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Interpretation of Helicopter Electromagnetic Data for the Coketon/Kempton Mine Complex in Maryland and West Virginia

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MARYLAND POWER PLANT RESEARCH PROGRAM

Martin O'Malley, Governor ♦ Anthony G. Brown, Lt. Governor

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INTERPRETATION OF HELICOPTER ELECTROMAGNETIC DATA FOR THE COKETON/KEMPTON MINE COMPLEX IN MARYLAND AND WEST VIRGINIA

PREPARED FOR:

POWER PLANT RESEARCH PROGRAM
MARYLAND DEPARTMENT OF NATURAL RESOURCES

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MAY 2010

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FOREWORD

In 1995 the Maryland Power Plant Research Program initiated research to use power plant combustion by-products in three specific areas that were expected to solve important environmental problems in Maryland, namely:

- Stabilization or solidification of problem materials;
- Mine restoration;
- A new approach to creating structural fills with fly ash.

All three of these areas of research would take advantage of the pozzolanic properties of fly ash to create materials with physical properties useful to engineers; and chemical, seepage, and leaching characteristics acceptable to environmental regulators. The Maryland Pozzolan Act provided a legal basis for such usage.

The quantities (about 2 million tons per year) of coal combustion by-products being produced in Maryland dictated that the uses for them be massive to avoid the high cost associated with transporting and disposing of them in approved landfills. Maryland's large cement industry could be expected to absorb up to 50% of this production leaving about a million tons per year for other uses. One important environmentally beneficial application that could use this quantity of material is mine restoration.

Maryland has numerous clay, and sand and gravel pit mines on the Coastal Plain; dozens of rock quarries in the Piedmont, Blue Ridge, and Valley and Ridge Provinces that make up central Maryland; and hundreds of abandoned underground coal mines in the Appalachian Plateau Province of far western Maryland. Each mine presents several hydro-geologic issues and environmental engineering problems for successful closure and restoration.

Kempton Mine No. 42 that operated from 1914 to 1950 is an outstanding example of a mine shut down overnight and abandoned without provision being made for: its impact on ground and surface water movement, potential impact of subsidence, and eventual flooding and production of acidic mine drainage.

The Helicopter Electromagnetic Survey reported on here was paid for by the U.S Department of Energy supporting their interest in remote sensing of water quality. The survey was arranged by the Maryland Power Plant Research Program to help identify the origins of acid mine drainage and its movement in the vicinity of Kempton Mine No. 42 to isolate possible targets for application of coal combustion by-product grouts. All of the survey data was immediately made available to local organizations concerned with abandoned mined land restoration.

Paul Petzrick
Power Plant Site Assessor
Maryland Power Plant Research Program

ACKNOWLEDGEMENTS

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- Joseph Giacinto and Leonard Rafalko, Environmental Resources Management, Inc., Annapolis, MD;
- Richard Hammack, U.S. DOE National Energy Technology Laboratory, Pittsburgh, PA;
- Jason Litten and Erica Breighner, Geospatial Research Group, Department of Geography, Frostburg State University, Frostburg, MD.

ABSTRACT

During 1999, the U.S. Department of Energy's National Energy Technology Laboratory (NETL) conducted helicopter electromagnetic (HEM) surveys over a 64 square kilometer area that included the Coketon/Kempton Mine Complex as part of a Cooperative Research and Development Agreement (CRADA) with the Maryland Department of Natural Resources (MDNR) Power Plant Research Program (PPRP). The HEM survey data was evaluated to assess the usefulness of the data for characterizing abandoned mine lands, and identifying areas of underground mine voids that could benefit from focused mine reclamation efforts utilizing Coal Combustion Byproducts (CCBs) either singularly or to augment other mitigation measures such as lime dosing.

One of the difficulties of performing focused remediation of AMD is that abandoned underground mine tunnels are often very difficult to locate from the surface, requiring, in some cases, iterative and costly subsurface drilling. Accordingly, the goal of the study was to determine whether the HEM technology could be used as a cost efficient, remote sensing technology to identify underground mine workings containing AMD.

Since acidic mine water tends to have a high electrical conductivity signature relative to unaffected groundwater and surrounding strata, HEM surveys could, in theory, be used to map conductivity anomalies that would correlate with underground mine tunnels containing AMD. However, the study showed that the method is not feasible with current technology for the project area due to limitations resulting from depth of penetration. Specifically, the majority of mine workings in the project area proved to be beyond the maximum exploration depth of the survey method.

Nonetheless, the HEM survey results were useful in delineating near-surface areas of relatively high conductivity associated with acid mine drainage (AMD) sources. Based on the survey data signatures, unreclaimed mine spoil piles generally exhibit a greater and continuing source of AMD than the reclaimed areas of mine spoil piles. The survey data signatures also indicate that spoil pile reclamation efforts by the Maryland Department of the Environment (MDE) have been successful in reducing the production of AMD production from these areas.

Conceptually, the HEM survey results indicate that zones of relatively high conductivity water, originating at unreclaimed mine spoil piles in the northwestern project area, extend hundreds of meters down-gradient of the mine spoil piles. The reworked areas of unreclaimed mine spoil piles are disturbed areas where relatively oxygen-rich surface runoff and stream flow may readily infiltrate through rubble into subsurface strata and create favorable conditions for acidic water production. The zones of high conductivity emanating from the unreclaimed piles are indicative of AMD sources traveling down-gradient and contributing to AMD in the mine pools and degraded surface water quality at seeps and wetlands in Western Maryland watersheds..

In locations where surface mining has breached the mine tunnel network, AMD from the mine spoil piles may infiltrate into the mine tunnel network and flow through the mine floor pavement. In these cases, the acid content is further enhanced by the reaction of the water with the residual pyritic compounds on the mine floor before reaching the mine pool.

1.0 INTRODUCTION

The Maryland Abandoned Mine Reclamation Plan (the Plan) approved in 1982 gave Maryland primacy over abandoned mined land activity in the State. Consistent with the Plan, PPRP has partnered with private industry and state and federal agencies to demonstrate the beneficial application of Coal Combustion Byproducts (CCB) to place pozzolan-based flowable and environmentally benign grouts in subsurface coal mines to reduce acid mine drainage (AMD), prevent subsidence, and restore disturbed hydrogeology affecting natural drainage patterns.

As part of a Cooperative Research and Development Agreement (CRADA) with MDNR, the U.S. Department of Energy's National Energy Technology Laboratory (NETL) conducted helicopter electromagnetic (HEM) surveys during 1999 over a 64 square kilometer area that included the Coketon/Kempton Mine Complex. A primary research goal of the CRADA and the Plan is to assess the potential to mitigate AMD through the beneficial use of CCBs.

One of the difficulties of performing focused remediation of AMD is that abandoned underground mine tunnels are often very difficult to locate from the surface, requiring, in some cases, iterative and costly subsurface drilling. Accordingly, the goal of the study was to determine whether the HEM technology could be used as a cost efficient, remote sensing technology to identify underground mine workings containing AMD.

Since acidic mine water tends to have a high electrical conductivity signature relative to unaffected groundwater and surrounding strata, HEM surveys could, in theory, be used to map conductivity anomalies that would correlate with underground mine tunnels containing AMD. However, the study showed that the method is not feasible with current technology for the project area due to limitations resulting from depth of penetration. Specifically, the majority of mine workings in the project area proved to be beyond the maximum exploration depth of the survey method.

Nonetheless, and as discussed in this report, the HEM survey results were useful in delineating near-surface areas of relatively high conductivity associated with acid mine drainage (AMD) sources. Based on the survey data signatures, unreclaimed mine spoil piles generally exhibit a greater and continuing source of AMD than the reclaimed areas of mine spoil piles. The survey data signatures also indicate that spoil pile reclamation efforts by the Maryland Department of the Environment (MDE) have been successful in reducing the production of AMD production from these areas.

The objective of this report is to present PPRP's evaluation of the HEM survey data, assess the usefulness of the data for characterizing abandoned mine lands, and identify areas that would significantly benefit from focused mine reclamation efforts. Useful information to be derived from the survey data includes identification of flooded mine workings, abandoned mine discharges, acid mine water recharge zones, extent of spoils piles, and groundwater flow directions.

1.1 REPORT PURPOSE

The purpose of this report is to document the results of the HEM survey, and potential application to the project area. This report presents the following:

- Documentation of the survey method and data processing performed for the data collected over the project area;
- Analysis of the survey results to determine the extent of mine pools and/or sources of AMD if evident; and
- Identification of surface and subsurface mined areas that could benefit from the application of engineered CCB material or CCB-based cement grout to reduce acid mine drainage.

1.2 PROJECT ACKNOWLEDGEMENTS

As part of the CRADA (1999), the HEM survey, data analyses, and this report are a cooperative effort between public and private sectors with a vested interest in environmental and economic aspects of coal mining and mine reclamation in Western Maryland. For this project, the team consisted of the following organizations:

- ***Maryland Department of Natural Resources Power Plant Research Program (PPRP).*** PPRP provided project management and funding;
- ***U.S. Department of Energy National Energy Technology Laboratory (NETL).*** NETL coordinated the airborne surveys with subcontractors,

pre-processed the survey data, assisted in the data review, and provided airborne survey documentation;

- ***Environmental Resources Management, Inc. (ERM).*** As PPRP's Environmental Integrator (EEI), ERM post-processed, reviewed, and analyzed survey data, created overlay maps, and interpreted the airborne electromagnetic data; and

- ***Frostburg Geospatial Research Group (GRG).*** The GRG has served as PPRP's primary source for geospatial mine map development, digitizing, geo-referencing and water resource evaluations.

This report is made possible through the leadership of Dr. Peter Dunbar (PPRP), and Mr. Paul Petzrick's (PPRP) management of PPRP projects targeting mine restoration, reclamation, and beneficial use of CCBs.

2.0 PHYSICAL SETTING AND MINE COMPLEX

Straddling the Maryland and West Virginia border, the project area is the Coketon/Kempton Mine Complex. The complex is part of a larger group of mines in the Upper Potomac basin (Figure 1) that were developed to mine economically viable coal seams. Topography in the project area generally slopes towards the northeast and southwest (Figure 2). The Upper Freeport coal seam outcrops in the western and southeastern project area.

The Eastern Continental Divide bisects the northern portion of the project area (Figure 1) and divides surface water flow into northeasterly and southeasterly directions. In the north, the project area includes the northeasterly-flowing headwaters of the North Branch of the Potomac River (North Branch) and Laurel Run, a tributary to the North Branch. In the southern project area, the North Fork of the Blackwater River flows towards the south and east.

2.1 GEOLOGY

The Coketon/Kempton Mine Complex is located in the Appalachian Plateau Physiographic province in the extreme southwestern corner of Garrett County, Maryland. Bedrock in this region consists primarily of shale, claystone, siltstone and sandstone. Gentle folding in the region has produced a series of elongated synclines and anticlines trending approximately N40°E and plunging 2° to 3° to the northeast. Coal-bearing strata of Pennsylvanian age are contained in the intervening synclinal basins.

The Coketon/Kempton Mine Complex was established to mine the Upper Freeport coal seam (Figure 2), which is approximately 1.2 to 1.4 meters (m) thick throughout the majority of the mine complex. The syncline trend and plunge (Figure 3) associated with the Upper Freeport coal seam is typical of the geologic structure in the project area. The Upper Freeport surficial outcrop (Figure 2) is coincident with mine spoil piles that delineate past surface mining operations in the outcrop area.

2.2 MINE COMPLEX

The Coketon/Kempton Mine Complex consists of nine interconnected abandoned mines, covering a surface area of about 60 square kilometers (Figure 2). Seven percent of the mine complex is within Garrett County Maryland; the remaining portion is in Tucker County, West Virginia. The Upper Freeport coal seam was mined using the room and pillar method (Swartz and Baker, 1920) by Davis Coal & Coke Company from the 1880s to 1950.

During mining activities, groundwater seeping into the mine was pumped to the surface to keep the mine tunnel network from flooding. After mining activity ceased, portions of the mine tunnel network gradually filled with groundwater. Currently, mine-impacted water exists in two mine pools: the Kempton Pool and Coketon Pool (Figure 1). The larger of the two pools is the Kempton Pool and contains about 1.1 billion gallons of water. The Kempton Pool discharges an average of 3.5 million gallons per day (gpd) of AMD into Laurel Run (PPRP, 2000), which is a tributary of the North Branch of the Potomac River. Although the majority of the Kempton pool lies in West Virginia, all of the discharge is to Laurel Run in Maryland.

The Coketon Pool is the smaller mine pool and lies entirely in West Virginia. The Coketon Pool contains approximately 690 million gallons of water and is believed to discharge an average of 3.3 million gpd in an unknown proportion between the North Fork of the Blackwater River in West Virginia and the Kempton Pool straddling the Maryland and West Virginia border (PPRP, 2000).

2.3 ACID MINE DRAINAGE

AMD is defined as drainage flowing from or caused by surface mining, deep mining or mine spoil piles. AMD is typically highly acidic with elevated levels of dissolved metals (particularly iron). AMD is formed by a series of chemical and microbial enhanced reactions that occur when oxygenated water comes in contact with pyrite (FeS_2). The result of the reaction is the formation of sulfuric acid and iron hydroxide. The general chemical equation for AMD formation is:

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O \leftrightarrow Fe(OH)_3 + 2\ H_2SO_4 \quad (1)$$

Pyrite is commonly present in the coal seams, the rock layers overlying the coal, and the mine refuse (spoil) piles. AMD formation typically occurs in surface mining areas where oxygenated surface water runoff and stream flow can readily infiltrate the spoil piles. AMD can also occur in deep mines which allow the entry of oxygen or oxygenated water to come into contact with pyrite-bearing coal seams, high sulfur mine pavement, and collapsed tunnel roof debris. The reactions raise the water acidity (i.e., lower the water pH) and degrade water quality to levels that are toxic to flora and fauna.

Mine refuse piles are commonly referred to "gob" piles when residual fuel (i.e., coal) exists in the piles, and referred to as "mine spoil" piles when little or no residual fuel value exists in the piles. Although some refuse piles are known to have residual fuel value in the project area, the distinction for purposes of this study is irrelevant. Therefore, mine refuse piles will be referred to as mine spoil piles for consistency in this report.

3.0 AIRBORNE SURVEY METHODS AND DATA COLLECTION

Airborne surveys were conducted with an electromagnetic sensor ("bird") towed over the project area by a helicopter (Figure 4). During the survey, a Fugro® DIGHEM^{VRES} bird was carried at a nominal altitude of 30 m to maximize sensitivity and spatial resolution. This type of survey is referred to as a Frequency Domain Electromagnetic (FDEM) Survey. The FDEM survey used paired transmitter and receiver coil operating at five frequencies to obtain different exploration depth intervals for each corresponding frequency. Lower frequencies penetrate deeper into the subsurface than the higher frequencies. For the project area survey, the transmitter receiver coils operated at frequencies of 390 hertz (Hz), 1,555 Hz, 6,254 Hz, 25,800 Hz, and 102,680 Hz. The low altitude and slow flying speed of helicopter provide for maximum conductor resolution and maximum sensitivity to weak conductors.

In the project area, the transmitter receiver coil pairs have the potential to determine a vertical conductivity distribution to a maximum depth of approximately 100 m. The ability to detect a mine pool, however, depends on the depth, thickness and conductivity of the mine pools as well as the thickness and conductivity of the overlying material (e.g., bedrock minerals, pore water, and voids). Over the project area, 124 flight lines (Figure 5) were flown in an east to west direction spaced approximately 50 m apart.

3.1 AIRBORNE ELECTROMAGNETIC SURVEYING

Electromagnetic (EM) conductivity techniques measure the conductivity of the earth by applying a varying magnetic field. The applied magnetic field induces eddy currents within subsurface conductors (e.g., mine pools), which in turn generate a secondary magnetic field that can be detected by sensors at ground surface or by sensors towed through the air by low-flying aircraft. The strength of both the primary (applied) magnetic field (H_p) and secondary magnetic field (H_s) are measured using a receiver antenna and are distinguished based on intensity, phase or direction. The ratio (H_s/H_p) is linearly proportional to the ground conductivity:

$$\frac{H_s}{H_p} = \frac{i\omega\mu_0\sigma s^2}{4} \qquad (2)$$

where H_s= secondary magnetic field; H_p= primary magnetic field; $\omega = 2\pi f$; f = frequency (Hz); μ_o= magnetic permeability of free space; σ = ground conductivity (siemens/m); s = distance between transmitter and receiver coils (m); and i = $\sqrt{-1}$.

The above expression is valid only if a low induction number can be assumed. The induction number (B) is dependent on the intercoil spacing (s) in the bird and the skin depth (δ) where (McNeill, 1980):

$$B = \frac{s}{\delta} \qquad (3)$$

For the project area, the assumption of a low induction number is valid given the coil configuration of the bird, and the average ground conductivity in the region. The skin depth is described as the depth at which the amplitude of the electromagnetic field drops to 1/*e* of the source amplitude (*e* being the natural base). Skin depth is a function of the transmitter frequency (f) and ground of the EM conductivity (σ). The exploration depth or skin depth (δ) for EM conductivity is determined by:

$$\delta = 500\sqrt{\frac{1}{\sigma f}} \qquad (4)$$

For σ units of siemens per meter (S/m), and f units of Hz, the skin depth units will be meters. As implied by this relationship, increases in ground conductivity and frequency values will decrease the skin depth, and therefore, decrease the depth of investigation (McNeill, 1980).

The effective exploration depth of EM methods is generally taken to be approximately one half of the skin depth (Hammack, 2000). In nearby Preston County, WV, average ground conductivities over mining areas have been calculated as 20 millimhos per meter (Mabie, 2003). For a ground conductor of 20 millimhos per meter (conductivity 50 mS/m), the average maximum exploration depth over the five EM frequencies is approximately 70 m for the project area with an average effective exploration depth of about 35 m. Using Equation 4, the skin depths for the corresponding EM frequency are summarized below.

f - frequency (Hz)	δ - skin depth (m)	½ δ (m)
390	180	90.0
1,555	90	45.0
6,254	45	22.5
25,800	22	11.0
102,680	11	5.5
Average:	**70**	**35**

The study determined that, based on the effective average exploration depths, nearly all of the mine complex and pools in the project area are below the detection depth of the survey methods.

3.2 DATA REDUCTION

Pre-processing of the raw EM data (Appendix A) was performed by the NETL Pittsburgh office with the EM1DFM (UBC, 2000) software application. The EM1DFM application is one-dimensional inversion program that assumes a mathematical model of the earth varies only with depth within a stack of uniform horizontal layers. All sensor measurements made at a single X and Y location are grouped together to generate a one-dimensional vertical model of conductivity. For each flight line, the separate one-dimensional models are combined to create a two dimensional conductivity/depth image (CDI) profile or cross section of conductivity values with depth (Appendix B).

For EM studies, vertical models are typically refined with surface and borehole geophysics coincident with flight lines. Within the project area, no such surface or borehole geophysical data were available; accordingly, an initial vertical exploration depth of 100 m was assumed based on past experience in the region. Conductivities values were calculated at one meter intervals along the depth profile by the data processing software. An important aspect of the one meter vertical spacing was to allow for a reasonably fine vertical discretization to capture signatures of AMD recharge areas or flooded mine tunnels.

In practice, the effective depth of exploration is dependent on site specific factors such as the thickness and conductivity of the mine pool as well as the thickness and the conductivity of overlying strata. Relatively conductive strata tend to subdue responses from deeper layers.

The initial depth model was based on the general conditions encountered in the region and is consistent with the maximum effective depth of exploration (90 m). The initial (100 m) depth model does not affect the conductivity values calculated and used in the development of the CDIs. If the depth used for the initial depth model is greater than the effective depth of exploration, conductivity values will not be calculated beyond this effective depth during data pre-processing.

3.3 DATA LIMITATIONS

Data limitations fall into the two basic categories of geography and survey equipment considerations. Geography includes consideration of the vertical and horizontal extents of the mine workings, and geology and signal interference from electrically conductive cultural features near towns and developments. Equipment considerations are associated with limitations inherent to the configuration of the electronics used for the survey as discussed in the section below.

For each area, the data limitations were considered when evaluating the electromagnetic data by inspecting aerial photographs and U.S. Geological Survey (USGS) 7.5 minute quadrangles for features coincident with the flight lines. The aerial photographs were taken during 1999, (the same year as the EM survey), and provided a valuable reference for evaluating signal interference from surface features. Although the revision dates for the USGS quadrangles were several years earlier than the EM survey, these maps provided useful insight into surface water drainage patterns and topography.

3.3.1 Geographic Considerations

Cultural noise, (i.e., EM interference from "man-made" objects), can be caused by many types of electrical conductors including metal towers, pipelines, power lines, railroad tracks, buried metal objects, and buildings. Frequencies of power lines can also distort survey signatures of the lower EM survey frequencies through a type of harmonic effect. The majority of cultural noise encountered was in the vicinity of populated areas, particularly near Thomas, WV (Figure 5). In this vicinity, significant flight line diversions were required to avoid populated areas. Coupled with the interruption in the uniformly spaced data collection grid, dense cultural features significantly distort the survey data signatures near Thomas, WV.

3.3.2 Equipment Considerations

Because the EM field strength will decrease by the distance from the source cubed (Fugro, 1999), variations in the height of the bird above land surface may significantly affect the signature of conductive features. During the survey, the helicopter was flown at a relatively constant elevation. As with any survey of this type, cross winds sometimes blow the bird off of a vertical line with respect to the helicopter. Although the bird remains traveling in an east-west direction, the location and height of the bird would be adversely affected by not being directly beneath the helicopter. Although the bird deviations were not recorded during the EM survey, an awareness of the bird deviations needs to be considered when interpreting survey signatures.

Within the helicopter, a GPS device recorded the location and elevation for each EM reading taken by the bird. If the bird is not directly underneath the helicopter, the coordinates calculated by the GPS are slightly offset with respect to the EM measurement made by the bird. An error in an X Y location of 5 m would not be unreasonable on a gusty or moderately windy day. Given the scale of the project area, the errors in X Y location would have negligible effect on the overall distribution of conductive features. The primary effect of a non-vertical line extending from the helicopter to the bird would be to increase the bird height above land surface thereby decreasing the signal strength from conductive features. In areas of abrupt topographic changes, decreased signal strength would also be expected due to the physical limitations of the helicopter/bird array to quickly adjust to extreme elevation changes.

4.0 RESULTS OF DATA INTERPRETATION

Due to exploration depth constraints, it was determined that the survey methods and data were not capable of delineating the areal extent of the mine pools over the project area. However, survey data signatures within the effective exploration depth were capable of reflecting other conductive features of interest including AMD recharge areas, mine spoil piles, and surficial expressions of AMD.

4.1 CONDUCTIVITY SIGNATURES

Information derived from the survey includes the raw (conductivity) data collected for each specific survey frequency, and the two-dimensional CDI profiles generated from the depth models along a flight line. The raw data represents an areal view of bulk or average conductivity measurements across the exploration depth interval associated with the corresponding survey frequency. The CDI profiles were developed by combining all of the one-dimensional conductivity depth models calculated along each corresponding flight line.

The CDI profiles are useful for delineating localized surface and subsurface targets and layered features while the raw survey data are useful for delineating the areal patterns of bulk conductivities over a given depth interval. The CDI profiles give a refined view of conductivities while the raw survey data give a broader view of conductive patterns over the corresponding depth interval.

4.1.1 Areal View of Bulk Conductivity

In the absence of cultural features, subsurface conductors may include areas of weathering mine spoil piles, saturated areas/wetlands, headwaters of streams, and acidic discharge areas. Over the project area, known AMD locations were found to be associated with higher conductivities near the head waters of Laurel Run (Figure 6), and near the Coketon Pool weir discharges along the Blackwater River in WV. A portion of the high conductivity signature near the Coketon weirs may be due to utility lines associated with the major roadway along the Blackwater River. In this area, however, the piezometric elevation of the Coketon mine pool is known to intercept land surface with significant discharges of AMD to the Blackwater River. Therefore, a significant portion of the high conductivity signature is believed to be due to the AMD discharge in this area.

Additional areas of high conductivity trend along the mine spoil piles in the western project area following the Upper Freeport outcrop (Figure 6). Signal interference from electrical conductors associated with cultural features is prevalent near population centers in the southern project area as well as locations near power lines, roads, and developments. Locations such as electrical substations (e.g., near William, WV) also generate significant amounts of cultural EM noise.

4.1.2 Conductivity Depth Images

In the northern study area, a prevalent feature in several of the CDIs is a relatively consistent conductive “layer” that tends to correlate with surface topography. Typically, this type of topography correlated pattern is characteristic of a water table in mountainous or hilly terrain. However, the relatively high values of conductivity in the conductive layer are atypical for a fresh water table signature. The relatively high conductive zones are generally found at, near and adjacent to many of the mine spoil piles. The conductive signatures are thought to be characteristic of AMD production at selected mine spoil piles.

The higher conductivity zones are particularly apparent at the mine spoil piles along the Upper Freeport outcrop along the northwestern project boundary. For example, flight lines 30230 and 30240 (Figure 7) have relatively high conductivities ranging from 80 to 100 mS/m with the highest values over 100 mS/m beneath the mine spoil piles. For comparison and as a point of reference, conductivity (specific conductance) measurements of AMD discharge at the Laurel Run Airshaft and Power Bore Hole (Figure 2) range from approximately 60 mS/m to 150 mS/m (ERM field sampling, 2003). These data values seem to corroborate the conductivity values derived from the HEM survey data. The higher conductivity values (Figure 7) diminish when traveling in a down-gradient direction towards the North Branch which may be due to dilution of the AMD from fresh water recharge sources.

To identify the areal extent of relatively high conductive zones in the project area, the maximum values of conductivity at each X Y coordinate in the conductive layer were extracted and contoured (Figure 8) for correlation with surface features. Due to the large number of X Y records (approximately 200,000), minimal interpolation between conductivity data points was necessary to create these contours.

Near flight lines 30230 and 30240 (Figure 5) northwest of Kempton, a zone of high conductivity extends from the mine spoil piles near the Upper Freeport outcrop towards the North Branch. Although a power line and a pipe line cross flight lines 30230 and 30240, the corresponding signal noise is localized to an area immediately adjacent to these features. Relatively high conductive signatures over portions of the mine spoil piles can be delineated in several other locations of the western project area (Figure 8).

Although AMD emanating from areas of mine spoil piles would not be unexpected (e.g., PADEP, 2000 and U.S. EPA, 2001), not all mine spoil piles would be expected to be a significant source of AMD. The production of AMD from the mine spoil piles is dependent on geographic considerations such as proximity to surface water recharge sources (e.g., creeks and streams), and the gradient of land surface slopes, and the permeability of surface soils. In addition, some mine spoil piles have been reclaimed (Figure 8) through re-grading to pre-mining topography as well as re-vegetated with trees and grasses.

In reclaimed areas, AMD reduction may take several years to become apparent due to the time delay in flushing the hydrologic system of residual AMD. In general, the areal extent of conductive signatures for reclaimed mine spoil piles are less than the unreclaimed spoil piles (Figure 8). The smaller conductive zones associated with reclaimed mine spoil piles is consistent with less or diminishing volumes of AMD emanating from reclaimed areas versus the unclaimed mine spoil piles. To determine whether the AMD sources at the reclaimed piles will be further reduced will require periodic monitoring of water quality data for evaluation of temporal trends.

5.0 *SUMMARY OF KEY FINDINGS, RECOMMENDATIONS AND FUTURE WORK*

The majority of mine workings in the project area are beyond the maximum exploration depth of the survey method. However, the survey results were useful in delineating surficial areas of relatively high conductivity associated with AMD sources. Based on the survey data signatures, unreclaimed mine spoil piles generally exhibit a greater and continuing source of AMD than the reclaimed areas of mine spoil piles. The survey data signatures also indicate that spoil pile reclamation efforts by MDE have reduced AMD production at these locations.

Originating at unreclaimed mine spoil piles in the northwestern project area, relatively high conductive zones extend hundreds of meters down-gradient. The reworked areas of unreclaimed mine spoil piles are disturbed areas where relatively oxygen-rich surface runoff and stream flow may readily infiltrate through rubble into subsurface strata and create favorable conditions for acidic water production. The high zones of conductivity emanating from the unreclaimed piles are indicative of AMD sources traveling down-gradient and contributing to AMD in the mine pools and degraded surface water quality at seeps and wetlands.

The mine spoil piles in the western project area are roughly parallel to topographic contours in the highlands of the watershed (Figure 9) and located along the highest mine tunnel floor elevations. In locations where surface mining has breached the mine tunnel network, AMD from the mine spoil piles may infiltrate into the mine tunnel network and flow through the mine floor pavement. In these cases, the acid content is further enhanced by the reaction of the water with the residual pyritic compounds on the mine floor before reaching the mine pool.

5.1 *AMD REDUCTION AND MINE SEALING*

In the project area, acid mine drainage is currently treated and neutralized with a number of methods including stream water dosing with calcium carbonate to neutralize acidic conditions, and anoxic treatment systems to reverse the AMD chemical equation (Equation 1). These methods are effective at mitigating AMD as it discharges toward streams. However, other methods could be used to reduce the amount or the severity of AMD formed by preventing pyritic minerals from contacting oxygenated water. This could be accomplished by preventing water from infiltrating into areas containing pyritic materials or by, encapsulating the acid producing minerals within an impermeable matrix such as a CCB-based grout. Where these techniques are not possible, neutralization of AMD recharge sources could reduce or eliminate the source of acid production.

Reclamation of spoil piles, as has been done with some of the spoil piles already, reduces the infiltration of water into the pyrite-containing rubble, which in turn reduces AMD production. A soil cap is placed over the mine spoil and the cap is vegetated. The trees and grasses planted on the soil cap increase the amount of evapotranspiration occurring over the mine spoil, thereby reducing the amount of water that is able to infiltrate into the spoil.

For AMD mitigation, engineered CCBs can also offer an environmentally friendly and cost-effective means of controlling AMD production through methods that include:

- Capping mine spoil piles with a low permeability engineered CCB fill;
- Injection of CCB cement grout in mine spoil piles for buffering AMD acidity and encapsulation of potential AMD-producing minerals; and
- Injection of CCB cement grout into mine voids to encapsulate potential AMD-producing minerals and debris.

CCBs, a result of coal combustion, include pozzolanic fly ash and non-pozzolanic bed ash. CCBs produced in Fluid Bed Combustion (FBC) plants, which co-fire coal and limestone, are self cementing when fly ash and bed ash are mixed in the proportions produced during normal plant operations. When a grout is formed from CCBs and water, the mix cures into a solid monolith similar to cement. When CCBs, soil and additional moisture are blended together, a low permeability fill material results.

Potential AMD-producing minerals can be encapsulated by sealing the minerals with a cement grout or paste. Due to material costs, conventional portland cement grout can be cost prohibitive for projects such as mine sealing where high grout volumes are required. Raw material for CCB-based grout can be obtained for negligible cost from nearby coal fired power plants to significantly lower the cost of high volume grouting projects typical of mine sealing. CCB-based grout has excellent engineering and material properties that are similar to conventional grout (Hemmings, 2005). For high grout volumes (typically thousands of cubic yards or more) required for mine void stabilization the total project cost savings over conventional cement grout would exceed 60 percent (Jenkins et al., 2006).

For mine tunnel voids, CCB grout may be hydraulically placed into mines to selectively seal and encapsulate acid producing surfaces such as the mine pavement and debris against acid production. For a PPRP mine grouting demonstration project in Western Maryland (Petzrick et. al, 2005), the durability and leaching characteristics of cured CCB grout has been monitored under acidic conditions over a ten year period. The project and monitoring results have shown that CCB grout is environmentally benign, has excellent long term structural properties, poses no threat to flora or fauna, and provides an excellent buffer (Warner et al., 2007) to help neutralize AMD.

A low permeable CCB soil cap on the spoils piles will restrict surface water infiltration and the subsequent formation of AMD, similar to the soil covers constructed by MDE. A top soil layer above the cap on the spoil piles would permit natural re-vegetation of these areas and increase evapotranspiration rates to further reduce surface water infiltration. The use of stabilized CCBs in capping and sealing AMD-producing areas provides a substantial volumetric and beneficial use for a product that may otherwise occupy increasingly valuable real estate of landfills.

Pressurized CCB borehole grouting of AMD-producing mine spoil piles would permit the free lime in the grout to buffer AMD production while allowing vegetative growth in the existing surface soils. An ancillary benefit would be the encapsulation of potential AMD-producing minerals within the grout matrix. In addition, cured CCB grout from applications to stream and creek beds that cross mine spoil piles will provide an infiltration barrier to eliminate a substantial source of surface water infiltration in losing bed reaches.

As discussed in the preceding paragraphs, MDE has constructed vegetated soil covers over mine spoil piles in the Kempton Mine Complex. These reclamation efforts have proven to reduce AMD production. The use of CCBs provides an alternative material to cap the spoils piles, buffer the spoils, and mitigate AMD formation in mine tunnels.

5.2 DATA VALIDATION AND FUTURE WORK

To validate the HEM survey results field investigation is required to confirm the structures and/or chemistry responsible for the conductive features reflected in the HEM survey data. Future work in the project area should include selection of a mine spoil piles area along a flight line to perform surface magnetic and borehole geophysical surveys. Surface magnetic surveys will provide a finer definition of the areal and vertical extents of selected piles for correlation with the corresponding HEM data signatures. For refinement of the CDIs, geophysical borehole surveys would provide depth calibration for associated conductive layers. Also, the borehole cuttings from the drilling would allow correlation of soil and rock types with the data signatures at the corresponding depth intervals to identify preferred groundwater pathways. Where applicable, the boreholes could be developed into groundwater observation wells for periodic water quality analyses of a selected suite of chemical parameters.

Correlating the HEM, surface magnetic, and borehole geophysical survey results, and comparing these results with the physical attributes of the spoil piles and associated groundwater chemistry will refine the HEM survey results and the CDI profiles. Once refined, the CDI profiles can be utilized to further refine and identify shallow AMD recharge zones within the project area. In addition, the results of the field studies may assist in the location and characterization of mine spoil (gob) piles that contain sufficient residual coal to use as fuel in FBC power plants or other plants using similar power generating technologies.

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FIGURES

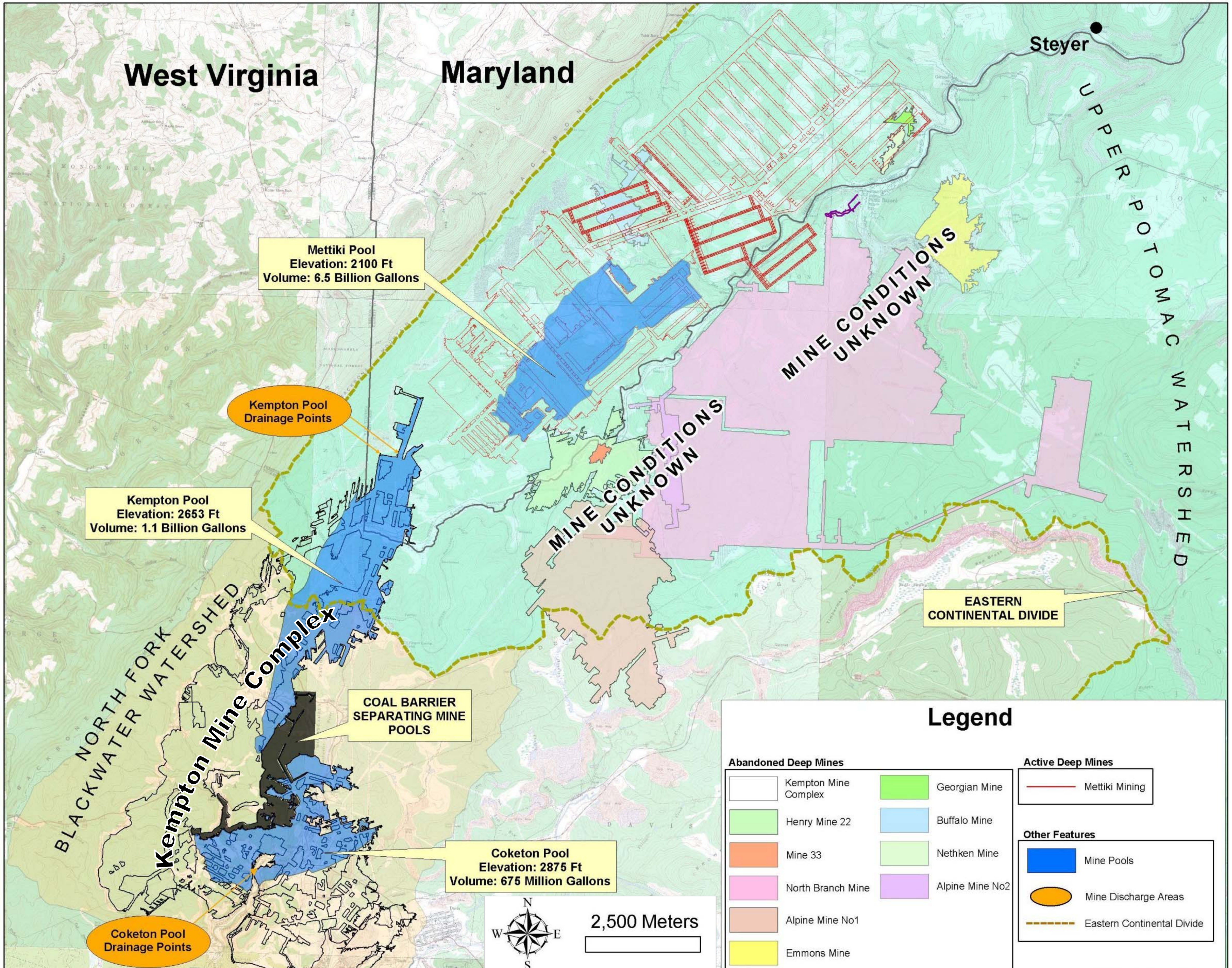


Figure 1. Mines of the Upper Potomac Basin.

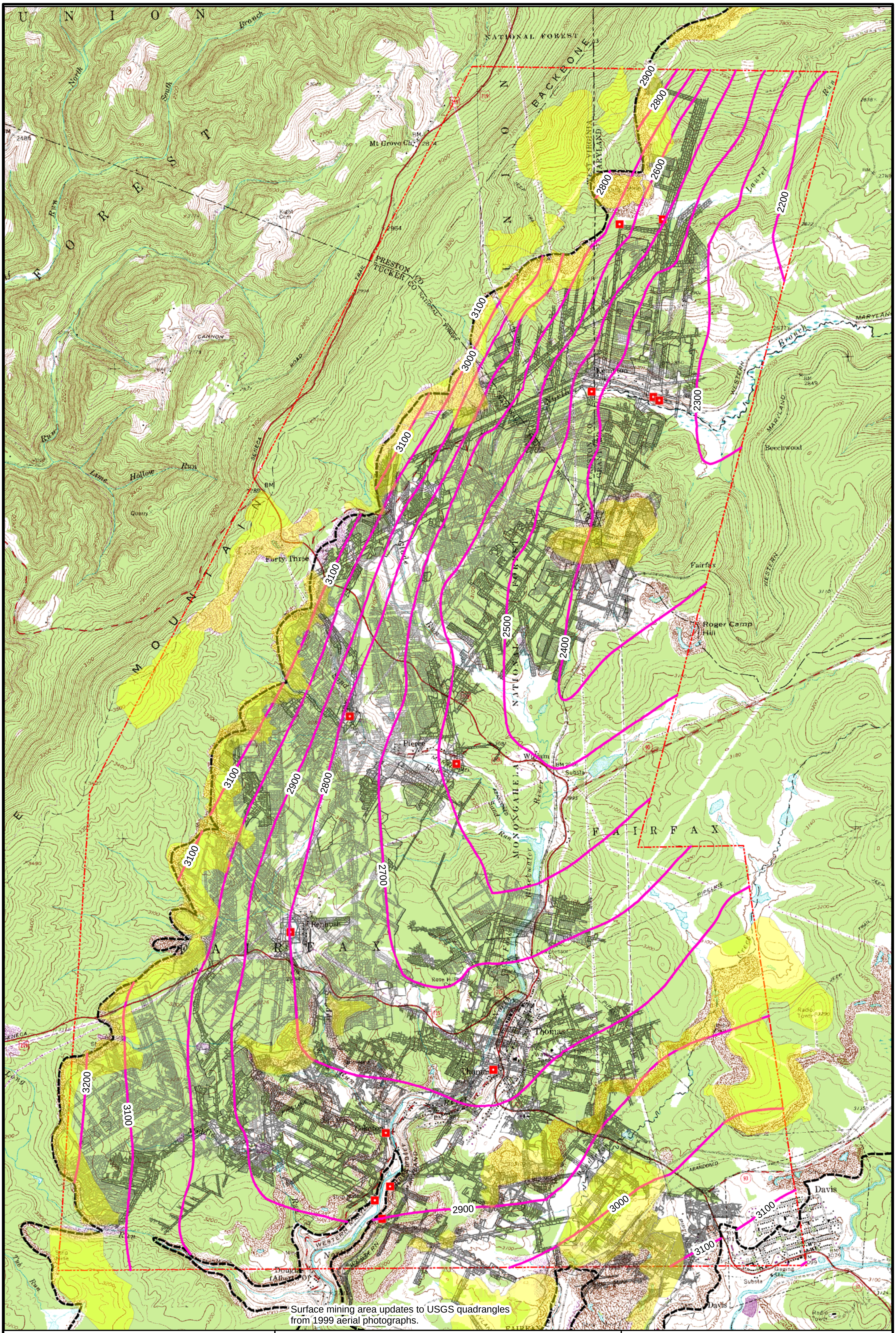


Figure 2.
Coketon/Kempton Mine Complex, Updated Surface Mining Areas, and Base Elevation (ft MSL) of Upper Freeport Coal Seam.

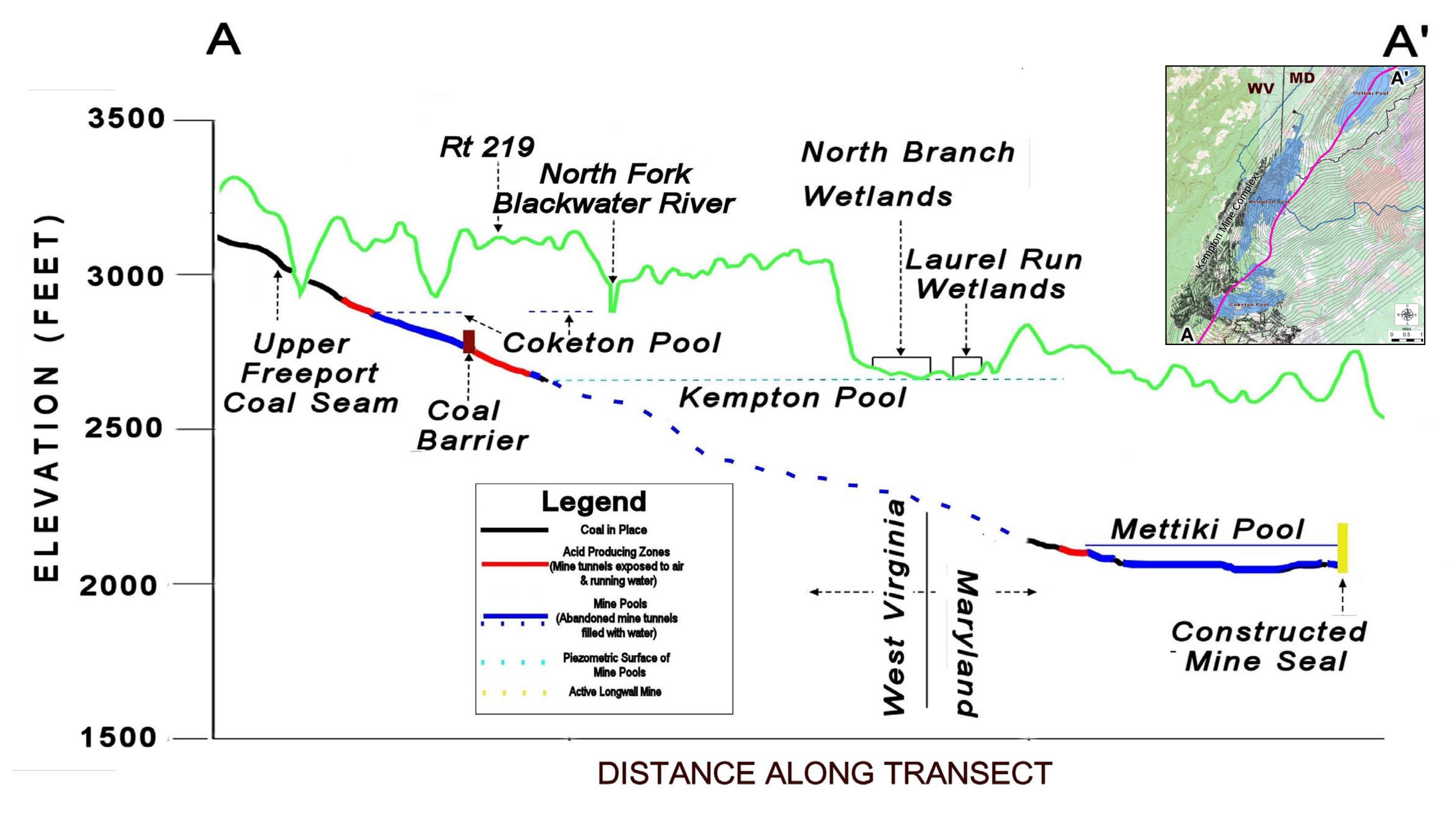


Figure 3. Profile Along Axis of Upper Freeport Coal Seam Syncline.

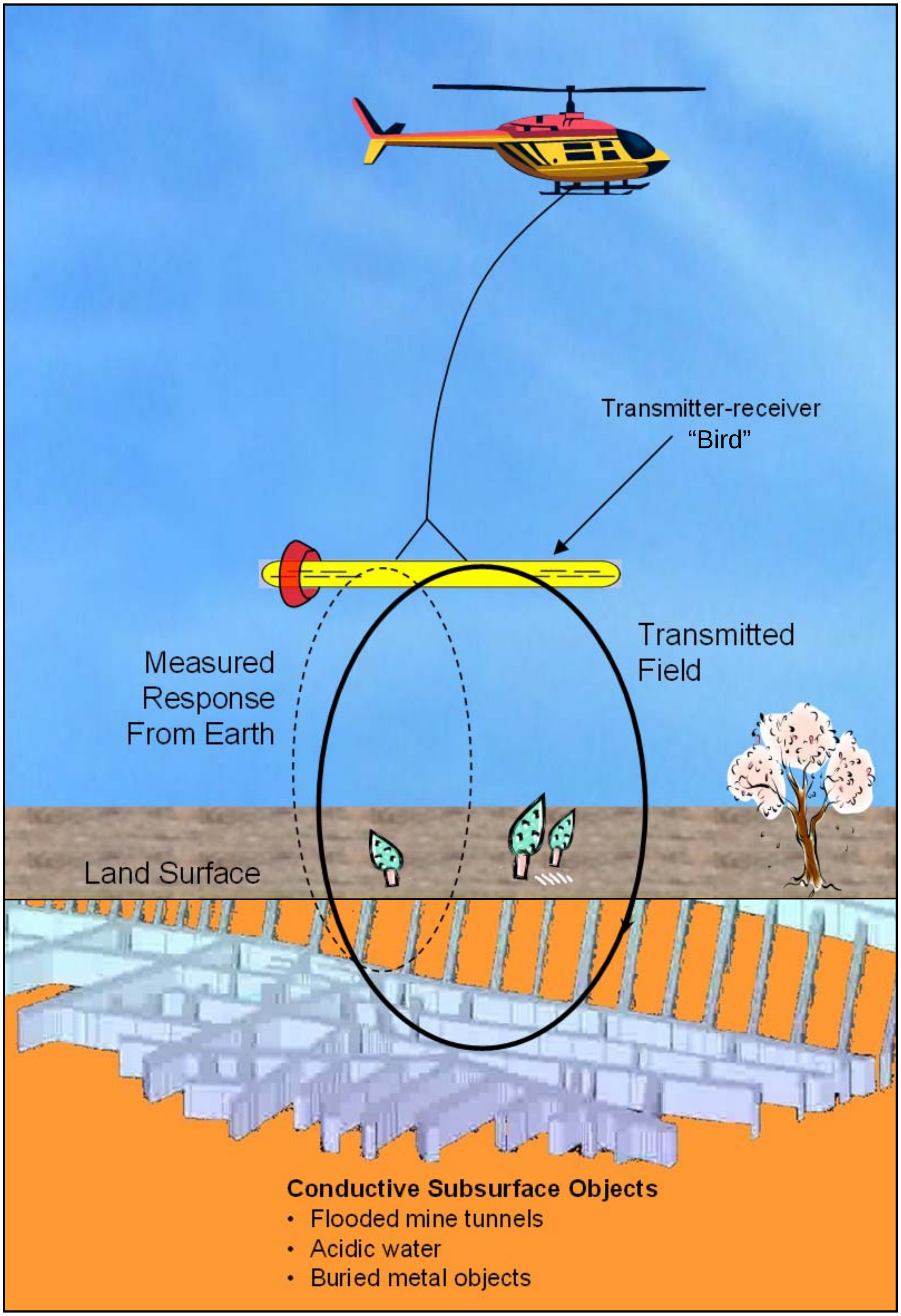
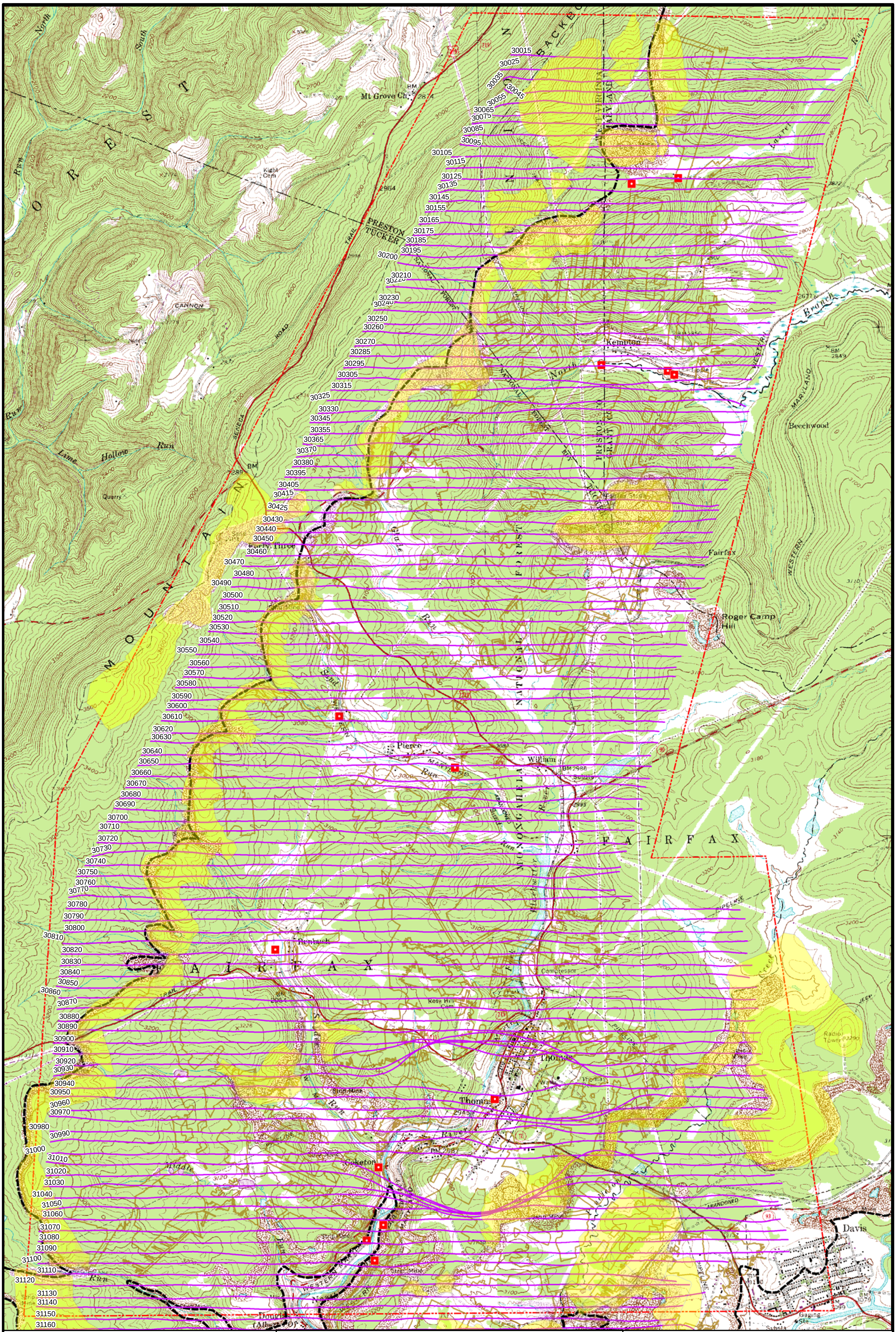


Figure 4.
Helicopter Electromagnetic Survey
Equipment Configuration.



N
W E
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1,000 m

Figure 5.
Flight Line and Flight Line Numbers
for Airborne Geophysical Survey.

Legend

- Mine Openings
- Upper Freeport Outcrop
- Project Area
- Mine Perimeter
- Surface Mining

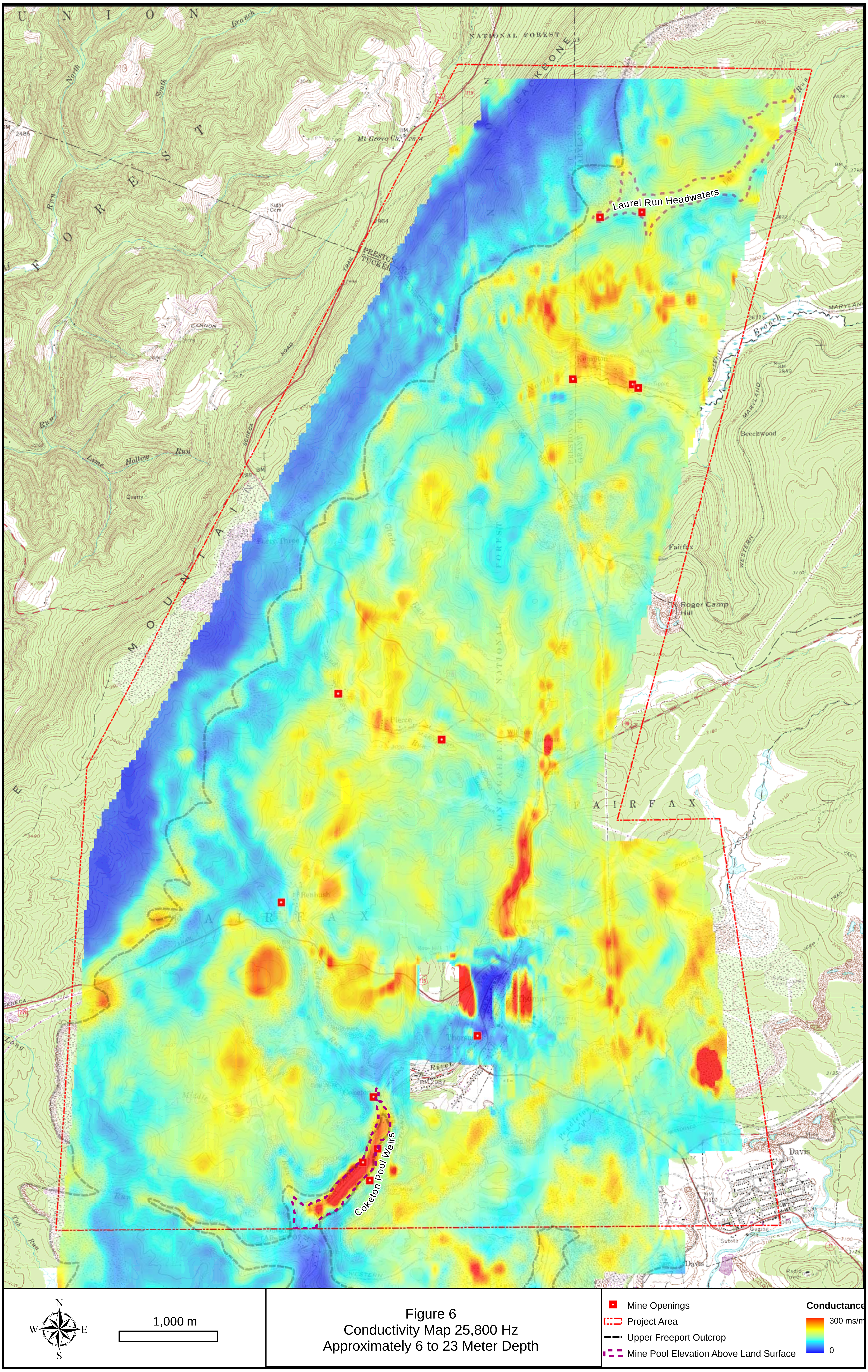
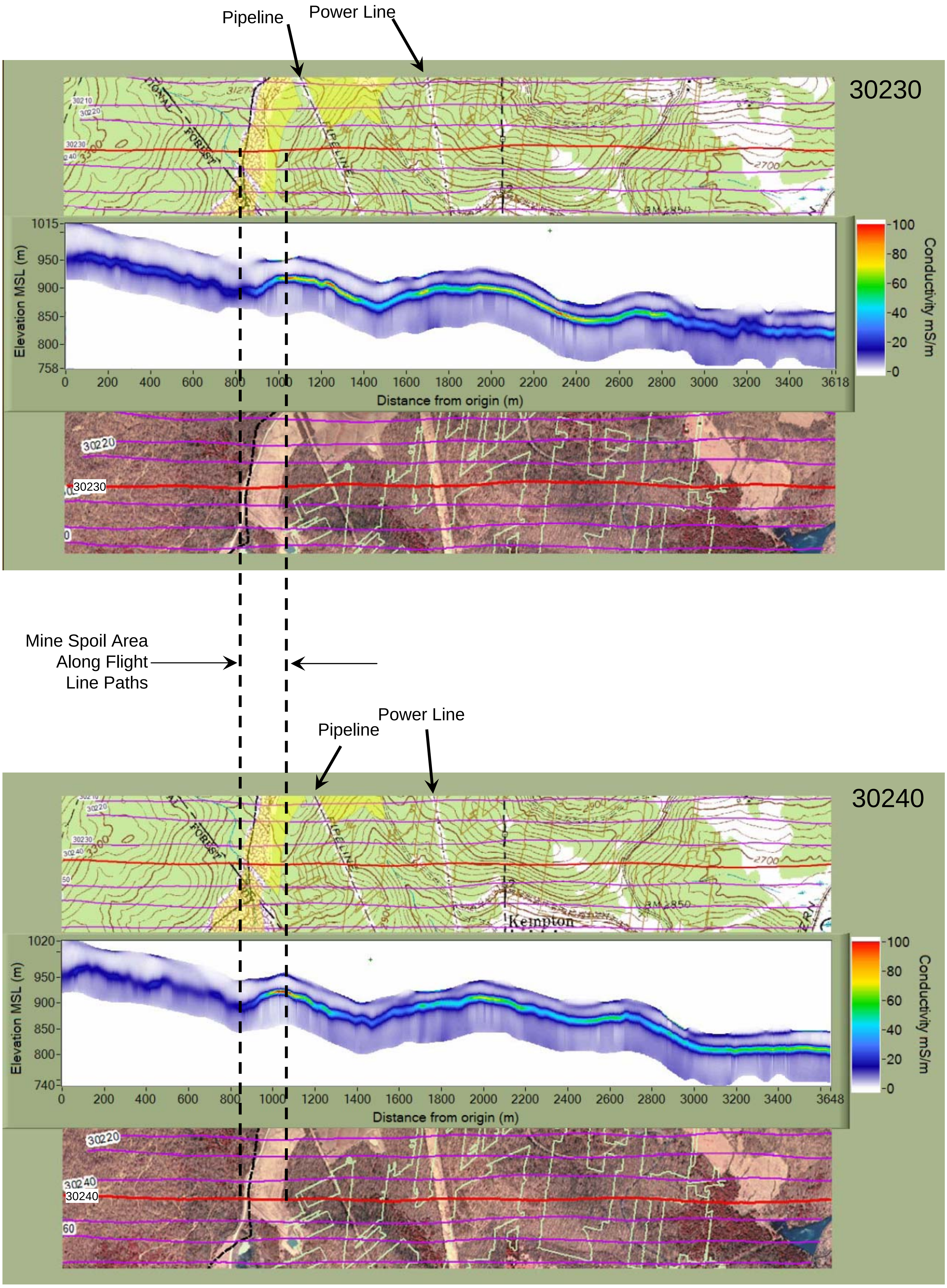
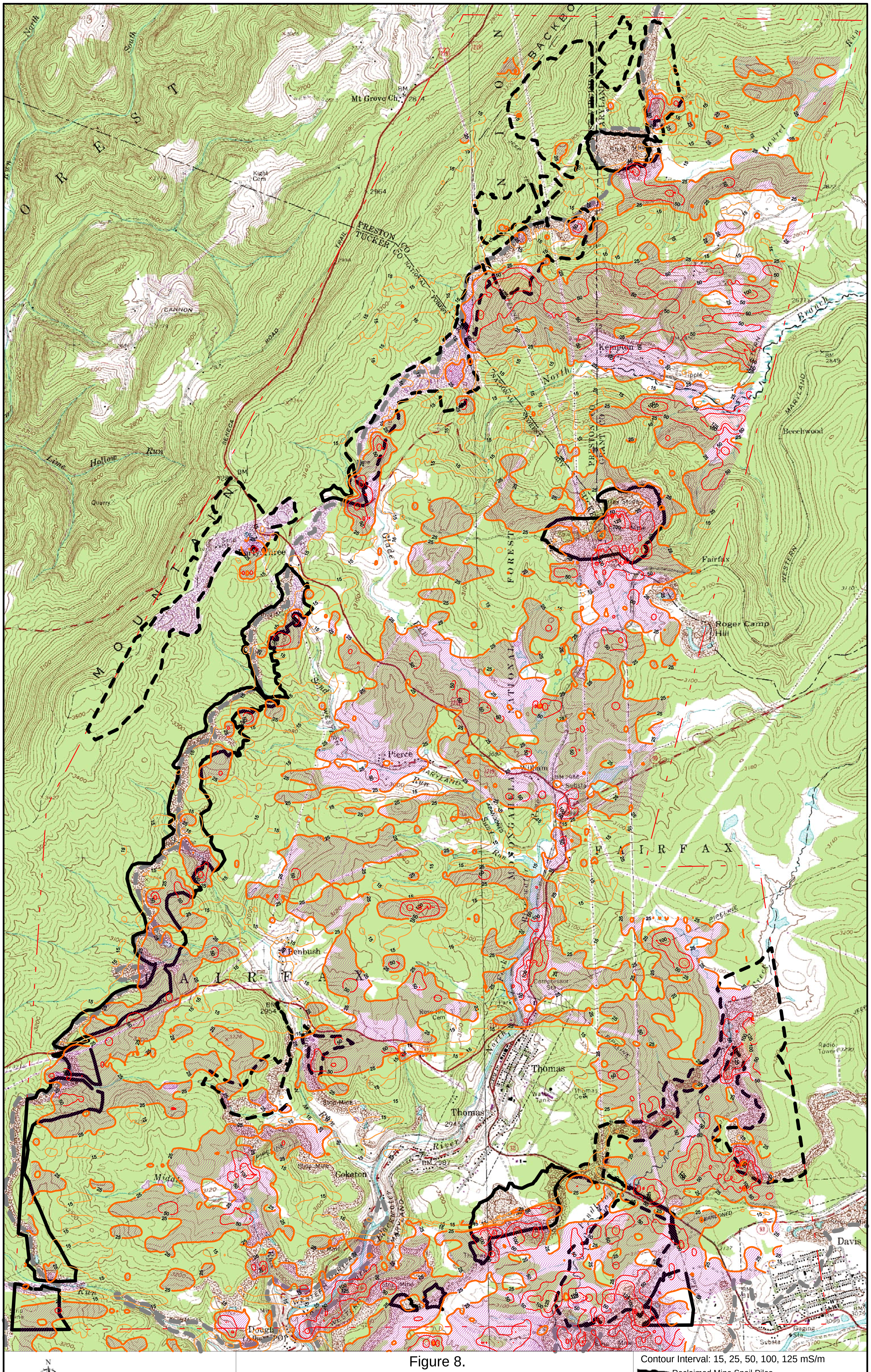


Figure 6
Conductivity Map 25,800 Hz
Approximately 6 to 23 Meter Depth



Notes:
- Strip map above each CDI is from U.S.G.S. 7.5 minute quadrangle.
- Strip map below each CDI is from 1999 aerial photograph.
- Corresponding flight line shown on each strip map as red line.
- Mine perimeter shown as light brown line on U.S.G.S. map, and as light blue lines on aerial photograph.

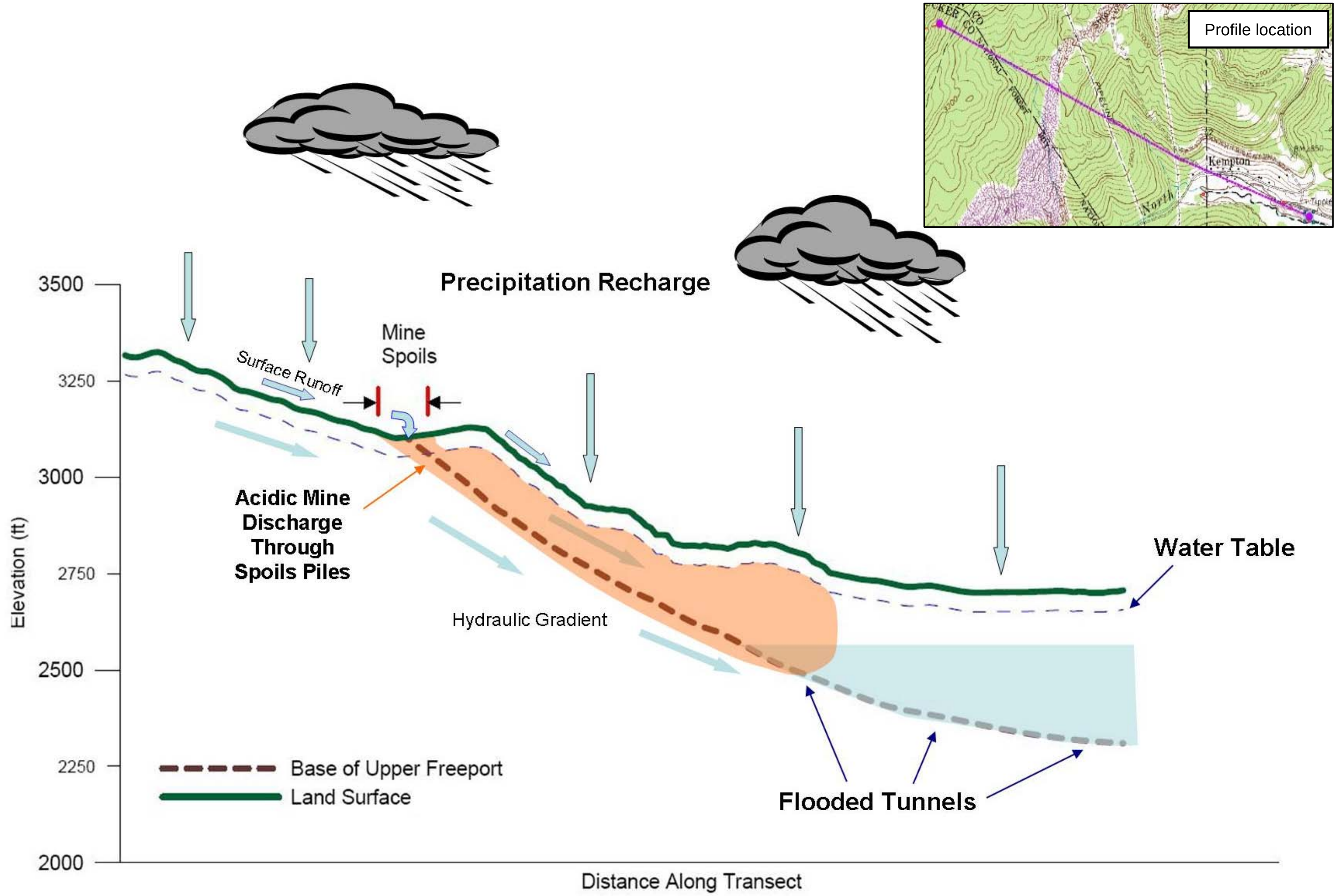
Figure 7.
Flight Line 30230 and 30240 Conductivity Depth Images.



0 m 1000 m

Figure 8.
Maximum Conductivities within Conductive Layer
Above a Value of 15 mS/m

Contour Interval: 15, 25, 50, 100, 125 mS/m
Reclaimed Mine Spoil Piles
Unreclaimed Mine Spoil Piles
Upper Freeport Coal Seam Outcrop



ERM

Figure 9.
Conceptual Cross Section of Land Surface and Upper Freeport Coal Seam.

APPENDICES

Appendix A
HEM Data Pre-Processed with EM1DFM Software

Coordinates in NAD 1983 UTM Zone 17N
Conductivities in milliSeimen/meter

Appendix B
Conductivity Depth Images for East-West Flight Lines