RESISTIVITY IMAGING OF ABANDONED MINELANDS

AT HUNTLEY HOLLOW, HOCKING COUNTY, OHIO

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Murad Ishankuliev

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by

MURAD ISHANKULIEV

has been approved for
the Department of Geological Sciences
and the College of Art and Sciences by

Douglas Green
Associate Professor of Geological Sciences

Benjamin M. Ogles
Dean, College of Arts and Sciences
Abstract

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RESISTIVITY IMAGING OF ABANDONED MINELANDS AT HUNTLEY HOLLOW, HOCKING COUNTY, OHIO (76 pp.)

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A geophysical survey of an abandoned mineland site in Hocking County, Ohio, was carried out with the goals of identifying and characterizing underground mine voids. The electrical resistivity tomography technique was employed in the Huntley Hollow drainage basin, which lies within the Monday Creek watershed of southeastern Ohio. Dipole-dipole surveys were run along a total of 2.4 km of transects with dipole spacings ranging from 1 m to 7 m. Borehole logging at three wells with an electromagnetic conductivity probe showed the following correlations of lithology and resistivity at this site: clay and shale, 7-30 ohm-m ($\Omega$-m); wet sandstone, 30-100 $\Omega$-m; dry sandstone and coal, 100-600 $\Omega$-m. These ranges were used to identify approximate lithologies in the resistivity tomography images and extreme resistivity values at the depth of the Middle Kittanning No.6 coal seam were interpreted as follows: water saturated $<7$ $\Omega$-m; air-filled voids, $>600$ $\Omega$-m. With this interpretation, several likely mine voids can be identified in the images. Voids seen on the western (up-dip) half of the Huntley Hollow basin tend to be flooded while those on the eastern half appear dry. This supports an interpretation with a blockage of down-dip drainage along the middle and southern portions of the basin, possibly due to the mine collapse or fill from later surface strip mining.
Approved: __________________________________________________________

Douglas Green

Associate Professor of Geological Sciences
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Chapter 1. Introduction

1.1 Huntley Hollow Research Objectives

Coal mining has been an important industry since the late nineteenth century in southeast Ohio and the northeast United States in general. Ohio has over 6000 abandoned underground mines and most of them are coal mines (Guy et al., 2003). Many of the older coal mines were undocumented and are the cause of such environmental degradation as subsidence and the discharge of Acid Mine Drainage (AMD; Fig. 1.1). The term subsidence is applied to physical phenomena such as collapse or shift of a ground surface downward due to the gravity. Subsidence features are typically seen in areas where underground coal voids are shallow. AMD is a chemical process due to the outflow of acid water from underground coal mine areas. This phenomenon is the product of chemical reactions of infiltrated and captured stream water with sulfide minerals in the coal seam. The Monday Creek watershed in southeast Ohio is heavily impacted by coal mining industry, being 75-80 percent underlain by abandoned underground mines.

The Ohio Department of Natural Resources (ODNR) is implementing a reclamation project for the entire Monday Creek watershed. Part of this work involves drilling wells to locate undocumented mining voids. The drilling will provide an estimate of the total thickness of mining workings, depth to voids or thickness of overburden and whether rerouting of existing streams is required to avoid stream capture. Thus it is necessary to identify air- and water-filled mining voids in order to achieve ODNR goals.

In order to provide recommendations on drilling locations, a geophysical survey of Huntley Hollow, Hocking County (Fig. 1.2), which is part of the Monday Creek
watershed, was carried out to locate air- and water-filled mine voids in the shallow subsurface. Geophysical surveys have been shown to be inexpensive techniques in subsurface characterization (see section 1.6). For instance, the cost of a drilled well is approximately 10 times more expensive than an electrical resistivity survey of the entire 0.9 km² Huntley Hollow site.

Underground mining occurred within the study area until the late 1930s. Coal production in the area resumed in the 1960s using strip mine technology. Although no mining has occurred in Huntley Hollow for decades, the environmental impacts of these activities remain in the form of subsidence and stream capture, coal tailings piles and acid-mine drainage in both Huntley Hollow and in adjacent, down-dip watersheds.

An electrical resistivity technique was applied in order to obtain subsurface information in the Huntley Hollow watershed. In this study, ODNR well core information as well as geophysical logging data were used to calibrate the electrical surveys. These surveys were able to locate likely mine voids and point to the possible locations of air-filled and flooded zones within the abandoned mine workings.

Figure 1.1. Environmental effects of coal mine subsidence. (http://dnr.state.il.us/mines/lrd/images/subpit.jpg).
1.2 Geography

Huntley Hollow lies $39^\circ37'38"$N and $82^\circ11'57"$W in the southeastern Ohio portion of the Appalachian Plateau and is a branch of the Brush Fork subwatershed (Fig. 1.2) in the Monday Creek and Hocking River drainage basin. It is approximately 1.7 km in length and covers an area of 0.9 km$^2$. The elevation ranges between 233 m and 330 m, with 97 m of topographic relief. The closest populated area is Murray City about 8 km to the south-east.

Huntley Hollow is crossed by an unimproved road, which runs from south to north and is passable only during dry weather. There are two gas wells and an electric power line present on the site. The owner of the site is Sunday Creek Coal Company. Regional vegetation can be classified as mixed mesophytic forest, and with its logging and mining history, the trees present are secondary growth and the understory is occupied by disturbance-related species (Bower et al., 2005).

1.3 Hydrology.

The main stream in Huntley Hollow is intermittent and is generally dry during summer months (June-August). For the rest of the year and during large precipitation events surface and base flow feed the main stream, which is in turn, largely captured by underground mine workings via subsidence features (Bower et al., 2005). Coal extraction resulted in several artificially depressed zones at the site. These depressions are often filled with water, forming ponds. The ground water table depths range from 8 m to 15 m.
Figure 1.2. Brush Fork watershed, the Huntley Hollow study area is outlined in green.
1.4 Stratigraphy

The Pennsylvanian (Allegheny Group) bedrock occupies a distal foreland basin setting and is characterized by several transgressive and regressive sequences incised by fluvial channels (Sturgeon, 1958; Fig. 1.3). Near the top of the section is the Freeport coal (No. 7). Because of the shallow depth at this site surface mine methods were used to extract coal from the No. 7 seam. The next 15 meter thick package is represented by shale with layers of freshwater limestone. Below this is a 17-meter thick succession of fluvial sandstones. The next lower sequence repeats with the same rock deposition but on a larger scale. The target of this research, Middle Kittanning Coal (No. 6) appears above the second sequence boundary and was deposited during a regional transgression (Sturgeon, 1958). The Middle Kittanning coal bed within the Monday Creek watershed dips approximately 16 m/km towards southeast.

Mining in Huntley Hollow exploited the Middle Kittanning coal via room-and-pillar and strip mines and the Upper Freeport Coal by strip mining (Fig. 1.4). Nearly the entire watershed is underlain by mine workings with the exception of the southernmost valley bottom where the Coal No. 6 was too shallow for effective underground mining (Fig. 1.4). However, there are some subsidence features and stream capture sites found there as well, indicating the presence of undocumented underground tunneling (Bower et al., 2005).

Middle Kittanning coal (No. 6) has a high sulfur content, and discharges of AMD from the mine workings down-dip (southeast) of Huntley Hollow in Murray City are currently an active target for remediation efforts (Bower et al., 2005). Locating these
mine workings in Huntley Hollow, particularly in likely stream and base flow capture areas, will aid these remediation efforts. The goals of this project were to identify these shallow workings, if possible, including the deepest ones, and to characterize the depth of strip-mine spoil piles by using both surface and subsurface geophysical methods.

Figure 1.3. Stratigraphic section of Huntley Hollow (modified from Sturgeon, 1958).
Figure 1.4. Coal mining methods (http://www.georgetown.edu/users/sal22/images/MineMethod.gif).


1.5 Previous Geophysical Work

Underground mine workings can be studied using many different methods including theoretical, graphical, as well as physical, and numerical modeling (Asadi et al., 2004). Huntley Hollow has a complicated geological environment (i.e., variations in elevation, the presence of the stream, and the stratigraphy) and the best method for detecting the presence of mine voids is not obvious. In order to ascertain the best geophysical for locating mine voids in this study a literature review was conducted.

Benson et al. (2003) employed the application of microgravity surveying to exploit the density contrasts between open voids and the surrounding intact coal. The method was found to be quite sensitive to terrain and temporal (i.e., tidal) effects and was of limited effectiveness in detecting deep (20-35 m) features. A further disadvantage of gravity methods is that flooded mine workings will have approximately half the density contrast of open mines and hence will produce half the gravity anomaly.

Ground-penetrating radar (GPR) application in Europe and Australia was studied by Griffin and Pippett (2002) and was found to be most effective at shallow depths (4-7 m). Radar penetration is limited by subsurface conductivity and GPR is not likely to produce useful results in the combination of clay rich soil and the shale common in the bedrock of Huntley Hollow, particularly under areas of higher surface elevation.

One of the earliest and simplest observations used to locate coal mine workings was based on correlation between barometric pressure and the gas emission in coal mines. Atmospheric pressure is the main factor that influences the efflux rate of subsurface gas, when the barometric pressure drops significantly, the ground surface temperature above
the mine workings increases (Donnelly and McCann, 2000). This technique is relatively simple; it requires ground surface temperature and barometric pressure measurements every 2.5 minute over a set time. The disadvantages of the method are the limitation to air-filled coal mine workings, terrain, and the underground mine workings have to be shallow in order to produce significant temperature fluctuation as the barometric pressure varies.

Multi-electrode resistivity imaging has proven to be successful at detecting open mine voids over a wide range of subsurface conditions. Johnson (2003) reviewed the theoretical and practical aspects of electrical resistivity tool in underground coal mine void detection. His results show that dipole-dipole and pole dipole electrical resistivity survey are effective to depths of 35m. Painter (2000) applied the technique successfully to abandoned mine sites in southeastern Ohio. Sheets (2001) also successfully identified shallow open mine workings at a highway subsidence site in Jackson and Vinton Counties in southeastern Ohio. Those results showed that open mines, either air-filled or flooded, could be detected at depths up to 40m under rugged terrain.

Surface deformation along State Route 32 in Vinton County prompted on investigation of the subsurface (Sheets, 2001). The surface electrical resistivity method was applied by Ohio Department of Transportation at two places along State Route 32 in Vinton and Jackson Counties, Ohio. One of the surveys was carried out along the road where subsidence features were visible. The second survey was applied at the surface of the known underground mine workings. Surveys included three types of electrical
**Figure 1.5.** Common configurations of electrical resistivity technique (modified from Parasnis, 1973). C- current electrode, P- potential electrode, a=electrode spacing, n=integer number of spacing, A-electric current, V-electric equipotential.
resistivity configuration: dipole-dipole, Wenner, and Schlumberger (Fig. 1.5). Based on electrical resistivity survey and available information they concluded that high resistivity responses represented the air-filled coal mine workings. The success of these and similar studies supports the use of electrical resistivity method in Huntley Hollow. More detailed information of the electrical resistivity method used in this study is described in the next chapter.
Chapter 2. Methodology

2.1 Data Collection

Data collection at Huntley Hollow began in the middle of June, and continued through the Fall of 2006. Three different data sets were collected: borehole logs of electrical conductivity, surface measurements of apparent resistivity, and topographic surveys. The borehole logging of the three wells (TH-1, TH-2, and Alt-B) drilled in Huntley Hollow by ODNR was conducted first. This consisted of lowering an electromagnetic probe (Geonics EM-39) down the borehole and recording the conductivity response of the strata every 0.2m as the probe was pulled uphole (Fig. 2.1).

Figure 2.1. Borehole logging technique, Geonics EM-39.
The electrical resistivity survey consisted of thirteen lines of dipole-dipole apparent resistivity measurements. These survey lines were located over zones of known or potential mine workings and were kept as straight as possible (Fig. 2.2). Survey line HH-1, with 610 m length and 5 m electrode spacing, was divided into seven sets. The survey lines HH-3, HH-3b, HH-4, HH-5, HH-6, HH-7, and HH-8 were measured with 7 m spacing due to the larger estimated maximum depth to the No.6 coal. Additional survey lines HH-9, HH-10, HH-11, and HH-12 were measured to characterize the shallow subsurface and used electrode spacings of 1 to 4 m.

The dipole-dipole electrical resistivity survey method applies a current (100 mA) at the ground surface via two stainless-steel electrodes and the induced electrical potential difference is measured between two collinear electrodes, also at the surface. The applied current, measured potential difference and the geometric arrangement of the four electrodes can then be used to determine an average, or “apparent”, resistivity for the subsurface beneath those electrodes.

For the fieldwork in Huntley Hollow, the AGI Sting/Swift multi-electrode system was employed (Fig. 2.3). In its standard configuration, this system allows for simultaneous deployment of 28 electrodes along two cables of 14 takeouts. Operating software controls the switching on and off for the various 4-electrode measurements. A field survey of 28 electrodes takes approximately two hours to complete.
Figure 2.2. Electrical resistivity survey line and well location, Huntley Hollow, Hocking County, Ohio. Contour interval is 20 ft.
Qualitatively, the current flow penetration into the subsurface will be greater with a large separation between the current electrodes (or the greater dipole spacing “a”). The calculated apparent resistivity can be roughly attributed to a subsurface point midway between the current (C) and potential dipoles (P) at a depth equal to half the distance (“n”) between the dipoles (Fig. 2.4). By moving the four electrodes along a survey line, the apparent resistivities beneath the line can be mapped out, producing a measured “pseudosection” (Fig. 2.5a).

Measuring apparent resistivities along a survey line can be done using just four electrodes, but this can become very cumbersome and time-consuming for long sections. Multi-electrode systems make the fieldwork more efficient placing by numerous electrodes and equal spacing along the survey line and then activating different combinations of four electrodes, in turn, to make the apparent resistivity measurements corresponding to different points in the subsurface.
Figure 2.4. A subsurface pseudosection in a multi-electrode dipole-dipole resistivity imaging survey. (Painter, 2000)
Figure 2.5. Standard output from RES2DINV, showing (a) measured apparent resistivities and (b) calculated resistivities based on (c) the inferred subsurface resistivity structure. Both horizontal distance and depth are in meters.
Electrode spacing depends mostly on the target depth. For example, in low-lying areas where the Middle Kittanning coal seam was shallow, a spacing as short as 2 m was sufficient. On the hillsides where the depth to the coal was greater, spacings as large as 7 m were used. Furthermore, the longest survey line (HH-1 with a length of 610 m) was divided into 7 sets of 28 electrodes each. In order to produce a single image, each set was overlapped and combined into a single line. To accomplish this, the first 14 electrodes of the second set were superimposed on the last 14 electrodes of the first set and so on. This technique was applied for HH-5, HH-7, and HH-9 survey lines having more than one 28-electrode set.

In the field, the first step was to clear out the survey path (Fig. 2.6) and place each of the electrodes with measuring tape, which sometimes took a full day. Then steel stake electrodes were hammered into the ground at the each location. Next, a cable with electrodes was laid out and connected to the electrodes. For each 28-electrode set, contact tests of the electrodes were conducted in order to identify faulty connections. Acceptable resistance values for the contact test were in the range of 200-2200[Ohm].

Figure 2.6. Left: Jesse Ayivor clears out path for survey line. Right: electrical resistivity equipment.
Overall, it took two hours to complete one survey and three sets of the electrical resistivity surveys could be measured per day. The stored data set in the memory of the Sting resistivity meter was transferred to an office computer daily. The entire electrical resistivity survey was completed in three weeks.

The pseudosection image of apparent resistivity is intended to serve as a means of portraying the measured field values. Analysis is required to determine the best estimate of actual subsurface resistivities that are consistent with these measured values. This analysis is carried out by the inversion software RES2DINV (Loke, 1999) via an iterative process. This program determines the optimal resistivity structure that could produce the measured pseudosection (Loke and Barker, 1996). RES2DINV produces four images for each survey line (e.g., Fig. 2.5 and 2.7). In the each image, the horizontal (X) axis represents distance (m) along the surface and also spacing between electrodes while the vertical (Y) axis represents depth (m). Color legends at the bottom of the image indicate either apparent resistivity or subsurface resistivity values. In Figure 2.5, for example, the bottom image (c) represents the subsurface resistivity structure that produced a calculated pseudosection (b) that best matched the apparent resistivities observed in the field (a). More details of the resistivity data analysis process are given in section 2.2.

The final resistivity images include topographic profiles for each section. In Figure 2.7 for example, RES2DINV applies a topography correction by interpolation of the elevation data for each electrode. For this correction, it was necessary to measure the location (x and y) and elevation (z) of each electrode with a total station (Fig. 2.8). In a typical day, 56-70 electrode positions were surveyed. In total, 471 electrodes were mapped in seven days for a combined 2414 m length of electrical resistivity images.
Figure 2.7. Final resistivity image corresponding to Fig. 2.5c, with topography taken into account. The level of the Middle Kittanning coal is also displayed.
Figure 2.8. Total station equipment.
2.2 Data Analysis

**Borehole Conductivity.** The conductivity logs were analyzed by converting measured conductivities to resistivities and plotting the resulting values against depth in the standard well log format (Fig. 2.9). Core descriptions are shown alongside the resistivity/conductivity logs. By examining all three resistivity-lithology log combinations, a correlation between resistivity ranges and lithology can be established. This correlation is then applied to the interpretation of the electrical resistivity images.

**Dipole-dipole Resistivity.** The recorded data sets stored in memory of the Sting R1 Meter were transferred to an office computer using AGI STINGDMP software and these were then converted to 2D dipole-dipole format using the Sting data conversion software program SWIFTCNV. The files from survey lines that have had more than one set, such as HH-1, HH-5, HH-7, and HH-9, were combined. Overlapping sections had duplicate resistivity records (Fig. 2.10), allowing an opportunity to determine if resistivity values correlated. Duplicate resistivity values were averaged together and the resulting values were transferred to a single final data file. Elevation data sets were combined with apparent resistivity values in the final data file.
Figure 2.9. Borehole conductivity and lithology logs.
The final data sets were processed using the RES2DINV software. The program uses an iterative process and determines the optimal subsurface resistivity structure that could reproduce the measured apparent resistivity pseudosection (Loke and Barker, 1996). The iteration process is continued until the RMS error between the measured and calculated apparent resistivity was minimized (Painter, 2000). The ideal RMS error is less than 5% although this was not always obtainable. Typically, five to eight iterations were applied.

![Overlapping scheme of dipole electrodes.](image)

**Figure 2.10.** Overlapping scheme of dipole electrodes.
Chapter 3. Results

3.1 Borehole Data

The range of measured downhole conductivities spanned from 6 to 20 mS/m, corresponding to resistivities ranging from $<1\,\Omega\cdot m$ to $>150\,\Omega\cdot m$ (Fig. 3.1-3.3). Although the extreme values are of less interest here, some general associations can be made between resistivity values and lithology.

Well TH-1 showed relatively high resistivity values in sandstones, especially in the dry near surface, as well as within ($\rho<30\,\Omega\cdot m$) the No.6 coal itself (Fig. 3.1). The lowest values ($\rho>60\,\Omega\cdot m$) were observed in the gray shale at the bottom of the well. Well TH-2 showed a nearly monotonic decrease in resistivity with depth, with dry, shallow sands giving values above $60\,\Omega\cdot m$ and unconsolidated clay, shale and coal producing a nearly uniform profile of $30\,\Omega\cdot m$ in the lower half of the well (Fig. 3.2). This well was drilled in tailings produced by strip mining of the No.6 coal in the lower portion of Huntley Hollow, so no intact rock or coal is present here. Alternate Corehole-B (Alt Core B) is sited on the eastern hillside above the floor of Huntley Hollow and consequently shows greater depth to the No.6 coal than does TH-1 (Fig. 3.3). This log generally follows the same trends seen in TH-1 and TH-2. In particular, clay-dominated sections tend to show lower resistivities while the higher values usually indicate sand-dominated lithologies or coal.

On the basis of these logs, a general scheme was developed for interpreting surface resistivity measurements in terms of intact lithologies. Sand-dominated lithologies and coal are indicated by resistivities above $60\,\Omega\cdot m$, shales tend to fall into
Figure 3.1. Measured borehole conductivity and lithology for well TH-1. The 30 and 60 Ω-m values shown separate the three resistivity ranges used in interpreting lithology from the dipole-dipole resistivity images.
Figure 3.2. Measured borehole conductivity and lithology for well TH-2. The 30 and 60 $\Omega$-m values shown separate the three resistivity ranges used in interpreting lithology from the dipole-dipole resistivity images. The water table is shown in green.
Figure 3.3. Measured borehole conductivity and lithology for well Alternate Core B. The 30 and 60 Ω-m values shown separate the three resistivity ranges used in interpreting lithology from the dipole-dipole resistivity images. The water table is shown in green.
the range of 30-60 Ω-m, and clay-dominated lithologies and unconsolidated spoils correspond to values below 30 Ω-m. This scheme is quite simplified and should not be overly interpreted as giving an exact subsurface stratigraphy. As will be seen in the next section, it is the extreme high and low resistivities that will be used to indicate potential mine voids.

3.2 Dipole-dipole Resistivity Data

The dipole-dipole apparent resistivities measured in the field were inverted for subsurface resistivity as described in Chapter 2. The inversion results for all sections, without topographic correction, are shown in Appendix A. While these images display an abundance of detail, their different resistivity scales and ranges make comparisons difficult. Therefore, the resistivity images are shown on the following pages with topography, coal seam elevation and a uniform resistivity scale.

The resistivity scale for intact lithology was taken from the borehole results of the previous section (Table 3.1). Extreme resistivity values, those either much less or much greater than those seen in the logs, are taken as potential indications of void space of seen at or near the elevation of the No.6 coal (Table 3.1). These extreme ranges were defined as ρ<7 Ω-m for water-filled voids (dark blue) and ρ>600 Ω-m for air-filled voids (red). The resistivity profiles will be discussed in groupings according to their location within Huntley Hollow: longitudinal (HH-1), eastern (HH-3b and HH-8), transverse (HH-3, HH-4, and HH-5), western (HH-6 and HH-7) and valley floor (HH-9, HH-10, HH-11, and HH-12).
**Longitudinal Profile: HH-1.** Based on the borehole logs and the core descriptions, the range of resistivity values determined for generalized lithologies at this site are: clay and shale, 7-30 ohm-m; wet sandstone, 30-100 ohm-m; dry and coal, 100-600 ohm-m (Table 3.1).

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<tr>
<th>Subsurface Materials</th>
<th>Resistivity Value (ohm-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated mine workings</td>
<td>&lt;7</td>
</tr>
<tr>
<td>Clay and shales</td>
<td>7-30</td>
</tr>
<tr>
<td>Shales and sandstone</td>
<td>30-60</td>
</tr>
<tr>
<td>Sandstones and intact coal</td>
<td>60-600</td>
</tr>
<tr>
<td>Air filled mine workings</td>
<td>≥600</td>
</tr>
</tbody>
</table>

**Table 3.1.** The resistivity values versus lithology.

Survey line HH-1 runs 610 m from south to north along the main trail in the valley. High-resistivity anomalies (>600 ohm-m) indicate several potential air-filled voids at the level of the coal No.6. These can be seen between locations 245 m and 485 m (Fig. 3.4). The anomalies near 360 m coincide with visible surface features of stream capture and subsidence. High-resistivity anomalies between 10 m and 135 m is in a region which may have experienced strip mining of the coal and so might be a result of that disturbance. The surface showed subsidence like features along this portion of HH-1. There were no low-resistivity anomalies along HH-1, similar to the profiles made along the eastern side of Huntley Hollow.
Figure 3.4. Resistivity image for profile HH-1. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Eastern Profiles: HH-3b and HH-8.

The survey line HH-3b was located on the east side of Huntley Hollow, and extended from north-west to south-east and nearly perpendicular to the line HH-3 (Fig. 2.2). The purpose of the line was to measure resistivity values along the highwall where a strip mine removed the No.7 coal. Transect HH-3b covered a distance of 161 m between profiles HH-3 and HH-8. High resistivity values (>600 ohm-m) were recorded at between 35-70 m and are interpreted as a region of air-filled voids (Fig. 3.5).

Figure 3.6 shows the modeled resistivity profile for the survey line HH-8. Transect HH-8 is located on the east side of study area and extends from north to south over 189 m (Fig. 2.2). The modeled resistivity shows extremely high resistivity values along the coal seam between the 40 m and 120 m locations. The extremely low resistivity values (<7 ohm-m) observed above the coal seam is associated with an artificial pond located about 10 m east of the survey line HH-8 at positions 70 m to 98 m.

Transverse Profiles: HH-3, HH-4, and HH-5.

The survey line HH-3 (Fig. 2.2 and 3.7) runs 189 m from west to east and intersects with survey line HH-1 at 126 m (HH-1, 145 m). The noticeable extremely low resistivity values at the surface, within distances of 84-95 m is an artifact due to metallic gas pipeline at that location. A resistive anomaly (>600 ohm-m) at 127 m coincides with the resistivity anomaly seen at location 140 m of transect HH-1 (Fig. 3.4).
Figure 3.5. Resistivity image for profile HH-3b. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Figure 3.6. Resistivity image for profile HH-8. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Figure 3.7. Resistivity image for profile HH-3. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
The survey line HH-4 (Fig. 3.8) is oriented from north-east to south-west (Fig. 2.2) intersects with HH-1 (245 m) at borehole TH-1 at 133 m. Generally high resistivity values were observed at the level of the No.6 coal with particularly high values seen at location 112 m, 133 m and 155 m. The anomaly at 133 m is consistent with that seen near well TH-1 in profile HH-1 (Fig. 3.4). The resistivity high at 155 m is unusual also in that it is located the most southwest of any observed high resistivity anomalies.

Survey line HH-5 (Fig. 3.9) covered 301 m from east to west across the northern edge of the study area (Fig. 2.2). It intersected HH-1 at the Alt Core-B and HH-6 at its western end. Resistivity anomalies near the No.6 coal are observed beneath surface locations 42-80 m at the eastern end of the profile.

**Western Profiles: HH-6 and HH-7.**

Survey line HH-6 (Fig. 3.10) is a north-south transect located on the west side of Huntley Hollow (Fig. 2.2). It covered 189 m of total length and intersects with survey line HH-5 (291 m) at location 35 m. The resistivity modeling shows extremely low values at the level of the No.6 coal between 84 m and 112 m. The anomaly can be explained as a water-saturated mine void which occurs right along the No.6 coal seam.

Figure 3.11 shows the modeled subsurface resistivity line HH-7. It is on the west side of study area, and runs 287 m from south to north (Fig. 2.2). The observed resistivity anomaly at 175 m was extremely low (<7 ohm-m), and is interpreted to be a water-saturated mine void. Another low-resistivity anomaly is apparent beneath location 45 m, although it is centered somewhat above the No.6 coal. Elsewhere on this line high resistivity values are observed along the coal seam. These observed anomalies at distance 63-145 m could be interpreted either as locally isolated air-filled mine voids or as high
Figure 3.8. Resistivity image for profile HH-4. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Figure 3.9. Resistivity image for profile HH-5. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Figure 3.10. Resistivity image for profile HH-6. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Figure 3.11. Resistivity image for profile HH-7. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
resistive layer of rock (coal).

**Valley Floor Profiles: HH-9, HH-10, HH-11, and HH-12.**

Profiles HH-9, HH-10, HH-11, and HH-12 were surveyed in a relatively small area on the valley floor of Huntley Hollow, near to and northwest of well TH-1. The purpose of these surveys was to search for evidence of undocumented mine tunnels in the shallow subsurface that would connect the large mine complexes on either side of the valley. Due to the both the shallow depth to the No.6 coal and the short lengths of these profiles, short electrode spacings (1m to 4 m) were used here.

Unfortunately, except for the 4 m spacing used for HH-9, these spacings were too small to allow current penetration to the depth of the coal. Survey line HH-9 (Fig. 3.12) shows no anomalous resistivities that would indicate subsurface mine voids. This is somewhat unexpected as apparent subsidence features were seen in this area. Although they did not image the coal seam, profiles HH-10 (Fig. 3.13), HH-11 (Fig. 3.14), and HH-12 (Fig. 3.15) produced consistent resistivity values associated with near-surface material sand intact rock.
Figure 3.12. Resistivity image for profile HH-9. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Figure 3.13. Resistivity image for profile HH-10. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Figure 3.14. Resistivity image for profile HH-11. The level of the Middle Kittanning coal is also displayed. Both horizontal position and depth are given in meters.
Figure 3.15. Resistivity image for profile HH-12. Both horizontal position and depth are given in meters.
Chapter 4. Discussion and Conclusions

There is generally good agreement between the resistivity observed in the three boreholes and those derived from the inversion modeling. A borehole log is more precise than surface measurements and reflects the properties of only those materials in the vicinity of the well. Surface resistivity on the other hand, tends to average out small local variations, particularly at depth. Also, high and low inferred resistivities in the profiles can be unrealistically exaggerated by the inversion algorithm as it attempts to maximize a fit to the measured apparent resistivities.

The variation of resistivity with depth in wells TH-1 and TH-2 (Fig. 3.1 and Fig. 3.2) fits the pattern seen in resistivity section HH-1 (Fig. 3.4). Similarly, section HH-4 (Fig. 3.8) shows a trend towards higher resistivities with depth that matches that seen in the lower portion of TH-1. Section HH-5 (Fig. 3.9) reproduces the resistivity/depth relations seen in Alt-Core B (Fig. 3.3). Both show low resistivity near the surface, intermediate values over most of depth range with zones of higher resistivity middle depths and near the bottom of the hole. Intersecting profiles also give consistent results at their crossing points. Both HH-3 and HH-4 (Figs. 3.7 and 3.8) indicate high resistivities near the No.6 coal, as does HH-1 (Fig. 3.4).

The resistivity images should not be expected to give perfect matches to the logs or to each other. The inversion process assumes that all resistivity variation is within the plane of the profile. In other words, there is assumed to be little variation in the direction perpendicular to the image. This is obviously an idealization, and out-of-plane anomalies will be projected into the image and will appear as though lying in the profile plane.
High ($\rho>$600 $\Omega$-m) and low ($\rho<$7 $\Omega$-m) resistivity anomalies, if present near the Middle Kittanning coal, are interpreted as indicators of potential mine voids. High and low anomalies are also seen away from the coal horizon and on the edge of some images, but these are taken to be zones of particularly dry or saturated materials, respectively.

The identified potential mine voids are listed in Table 4.1 along with their inferred saturation state and geographical location within Huntley Hollow. Evident in the table is the predominance of dry voids in the east, with saturated mine space appearing only in the western portion of valley. This relationship is shown in Fig. 4.1. The overall interpretation of this pattern is that mine workings underneath the western slopes of Huntley Hollow are flooded while those underneath the eastern slopes are not and presumably drain down-dip towards the southeast.

A possible mechanism for producing flooded mines to the west and dry voids to the east is depicted in Fig. 4.1. Blockage of down-dip drainage along the western edge of Huntley Hollow would produce flooding there (Fig. 4.2). This blockage could be due to the entrance collapse, surface subsidence, or disturbance by later strip mining. The pooled waters would be slowly released by springs along the southwest edge of Huntley Hollow, slow seepage into the creek or flow around to the east through mine workings to the north of the study area. Waters reaching the mines beneath the eastern portion of Huntley Hollow, due to either infiltration or stream capture, would drain eastward towards Murray City.
<table>
<thead>
<tr>
<th>Section</th>
<th>Position</th>
<th>Sat./Dry</th>
<th>East/West</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH-1</td>
<td>130 m</td>
<td>Dry</td>
<td>----------</td>
</tr>
<tr>
<td>HH-1</td>
<td>175 m</td>
<td>Dry</td>
<td>----------</td>
</tr>
<tr>
<td>HH-1</td>
<td>260 m</td>
<td>Dry</td>
<td>----------</td>
</tr>
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<td>300 m</td>
<td>Dry</td>
<td>----------</td>
</tr>
<tr>
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<td>360 m</td>
<td>Dry</td>
<td>----------</td>
</tr>
<tr>
<td>HH-1</td>
<td>390 m</td>
<td>Dry</td>
<td>East</td>
</tr>
<tr>
<td>HH-1</td>
<td>480 m</td>
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<td>East</td>
</tr>
<tr>
<td>HH-3b</td>
<td>46 m-70 m</td>
<td>Dry</td>
<td>East</td>
</tr>
<tr>
<td>HH-8</td>
<td>40 m-120 m</td>
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</tr>
<tr>
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<td>140 m</td>
<td>Dry</td>
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<tr>
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<td>112 m</td>
<td>Dry</td>
<td>East</td>
</tr>
<tr>
<td>HH-4</td>
<td>133 m</td>
<td>Dry</td>
<td>----------</td>
</tr>
<tr>
<td>HH-4</td>
<td>155 m</td>
<td>Dry</td>
<td>West</td>
</tr>
<tr>
<td>HH-5</td>
<td>42 m-80 m</td>
<td>Dry</td>
<td>East</td>
</tr>
<tr>
<td>HH-6</td>
<td>84 m-112 m</td>
<td>Saturated</td>
<td>West</td>
</tr>
<tr>
<td>HH--7</td>
<td>45 m</td>
<td>Saturated</td>
<td>West</td>
</tr>
<tr>
<td>HH-7</td>
<td>63 m-156 m</td>
<td>Saturated</td>
<td>West</td>
</tr>
<tr>
<td>HH-7</td>
<td>175 m</td>
<td>Dry</td>
<td>West</td>
</tr>
<tr>
<td>HH-7</td>
<td>210 m-238 m</td>
<td>Dry</td>
<td>West</td>
</tr>
</tbody>
</table>

*Table 4.1. Potential mine voids.*
Figure 4.1. Distribution of potential mine voids.
Figure 4.2. Subsurface structure along No.6 coal seam, Huntley Hollow, Ohio. Scale is not applied.
The high resistivity anomalies seen near the intersection of HH-4 and HH-7 do not fit the pattern. One of possible explanation for these broad high-resistivity zones at the level of the Middle Kittanning coal is that they represent intact (unmined) coal and high-resistivity rock. Another, less likely, interpretation of these observed high resistivity values could be that they are isolated flooded mine workings.

The interpretation presented here can be explored further in future work. In accessible areas, shallow drill holes could verify the existence of mine voids at the resistivity anomalies. This could be done at locations 165 m and 360 m on HH-1 (Fig. 4.3). The valley floor section HH-10, HH-11, and HH-12 could be investigated again using a dipole spacing of 4m to ensure current penetration to the depth of the coal. In addition investigation with other geophysical methods, such as surface-wave tomography (e.g., Sheehan, 2002), would help verify the anomalies seen here.
Figure 4.3. Recommended borehole locations TH-3 and TH-4.
References


Sheehan J., 2002. Shear-wave profiles of surficial deposits in Ohio using multichannel

Sheets R.A. 2001. Use of Electrical Resistivity to Detect Underground Mine Voids in
Investigations Report 02-4041, p. 12.

Sturgeon M. T., 1958. The geology and mineral resources of Athens
County, Ohio, Ohio Geological Survey Bulletin 57, p. 600.
Appendix A

Subsurface Resistivity Inversion Images, Huntley Hollow, Ohio

Standard output from resistivity processing software RES2DINV. Each of the following pages displays three images for each section. The top is apparent resistivity pseudosection representing the field data. The middle image is a calculated apparent resistivity pseudosection showing what would have been observed in the field if the subsurface resistivity structure is as shown in the bottom image. Thus, the bottom image represents the results of the processing. Its validity is indicated by the match between the top two pseudoseCTIONS, or by the degree to which the RMS error value is minimized. Topography is not taken into account here, but has been corrected for in the images shown in Chapter 3. In all of the following images, both horizontal distance and depth are given in meters.