reflection correlating to the overburden and bedrock interface (above the mine workings) was consistently identified in raw field records, and our data processing and imaging targeted this high impedance contrast. Data quality was high enough to permit resolution of vertical offsets of 3–4 ft (0.91–1.2 m) and horizontal disruptions of about 20 ft (6.1 m) in the otherwise continuous bedrock horizon at two locations close to the previous collapse, suggesting a relatively high risk for future roadway failure in these areas. SH-wave data interpretations were supported by exploratory drilling results which confirmed that bedrock had subsided into underlying coal-mine workings at these two locations. Our results show that high-resolution SH-wave seismic reflection surveys can be effective for diagnosing mine-induced subsidence potential beneath heavily traveled roadways.

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1. Introduction

Over 6000 abandoned underground mines (the majority of which are coal mines) exist throughout Ohio, and mine-related subsidence has been a problem in the state since 1923 (Crowell, 1997). Our work is part of a research project that focuses on understanding coal mine-related subsidence mechanisms and locating areas with a high risk for future surface collapse along an undermined 2200-ft (671

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m) section of Interstate highway 70 (I-70) in eastern Ohio (Fig. 1). We conducted shear-wave (S-wave) reflection surveys to determine whether subsurface subsidence processes had continued along a 200-ft (61 m) section of the eastbound lanes after remediation of a previous mine-related collapse there. A second objective was to identify other areas of active subsidence or soil piping into subsurface collapse features along the 2200-ft (671 m) section of highway. Three lines of crossline–crossline (SH–SH) S-wave reflection data were acquired during two separate surveys, using sources and receivers oriented transversely to the seismic lines.

1.1. Geological setting

The I-70 study area is in the unglaciated region of the Appalachian Plateau physiographic province. The geology consists generally of relatively flat to mildly dipping Paleozoic sedimentary rocks with unconsolidated overburden materials that formed by periglacial erosion and deposition. The upper 5–15 ft (1.5–4.6 m) of material beneath I-70 consists of silt and clay fill. Beneath this fill are silts and clays down to bedrock, with frequent interbedded lenses of sand and gravel. The total thickness of unconsolidated materials above bedrock ranges from 30 to 50 ft (9.1–15.2 m) across the study area. Bedrock correlates as the Lower Mahoning Sandstone and Shale member (upper Pennsylvanian series) in the Lower Glenshaw Group, and is predominantly arenaceous shale in the study area. The Lower Glenshaw Group is a regionally thick, repetitive sequence of sandstone, mudstone, sandy shale, and thin beds of coal, clay, and limestone (Condit, 1912). The Lower Mahoning member lies above the bituminous Upper Freeport complex.
Coal (No. 7, middle Pennsylvanian series), and ranges in thickness from 10 to 25 ft (3.0–7.6 m) in the study area. The Upper Freeport Coal is 5–7 ft (1.5–2.1 m) thick, is underlain by claystone, and was mined an average of 6 ft (1.8 m) in thickness in the study area using the room-and-pillar mining method. The water table is above the Upper Freeport Coal seam in the study area, and water flows across the area through granular soils, fractures, and voids in the bedrock and coal units.

1.2. Subsidence history and mechanisms

The Murray Hill No. 2 mine complex that underlies the I-70 study area was in operation from 1912 to 1935. During 1994, the abandoned, underground Kings coal mine (down dip and south of the Murray Hill complex) was intercepted by a surface mining operation. For surface mining to proceed, water had to be pumped from the Kings mine. As a result, extensive dewatering occurred in the Murray Hill mine, because the Kings and Murray Hill complexes are connected by entries. Subsequent to this dewatering, localized roof failure between coal pillars and soil piping above the mine workings occurred in the I-70 study area (Hoffman et al., 1995). Surface mining and dewatering stopped and water levels returned to predewatering levels. Nonetheless, subsidence of the weak overburden continued and eventually resulted in catastrophic failure of the I-70 eastbound lanes in March 1995. A surface collapse pit, roughly 10 ft (3 m) in diameter, was centered at road station 48345 in the eastbound travel lane of I-70 (Fig. 2). The roadway collapse was sudden and caused an accident involving four vehicles. (Note, road stations are in feet along the highway’s center line from the western Guernsey County line. Highway engineers designate stationing as hundreds of feet plus the remaining feet, for example, 483+45. In this paper we combine these numbers, for example, 48345.)

Following the 1995 collapse a mine remediation project was conducted. This work consisted of drilling and grouting along the study area to secure voids and fill rock fractures. After the roadway reopened, additional surface depressions developed in the I-70 study area during 1996 in the location of previously drilled boreholes. Exploratory drilling revealed unconsolidated soils and voids in several previously grouted locations. A second phase of grouting occurred during 1997. Since then, the

![Figure 2](image-url)

Fig. 2. Map view of the eastbound lanes of I-70 (road stations 48300–48500) showing the locations of seismic reflection lines. The locations of mine workings relative to the roadway are based upon a map of the Murray Hill No. 2 coal mine (USDI, 1935). The area of previous roadway failure is also shown, where a surface collapse feature roughly 10 ft (3 m) in diameter was centered in the eastbound travel lane at road station 48345.
roadway has not collapsed again. However, concern continues regarding roadway stability. Consequently, our research has focused on subsurface characterization to determine the cause of the voids, loose soils, and lack of grout, and to determine whether there is active subsidence and where there is a high risk for future roadway collapse.

2. Data acquisition

We acquired three lines of high-resolution SH-wave reflection data along the flat, 200-ft (61 m) section of the eastbound lanes that contained the roadway collapse of March 1995 (Fig. 2). These lines (Table 1) were acquired during two separate field programs, using vibratory sources configured to generate preferential shear particle motion transverse to the lines, and receivers containing horizontal elements oriented transverse to the lines. Line Test-1 was acquired during 1999 and was positioned parallel to and 60 ft (18.3 m) south of the southern edge of the I-70 eastbound lanes between road stations 48300 and 48400. Line Test-1 was a baseline survey to image the subsurface away from disturbances caused by highway remediation activities (e.g., drilling and grouting). Line GUE-I70-1, also acquired during 1999, was positioned along the southern edge of the eastbound lanes between road stations 48300 and 48500. Line EBPassYY was acquired during 2001 and positioned along the north edge of the eastbound lanes between road stations 48300 and 48500.

A consistently strong reflection, with zero-offset times ranging from 105 to 120 ms and apparent normal move-out (NMO) S-wave velocities ranging from 600 to 800 ft/s (183–244 m/s), was observed on shot gathers from all three lines (Fig. 3). Depths estimated using velocities derived from reflection data and correlated with drill logs indicate that this strong reflection is from the overburden and bedrock boundary.

Love waves have particle motion that is parallel to the ground surface and perpendicular to the propagation direction, require a low-velocity near-surface layer to exist, and were a major concern as they often serve as a strong source of noise in shallow SH-wave surveys (Deidda and Ranieri, 2001; Miller et al., 2001). Detrimental Love wave noise was not observed on the majority of the shot gathers, because the S-wave velocity structure across the site was such that near-surface materials (asphalt and road-fill materials) had a higher velocity than the underlying materials at most locations.

Interstate traffic was ongoing and heavy during data acquisition, and noise from roadway vehicles was frequently observed on shot gathers. However, this traffic noise was predominantly low frequency (e.g., 5–25 Hz) and could be largely suppressed using a low-cut frequency filter.
Fig. 3. Shot gathers (uninterpreted and interpreted) with zero-phase Ormsby band-pass filters (<12 dB/octave slopes) and AGC gain (100 ms window) applied: (a) line Test-1 gather with 80–180 Hz (unit amplitude) filter, (c) line GUE-170-1 gather with 100–180 Hz (unit amplitude) filter, and (e) line EBPassYY gather with 80–160 Hz (unit amplitude) filter. The hyperbolic reflection events (indicated using dot-dash curves) on the interpreted gathers in (b), (d), and (f) correlate as the top of bedrock. The location axis is in road-location units (feet); the flags mark the source location.
3. Target resolution potential

We considered both vertical and lateral resolution to assess whether the data would allow us to detect and resolve reflecting horizons, differentiate reflectors and diffractors, and identify discontinuities in reflecting horizons. For lines Test-1 and GUE-I70-1, unfiltered shot gathers contained, on average, a dominant reflection frequency of 80 Hz. For line EBPassYY unfiltered shot gathers, the average dominant reflection frequency was 100 Hz. Lines Test-1, GUE-I70-1, and EBPassYY were acquired with small common midpoint (CMP) intervals of 0.5, 0.5, and 1 ft (0.15, 0.15, and 0.30 m), respectively.

3.1. Reflecting horizon resolution potential

We compared synthetic shot gathers with the I-70 field records to investigate the resolution potential of field data relative to the study-area geology. The synthetic seismograms were produced using a finite-difference (Alford et al., 1974; Kelly et al., 1976) acoustic modeling code within the ProMAX software package. In all cases, we modeled the source using a zero-phase Ricker wavelet located at the surface and specified reflecting boundary conditions. Grid dispersion was minimized by specifying at least seven grid points per wavelength everywhere in the models. Table 2 gives the S-wave interval velocities and layer thicknesses we used to generate the synthetic seismograms shown in Fig. 4. We obtained these velocities and depths through analysis of a line Test-1 shot gather (Fig. 4) and drill log information.

Table 2

| Velocity model used to generate the synthetic seismograms shown in Fig. 4 |
|---------------------|------------------|
| S-wave interval velocity | Layer thickness |
| (ft/s) | (m/s) | (ft) | (m) |
| 670 | 204 | 39 | 11.9 |
| 2500 | 762 | 20.5 | 6.25 |
| 2395 | 730 | 7 | 2.14 |
| 2500 | 762 | 150 | 45.7 |

We obtained these velocities and depths through analysis of a line Test-1 shot gather (Fig. 4) and drill log information.

Table 2 gives the S-wave interval velocities and layer thicknesses we used to generate the synthetic seismograms shown in Fig. 4. We obtained these velocities and depths through analysis of a line Test-1 shot gather (Fig. 4) and drill log information.

Reflections correlating to the top or bottom of the coal seam were not observed in field records and, therefore, we could not directly measure the coal’s shear velocity. Instead, to model the Upper Freeport Coal, we used the S-wave velocity of 2395 ft/s (730 m/s) from the Lower Freeport coal (Wolfe et al., 1989). The Lower Freeport coal (No. 6A, middle Pennsylvanian series) is a bituminous coal that is located stratigraphically beneath the Upper Freeport Coal.

Uninterpreted synthetic seismograms are shown in Fig. 4a (300-Hz source frequency) and Fig. 4c (100-Hz source frequency), with interpretations shown in Fig. 4b and d, respectively. The shot gather from which the parameters in Table 2 were derived is shown in Fig. 4e (uninterpreted) and Fig. 4f (interpreted).

When using a 300-Hz source wavelet, a dominant reflection frequency of 250 Hz results, and reflections from the three model impedance contrasts were distinguishable at near offsets (Fig. 4b). Although reflections from the coal top and bottom are low amplitude relative to the overburden–bedrock event, the reflected wavelets from the coal top and bottom are separated in time because the coal thickness (7 ft = 2.1 m) is greater than half of the wavelength of the seismic wavelet in the coal (λ/2 = 4.8 ft = 1.46 m). As a result of the relatively low overburden velocity and the high overburden–bedrock velocity contrast, the overburden–bedrock reflection in Fig. 4b is distorted where deeper reflections from the coal top and bottom cross it. Despite this interference, the shape and amplitude of the composite wavelet is still dominated by the character of the overburden–bedrock reflection.

A second synthetic seismogram generated using a dominant source frequency of 100 Hz (resulting in a dominant reflection frequency of 80 Hz) is shown in Fig. 4d. For comparison, the same inter-
pretations from Fig. 4b are superimposed on the data in Fig. 4d. The high amplitude primary reflection is clear and interpretable at near offsets, but interference of reflection energy does not allow interpretation of lower amplitude events from the coal top and bottom. At near offsets the opposite
polarity events from the bedrock and coal top interfere (the composite wavelet is dominated by the primary reflection). In this case, we would not be able to distinguish the coal top and bottom because the coal thickness (7 ft = 2.1 m) is less than half of the dominant wavelength in the coal \((\lambda/2 = 15 \text{ ft} = 4.6 \text{ m})\). Interference of the primary reflection and lower amplitude crossing events associated with the coal seam occurs across a larger range of offsets than in Fig. 4b. Interference effects have no evident effect on the composite wavelet across this offset range though, which is still dominated by the character of the primary reflection. However, with a frequency of 80 Hz, it is unlikely that we can infer lateral changes in material properties beneath the overburden–bedrock interface because of interference.

The dominant frequency of the field record (Fig. 4e) and the synthetic seismogram in Fig. 4c are comparable, and interpretations of the overburden–bedrock interface reflection and refraction events are the same for the synthetic and field data (compare Fig. 4d and f). No reflection from the coal seam beneath the overburden–bedrock interface exists in the field data. Our modeling results indicate that this lack of a coal reflection results from the high reflection coefficient associated with the overburden–bedrock interface, low signal-to-noise ratio, interference effects, additional wavelet cycles, and source-related noise at near offsets.

### 3.2. Discontinuity resolution potential

In addition to affecting the potential for imaging reflecting horizons, vertical resolution also affects the potential for inferring discontinuities associated with mine-related subsidence along reflecting horizons. Resolution is strongly dependent on frequency and velocity (Widess, 1973), although numerous additional factors (e.g. the noise level in data) also influence the resolving potential of shallow reflection data (Miller et al., 1995). A generally accepted threshold for easily inferring vertical offset along a horizon is that offset \((\Delta h)\) must be at least a quarter of the dominant wavelength \((\lambda/4)\) (Sheriff and Geldart, 1982; Yilmaz, 2001). At a dominant unfiltered data reflection frequency of 80 Hz, the dominant wavelength in the overburden (at a velocity of 670 ft/s = 204 m/s) for the line Test-1 and line GUE-170-1 data would be about 8.4 ft (2.6 m). For the Line EBPassYY data, at a dominant unfiltered data reflection frequency of 100 Hz, the dominant wavelength would be 6.7 ft (2.0 m) in the same overburden. So, if we were to assume that the quarter wavelength criterion applies to our data, then we would expect to be able to resolve vertical distances \((\Delta h)\) greater than quarter wavelengths \((\lambda/4)\) of 2.1 and 1.7 ft (0.64–0.52 m), respectively.

The Fresnel zone diameter can be used to estimate lateral resolution and the potential of data to allow differentiation of reflectors and diffractors. The diameter \((d_f)\) of the first Fresnel zone (where \(h\) is depth to the reflector, \(\lambda\) is wavelength, \(V\) is the average velocity above the reflector, \(t\) is the arrival time, and \(f\) is frequency) is defined as:

\[
d_f \sim (2h\lambda)^{1/2} = 2[(V/2)(t/f)]^{1/2}
\]

Using the field data parameters in Fig. 4f, we estimate the diameter \((d_f)\) of the Fresnel zone for the bedrock interface \((h = 39 \text{ ft} = 11.9 \text{ m})\) to be from 22.9 to 25.6 ft (7.0–7.8 m), depending on whether the dominant reflection frequency of unfiltered data is 100 or 80 Hz, respectively. We would expect to be able to resolve features with horizontal dimensions \((d_c)\) that are close to or greater than the Fresnel diameter \((d_f)\), that is, when the ratio \(d_c/d_f\) is close to 1 or greater.

### 4. Data processing

The processing flow applied to the each of the three SH-wave lines was similar (Table 3) and performed using ProMAX software (Landmark Graphics). We focused our attention on the reflection from the overburden–bedrock interface because it had a high impedance contrast and could be identified consistently in field records. Our resolution analyses (see above) suggested that it would be possible to infer (a) vertical bedrock-horizon offsets on the order of a few feet and (b) horizontal disruptions or discontinuities with lateral extents less than the width of mined-out rooms between coal pillars (Fig. 2). Our approach seemed reasonable for identifying past and active subsidence, because collapse features must propagate up and
disrupt the overburden–bedrock interface on their way to the surface.

In order to suppress as much noise as possible without degrading reflection signal quality, we applied a zero-phase Ormsby band-pass filter (with $<12$ dB/octave slopes) to shot gathers from each line. An Ormsby filter is built by specifying four corners of a trapezoid in the frequency domain; these two pairs of frequencies define the low side and high side slopes, and between the two center corners the trapezoid has unit amplitude. Lines Test-1 and EBPassYY were acquired with the source baseplate located on relatively soft soil, whereas line GUE-I70-1 was acquired with the source baseplate located on the relatively hard roadway pavement. Line GUE-I70-1 shot gathers contained periodic noise at an average dominant frequency of 65 Hz that resulted from decoupling of the source baseplate. For band-pass filters applied to lines Test-1 and EBPassYY, the low end unit amplitude was 80 Hz. For the filter applied to line GUE-I70-1, however, a higher low end amplitude unit of 100 Hz was specified in order to suppress source-related periodic noise.

After trace editing we applied a scalar trace-to-trace amplitude-balancing function (Hatton et al., 1986) to shot gathers to obtain statistically optimum stacks. This function minimizes differences in sample amplitudes resulting from differences in acquisition equipment performance and source and receiver coupling with location. The recording geometries for lines Test-1 and GUE-I70-1 were such that for many of the field records, long source-to-receiver offsets containing high amplitude refraction energy from the bedrock interface were not recorded. For records containing refraction energy, we found that top muting degraded reflection signal and we could eliminate most refraction energy by appropriate (post NMO correction) stretch muting. A major concern when not using a top mute is that refraction energy can appear as coherent events on processed images (Steeples and Miller, 1998). So we took care to ensure that structural interpretations of the subsurface would not be adversely affected by unmuted refraction energy.

Elevation static corrections did not need to be performed because the data were acquired on a flat, horizontal surface. As previously mentioned (see above), the shooting geometries were such for lines Test-1 and GUE-I70-1 that the necessary offsets for refraction static calculations were not recorded for most field records. For records containing refraction energy, direct arrival and refraction static shifts were observed to be inconsistent with reflection static shifts, indicating that for these records reflections would be incorrectly shifted by applying corrections based on earlier arriving events. We found through experimentation that using post-velocity-analysis surface-consistent residual-static corrections did not significantly improve stacked signal quality or reflection continuity. Not applying residual-static corrections to our data did not lead to erroneous structural interpretations; all interpretations regarding structural integrity that we present in this paper are shown to have been confirmed by exploratory drilling results (Guy, 2002).

### Table 3

<table>
<thead>
<tr>
<th>Processing step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data reformat</td>
<td>From SEG-Y to ProMAX format</td>
</tr>
<tr>
<td>Vibroseis correlation</td>
<td>Line Test-1 using synthetic sweep, line GUE-I70-1 using AUX channel-2, line EBPassYY using pilot sweep</td>
</tr>
<tr>
<td>Geometry</td>
<td>Defined using field notes and loaded to headers</td>
</tr>
<tr>
<td>Data truncation</td>
<td>Records truncated to 300 ms</td>
</tr>
<tr>
<td>Trace editing</td>
<td>Bad/noisy traces killed</td>
</tr>
<tr>
<td>Trace equalization</td>
<td>Amplitude balancing function calculated using CMP gathers (150 ms spatially varying window) and applied to shot gathers</td>
</tr>
<tr>
<td>Band-pass filtering</td>
<td>Zero-phase Ormsby filters ($&lt;12$ dB/octave slopes) applied, line Test-1 unit amplitude: 80–180 Hz, line GUE-I70-1 unit amplitude: 100–180 Hz, line EBPassYY unit amplitude: 80–160 Hz</td>
</tr>
<tr>
<td>CMP sort</td>
<td>Sorted from shot gathers to common midpoint gathers</td>
</tr>
<tr>
<td>Velocity analysis</td>
<td>Integrated analysis of shot gathers, constant velocity stacks, and semblance plots</td>
</tr>
<tr>
<td>NMO correction</td>
<td>Applied based on optimum stacking velocities</td>
</tr>
<tr>
<td>Stretch mute</td>
<td>30%</td>
</tr>
<tr>
<td>AGC scaling</td>
<td>100 ms window</td>
</tr>
<tr>
<td>CMP ensemble/stack</td>
<td>Summed NMO-corrected CMP gathers</td>
</tr>
</tbody>
</table>

Elevation static corrections did not need to be performed because the data were acquired on a flat, horizontal surface. As previously mentioned (see above), the shooting geometries were such for lines Test-1 and GUE-I70-1 that the necessary offsets for refraction static calculations were not recorded for most field records. For records containing refraction energy, direct arrival and refraction static shifts were observed to be inconsistent with reflection static shifts, indicating that for these records reflections would be incorrectly shifted by applying corrections based on earlier arriving events. We found through experimentation that using post-velocity-analysis surface-consistent residual-static corrections did not significantly improve stacked signal quality or reflection continuity. Not applying residual-static corrections to our data did not lead to erroneous structural interpretations; all interpretations regarding structural integrity that we present in this paper are shown to have been confirmed by exploratory drilling results (Guy, 2002).
4.1. Velocity analysis

We determined from analysis of the overburden–bedrock reflection that the apparent average overburden velocity varied by as much as 20% over the course of 100 ft (30.4 m) laterally. Relatively lower amplitude reflections above this reflection (correlating as unconsolidated overburden sandy units) were also evident on a small percentage of gathers and generally exhibited move-out similar to the local top-of-bedrock reflection. Therefore, a single-layer overburden model with laterally varying velocity above bedrock seemed most appropriate for image construction purposes.

The procedure for stacking-velocity analysis involved an integrated evaluation of shot gathers, constant velocity stacks, and semblance plots. We used estimates of velocity and velocity variations obtained from shot gather and constant velocity stack analysis to define optimal input parameters for semblance analysis. Fig. 5 shows velocity spectra and picks for three EBPassYY CMP supergathers (left) and the same supergathers after applying NMO correction and stretch mute (right). These data indicate that the optimum stacking velocity for the overburden–bedrock event (zero-offset time of about 110 ms in these supergathers) ranges from about 660 to 790 ft/s (200–240 m/s). A second relatively lower amplitude event also stacks at these velocities on each of the supergathers at a zero-offset time of about 90 ms. The depth of this event correlates with the top of a sandy unit above bedrock. At road station 48320 (Fig. 5c), this second event has a distorted hyperbolic move-out with the hyperbola apex shifted to the right of the zero-offset axis, indicating that this may be a diffraction event, or that the upper surface of the sandy unit dips somewhat at this location. Semblance-based velocity models were built by incorporating only the highest quality velocity picks, such as the ones shown in Fig. 5.

5. Data interpretations

The strong overburden–bedrock reflection is interpretable across stacked sections for each of the three lines. Lower amplitude and less continuous reflectors above the bedrock horizon are evident on stacked sections also, and correlate to sandy units mapped within the overburden.

5.1. Line test-1

As indicated earlier, line Test-1 was a baseline survey over geology undisturbed by highway remediation operations. Its stacked time and depth sections are shown in Fig. 6. We interpret the reflection at 110–120 ms (Fig. 6a) to be the top of bedrock (Fig. 6b). The horizon is continuous and undulates slightly across the line. No significant vertical displacements or discontinuity can be detected along the bedrock horizon in the line Test-1 section. Therefore, mine-related subsidence activity and, consequently, surface collapse potential is minimal across this line.

For this line, it is difficult to infer possible effects of the mine on the bedrock-horizon topography and stacking velocities because we have no data regarding the location of rooms and pillars beneath line Test-1. However, the eastern edge of the coal pillar mapped to the north of line Test-1 (Fig. 2) can be projected to pass beneath line Test-1 at CMP 48345 (indicated by the arrow in Fig. 6). Immediately east of this location, the overburden–bedrock horizon dips down to the east and the stacking velocity decreases (Fig. 6a). Although unconfirmed, these observations suggest that removal of coal here may have influenced the bedrock topography and weakened the overburden material.

5.2. Line GUE-I70-1

The stacked time and depth sections from line GUE-I70-1 are shown in Fig. 7. This line runs immediately south of the roadway collapse just off the shoulder of the eastbound travel lane (Fig. 2). The reflection at 110–120 ms (Fig. 7a) is the top of bedrock (Fig. 7b). A number of secondary weak reflectors between 50 and 100 ms are also evident within the overburden. It is difficult to infer whether discontinuity or truncation of these secondary events has depositional origins or results from subsidence-related fracturing or faulting within the overburden materials.

There are apparent dips and undulations of the bedrock horizon at numerous locations across the section. There is a bedrock high apparent at CMP
Fig. 5. Velocity spectra and picks for line EBPassYY CMP supergathers: before (left), and after NMO correction and 30% stretch mute application (right), showing lateral variation in optimum stacking velocity along this line. The supergathers are centered at: (a) road station 48470, (b) road station 48410, and (c) road station 48320.
Fig. 6. Line Test-1 stacked time section with fold (TR_FOLD) plot (a). The continuous reflection at 110–120 ms (a) is the top of bedrock (indicated using a dot-dash line) on the depth section (b). The scale at the bottom of (a) shows bedrock horizon stacking velocities. CMP locations (CMP_X) correspond to road stations. To the east of CMP 48345 (indicated by arrow) the overburden–bedrock horizon dips down to the east and the stacking velocity decreases, suggesting that removal of coal here may have influenced the bedrock topography and weakened the overburden material.
Fig. 7. Line GUE-I70-1 stacked time section with fold (TR_FOLD) plot (a). The reflection at 110–120 ms (a) is the top of bedrock (indicated using a dot-dash line) on the depth section (b). The scale at the bottom of (a) shows bedrock horizon stacking velocities. CMP locations (CMP_X) correspond to road stations. A bedrock discontinuity is interpreted at CMP 48391, and an area of disrupted bedrock is interpreted between CMPs 48380 and 48408 (indicated by arrows and dashed lines). The interpreted area of disruption is based upon wavelet character and the analysis of the shot gathers (locations indicated by flags) in Fig. 9.
48460 that agrees with a bedrock high interpreted from drill log data. A coal pillar is present beneath bedrock (Fig. 2) and the stacking velocities are relatively high at this location (Fig. 7a). These observations suggest that the coal pillar supports the overlying materials allowing the original bedrock topography and overburden material stiffness to be maintained during and after mining activity. To the west of the bedrock high, where Fig. 2 indicates a room beneath line GUE-I70-1, the bedrock horizon dips west and stacking velocities begin to decrease. This bedrock-surface dip and decreasing velocity may have resulted from coal removal. However, we cannot rule out the possibility that the bedrock surface dipped in this area before mining, as we do not have data on bedrock elevations before mining.

The geologic cross-section shown in Fig. 8 resulted predominately from core recovery from wells along the section; core recovery is indicated by solid vertical lines in the figure. Between CMP locations 48330 and 48400.

Fig. 8. Geologic cross-section constructed from drill log data acquired along the southern edge of the I-70 eastbound travel lane. Exploratory drilling results support the line GUE-I70-1 seismic data-based interpretation (Figs. 7 and 9) of bedrock offset at road station 48391 and an area of bedrock disruption between road stations 48380 and 48408.
48360, a bedrock low was interpreted (Fig. 8). A similar bedrock low is apparent on the seismic section (CMP locations 48330 to 48370 in Fig. 7). Although Fig. 2 indicates the presence of a mine room in this region and the previous localized collapse was centered about 15 ft (4.6 m) north of CMP 48345, stacking velocities are somewhat higher in this area relative to laterally adjacent areas, and no offset or significant disruption of the bedrock horizon is evident from the seismic section (Fig. 7). These observations indicate that either the subsidence processes responsible for the roadway collapse were predominately active north of Line GUE-I70-1, outside the Fresnel zone diameter ($d$), and did not affect the GUE-I70-1 section, or that remediation of the collapsed area has stabilized and prevented further subsidence activity at this location. It is also possible that any evidence of past or ongoing bedrock disruption resulting from coal mine-induced subsidence is below our ability to resolve it using these data. There is no evidence on the seismic sections that the voids encountered during the drilling of boreholes GC212, GC213, and GC214 (Fig. 8) have continued to propagate upwards and pose an immediate risk for surface collapse.

We interpret a vertical-offset discontinuity in the bedrock at CMP 48391 in the seismic section (Fig. 7b). The vertical offset is about 3–4 ft (0.91–1.2 m), based on the apparent differences in travel time and depth across the discontinuity; this offset is greater than a quarter of the dominant wavelength in the overburden (see above). Stacking velocities are about 670 ft/s (204 m/s) and did not change abruptly in the vicinity of this discontinuity (Fig. 7a); these relatively low stacking velocities may indicate a fractured and relatively weak overburden. The bedrock surface appears to be fairly continuous on either side of the discontinuity. Based on our interpretation of discontinuity at CMP 48391, an exploratory boring (borehole B412E) was drilled to the immediate east of this location at road station 48395 (Fig. 8). Borehole B412E confirmed that bedrock had been down-dropped along a normal fault between road stations 48380 and 48395 (Guy, 2002). This evidence supports our interpretation that vertical offset is real and not a processing artifact from velocity-model problems or unresolved statics.

Fig. 9a shows uninterpreted shot gathers acquired at the source locations indicated by flags on the location axis of Fig. 7b, and the gathers are interpreted in Fig. 9b. For the 48365.5 shot gather on the left, the bedrock reflection is a fairly well-behaved hyperbola. The hyperbola shifts to the right of the source in shot gather 48375.5, indicating an apparent westward dip of the bedrock surface at this location, which agrees with the dip apparent at this location on the seismic section. We did not apply dip move-out (DMO) corrections to the data to compensate for occasionally apparent dips, and as a result we have less confidence in our estimates of depth to bedrock at such locations. The bedrock reflection is severely distorted in shot gather 48389.5 at near offsets. This observation further supports our interpretation of the discontinuity at CMP 48391 on the stacked section in Fig. 7b.

We interpret an area of bedrock disturbance and increased risk for future surface collapse resulting from mine-induced subsidence processes between CMP 48380 and CMP 48408 (Figs. 7 and 9). This interpretation is supported by exploratory drilling results (Fig. 8), and by cross-hole radar measurements acquired after the seismic data (Guy, 2002). Bedrock and overburden EM-wave amplitudes and velocities (derived from radar data) were low between boreholes GC217 and B412E relative to those measured between boreholes GC211 and GC215, suggesting an increase in bedrock and overburden fracture density (and water content) between road stations 48380 and 48395 (Guy, 2002; Guy et al., 2003). The interpreted lateral extent of subsurface disruption (between arrows and vertical dashed lines in Fig. 7b) is also supported by the character of near surface reflectors (within the overburden) in this area, which exhibit apparent dip and offset on the seismic section (Fig. 7). NMO corrections using velocities to fit hyperbolas to the bedrock reflection tended to smooth such small-scale features on the stacked section. However, by paying attention to event character in shot gathers during stacked section interpretation, such features were not overlooked.

The mine map (Fig. 2) indicates that the southwest end of a coal pillar is present beneath line GUE-I70-1 between road stations 48375 and 48400. Boring B412E encountered heavily fractured bedrock material and did not encounter coal at road station 48395. This suggests that the mine map has placed the eastern edge of the coal pillar slightly too far to the east. Complete crushing of the pillar would have
likely resulted in a broad region of bedrock subsidence, but the seismic data suggest that bedrock is intact and at a relatively high elevation at road station 48380, despite the fact that voids were encountered within the bedrock during drilling at this location (Fig. 7). It therefore appears that the bedrock disruption resulted from collapse of bedrock material into the mine room located immediately southeast of the coal pillar.

5.3. Line EBPassYY

The stacked time and depth sections from line EBPassYY are shown in Fig. 10. This line was
Fig. 10. Line EBPassYY stacked time section with fold (TR_FOLD) plot (a). The reflection at 105–115 ms (a) is the top of bedrock (indicated using a dot-dash line) on the depth section (b). The scale at the bottom of (a) shows bedrock horizon stacking velocities. CMP locations (CMP_X) correspond to road stations. The bedrock horizon is continuous across the section, except between CMPs 48329 and 48354 (indicated by arrows), where discontinuity is interpreted.
acquired off the shoulder of the eastbound passing lane, north of the previous roadway collapse feature (Fig. 2). The reflection at 105–115 ms (Fig. 10a) is the top of bedrock (Fig. 10b). Bedrock is seen to be continuous across the length of line EBPassYY, except for between CMP 48329 and CMP 48354. In this range (between arrows in Fig. 10b), the bedrock horizon is interpreted to have been down-dropped and experienced significant disruption resulting from pit-type subsidence mechanism (Waltham, 1989; Whittaker and Reddish, 1989). The map in Fig. 2 indicates that a mine room is present beneath line EBPassYY in this region, bordered by a coal pillar to the west (road locations 48290–48330).

The stacking velocities slowly increase towards the west across the disrupted bedrock region. The horizon would not stack coherently across this region at any of a wide range of applied stacking velocities, indicating that the disruption is not the result of velocity-model problems. The horizon appears to be coherent and continuous on both sides of the interpreted disrupted area, suggesting that the disrupted area did not result from unresolved statics. We estimate the downward displacement of the horizon to be between 3 and 4 ft (0.91–1.2 m) along small faults in the CMP location ranges of 48329–48339 and 48348–48354. In between these faults, there is additional downward displacement.

The disruption responsible for this seismic anomaly need not be centered directly beneath the seismic line. It need only be within the Fresnel zone diameter ($d_f$), which we estimate to be about 23 ft (7 m) at the top of bedrock. There is low-amplitude scattering above the down-dropped bedrock across the disrupted region. This scattering may result from an impedance contrast across an arch that formed when overburden material subsided into the subsurface collapse feature. Alternatively, this low-amplitude energy could have resulted from out-of-plane scattering related to remediation efforts conducted in the roadway south of this line. However, remediation of the collapse feature occurred approximately 20 ft (6.1 m) south of this line EBPassYY, centered at road location 48345 in the eastbound travel lane, suggesting that this latter explanation is less likely. Nonetheless, the close proximity of this bedrock disruption and the roadway collapse is intriguing and may be more than suggestive.

A geologic cross-section constructed from drill logs acquired during 1999 along the north shoulder of the eastbound passing lane is shown in Fig. 11. The cross-section indicates that bedrock is continuous across the length of the seismic line, except for in the vicinity of the disrupted zone interpreted from the seismic data. Drill log data indicate that a bedrock low exists in the approximate road station range of 48314 to 48340 (borings GC202–GC205 in Fig. 11). Voids were also encountered during drilling below the

![Fig. 11. Geologic cross-section constructed from drill log data acquired along the northern edge of the I-70 eastbound passing lane.](image-url) Exploratory drilling results support the line EBPassYY seismic data-based interpretation (Fig. 10) of a down-dropped region of bedrock caused by pit-type subsidence processes.
bedrock surface. The disturbed area in seismic data (CMPs 48329–48354) overlaps about 10 ft (3 m) on its west with the bedrock low interpreted from the drill log data. Both features have similar lateral extents, 26 ft (7.9 m) and 25 ft (7.6 m) for the drill-log and seismic data, respectively. Cross-hole radar measurements acquired after the seismic data between boreholes GC201 and GC206 (see Fig. 11 for boring locations) further support interpreted area of mine-related bedrock disruption from seismic data (Guy, 2002; Guy et al., 2003). Between road stations 48314 and 48354, bedrock EM-wave amplitudes and velocities were low relative to values measured at adjacent road stations, suggesting an increase in bedrock fracture density (and water content).

6. Conclusions

High-resolution SH-wave reflection surveys conducted along a 200 ft (61 m) section of the eastbound lanes of I-70 enabled the detection of two areas along the roadway with a high risk for future mine-related collapse. An otherwise continuous bedrock horizon has experienced offset and significant disruption between road stations 48380 and 48408 (Line GUE-I70-1, Figs. 7–9) along the south side of the roadway, and between road stations 48329 and 48354 (Line EBPas-sYY, Figs. 10 and 11) along the north side of the roadway. Line GUE-I70-1, acquired immediately south of the previous roadway collapse feature (CMP 48345 ± 10 ft), does not indicate significant disturbance of the bedrock horizon at this location (Fig. 7). This suggests that either the responsible subsidence processes were predominately active to the north of this seismic line, or that remediation efforts since the roadway collapse have prevented the continuation of subsidence processes at this location. Our results show that high-resolution SH-wave seismic reflection surveys can be effective for characterizing the subsurface and identifying subsidence features beneath heavily traveled roadways.

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