AN EVALUATION OF HELICOPTER TIME DOMAIN ELECTROMAGNETIC SURVEYS FOR DETECTING DEEP, FLOODED MINE WORKINGS[1]

Richard Hammack[2], Ken Witherly, Mark Zellman, Brian Lipinski, Bill Harbert, and Terry Ackman[2]

Abstract. The recent entrapment of nine coal miners by water at Quecreek Mine has directed national attention to the hazards of mining in proximity to inaccurately mapped or unmapped mine workings. Previous work by the National Energy Technology Laboratory has shown that helicopter frequency domain electromagnetic (FDEM) surveys can detect underground mine workings if: 1) the workings are flooded with conductive water, 2) the overburden conductivity is less than 30 mS/m, and 3) the workings are no deeper than 50 m. Currently, most active mines are at depths greater than 50 m, too deep to be detected with FDEM. This survey attempted to use helicopter TDEM, a technique with greater exploration depth than FDEM, to locate flooded mine workings at 100- to 200-m depths. Four mined areas in southwestern Virginia were selected for study: two areas contained active mines adjacent to flooded, abandoned mines (Quecreek Mine Scenario); two other areas contained abandoned and presumably flooded underground mines that were overlain by water impoundments; a municipal water supply reservoir and a coal slurry impoundment. The selected areas were especially challenging because they contain multiple levels of mining, thin seams, and mine water of relatively low conductivity. The rationale behind the choice of field sites was that if a technology worked in this admittedly difficult region, it could be applied to any coalfield. However, the survey was unsuccessful; mine workings known to be flooded were not detected. This paper discusses problems that were encountered, particularly electromagnetic noise, which rendered 25-50 pct of each flight line unusable.

Additional Key Words: Quecreek Mine, mine pools, mine voids, airborne geophysical surveys

Introduction

Since 1999, the U.S Department of Energy's National Energy Technology Laboratory (NETL) has conducted helicopter electromagnetic (HEM) surveys of 11 coal mining areas in Virginia, West Virginia, Pennsylvania, Ohio, and Maryland (Fig. 1). The purpose of these surveys was to determine if HEM surveys can provide

Figure 1 HEM surveys of coal mining areas conducted by NETL (symbol may denote more than one area).

hydrologic information that is useful for hazard identification and for mine water remediation efforts. Such information could include the location of: flooded mine workings, abandoned mine discharges, mine water recharge zones, and groundwater flow paths.

This paper addresses the utility of using HEM surveys to identify and map pools that form in underground mines. Mine pools are more conductive than the strata above and below the mine, and therefore, often offer high-contrast targets for electromagnetic survey methods. Generally, the water that comprises the mine pool contains from 0 to 3 m of water but is overlain by 10 to 400 m of less conductive strata. The ability to detect mine pools diminishes with depth and with decreasing contrast between the conductivity of the water in the mine pool and the conductivity of the overburden.

Airborne EM Surveys of Coal Mining Regions

Airborne electromagnetic surveys have been conducted from both helicopters and fixed-wing aircraft, but only helicopters are used for surveying coal mining areas in the eastern United States because of rugged topography. Electromagnetic surveys require low-altitude flight (sensor altitude $\cong$ 30 m above ground level) to maximize sensitivity and spatial resolution. Only helicopters can maintain a relatively constant sensor altitude while flying over rapidly varying terrain.
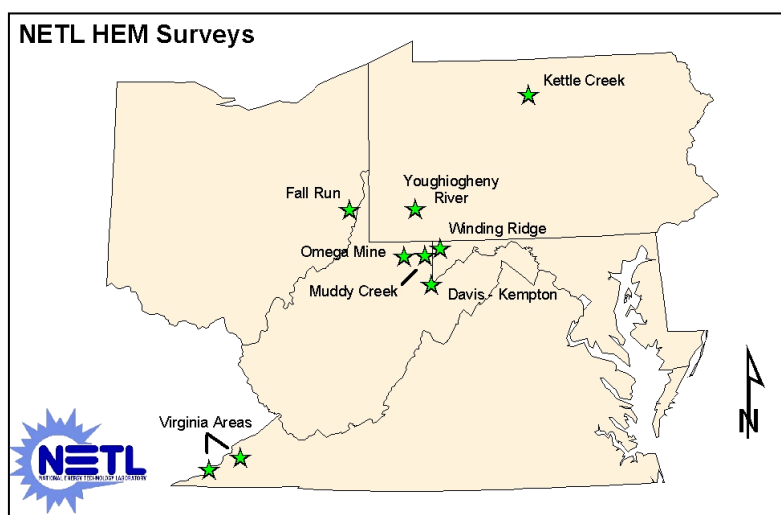
Frequency Domain Electromagnetic Surveys

Previous work (Hammack and others, 2002) has shown that frequency domain electromagnetic (FDEM) surveys can detect mine pools at depths less than 50 m if the mine pool is conductive and the overlying strata are resistive. However, most mine pools occur at depths greater than 50 m and are not detected using FDEM.

Time Domain Electromagnetic Surveys

Time domain electromagnetic surveys (TDEM) differ from FDEM surveys in the equipment that is used (Fig. 2 and 3) and in the manner that data are acquired (Fig. 4). Compared with FDEM, TDEM uses a larger, more powerful transmitter coil that operates at a single, low frequency (30 hz). The primary magnetic field that is generated penetrates deeper into the ground, providing a greater exploration depth. Unlike FDEM, where the transmitter and receiver are constantly on, with TDEM, the receiver is only turned on after the transmitter has been turned off. When current flows in the transmitter coil of a TDEM system, a magnetic field is instantaneously established in the ground and eddy currents flow within in-ground conductors. When the transmitter current is turned off and the primary electromagnetic field collapses, eddy currents again flow within in-ground conductors giving rise to a secondary magnetic field that is measured by the receiver. With TDEM, the measurement of weak secondary magnetic fields is made in the absence of the much stronger primary field. TDEM data consists of secondary magnetic field measurements made during numerous preset decay windows following turn-off of the primary field (Fig. 3). This information can be processed to obtain the vertical distribution of conductivity within the ground. Potential advantages of TDEM over FDEM include greater exploration depth and better depth resolution. Helicopter TDEM systems have provided results comparable to ground-based TDEM systems (Sorensen and others, 2004).

Survey Description

NETL has conducted HEM surveys of 11 coal mining areas in the eastern United States (Fig. 1). Of these, seven surveys were conducted using FDEM surveying methods. In May 2003, four TDEM surveys were flown in southwestern Virginia using the VersaTEM, a prototype system built and operated by Geotech, Ltd. The TDEM surveys are described in this paper.
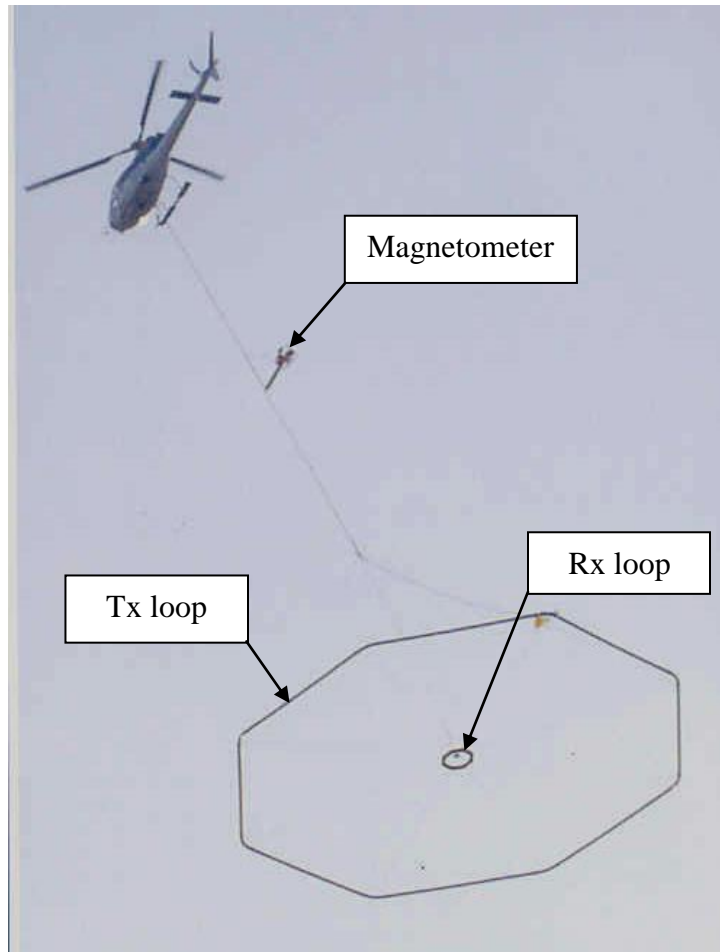
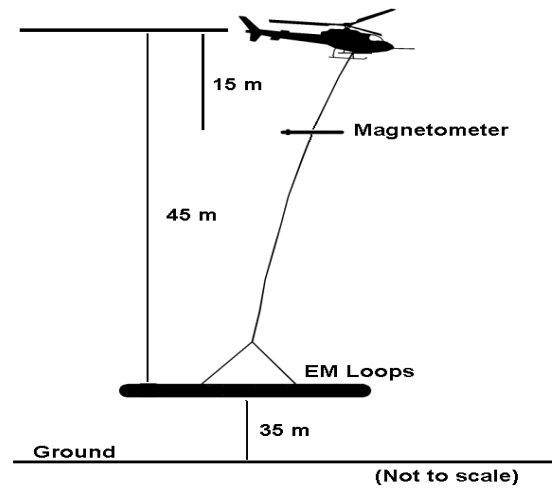**Figure 2.** TDEM system (VersaTEM™) used in this study.

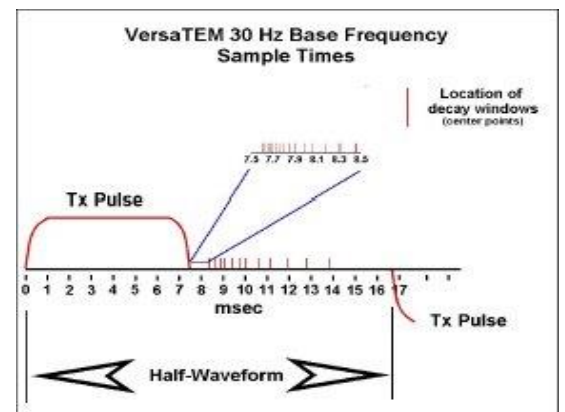**Figure 3.** Geometry of VersaTEM system.

Figure 4 Waveform and decay windows for VersaTEM™ system

Description of VersaTEM system

The VersaTEM is a helicopter-borne (sling-load), TDEM system of coincident loop design (Fig. 2). System specifications are listed in Table 1. VersaTEM surveys were conducted at a nominal altitude of 35 m along parallel flight lines spaced 100-m apart. The temporal relationship between the transmitted waveform and the recorded off-time channels is shown in Fig. 4.

Table 1. Specifications of the VersaTEM system as configured for this study.

Transmitter	Receiver
Coil orientation: vertical axis	Coil orientation: vertical axis
Loop diameter: 18.5 m	Loop diameter: 1.1 m
Number of turns: 5	Number of turns: 30
Wave form: trapezoid	Sample rate: 50 kHz
Pulse width: 7.5 msec	Interval recorded: 26 off-time channels
Base frequency: 30 Hz	Bandwidth: up to 50 kHz
Peak dipole moment: 166,000 Am^2	Spherics noise rejection: digital; 3 levels
Loop area: 266 m^2	Industrial noise reduction: digital; 50/60 Hz rejection
Peak current: 110 A	
	Data recording: PCMCIA drive

Data processing

Raw data were processed to remove major spheric events (naturally occurring electromagnetic phenomena) and to improve signal to noise ratio. First, major spheric events were removed using a 16-point non-linear filter. Then a zero phase shift, symmetrical linear filter was applied to suppress variations with a wavelength less than 1 second or 20 meters. Filtered data was further processed by Condor Consulting, Ltd. to generate conductivity/depth images (CDI), which show the distribution of conductivity with depth along flight lines. Two CDI-generating software applications were used: EM Flow and Airstem. EM Flow is commercial software available from Encom Ltd. that fits an approximate layered earth model to EM data. EM Flow can be used with both frequency domain and time domain EM data. Airstem is a proprietary inversion code developed by Dr. Robert Ellis of BP Billiton Exploration to invert time domain EM data and produce a layered earth model.

Site selection

Personnel from the Virginia Department of Mines, Minerals, and Energy, the Office of Surface Mining, and NETL selected four study areas in Wise and Lee Counties, Virginia to test the use of helicopter TDEM to detect pools of water in underground coal mines. The selected areas were either areas of active mining adjacent to flooded, abandoned workings (Quecreek Mine Scenario) or water impoundments that are overlying underground mine works (Martin County, KY Scenario). Both scenarios represent situations that pose a potential hazard to miners and the environment. Powell Mountain and Wet Flats, which are areas of active mining adjacent to flooded mines, and Wise Reservoir and Tom's Creek, which are water impoundments that overlie underground mines were the selected sites (Fig. 5).

Figure 5 Location of four TDEM surveys.

Powell Mountain

The Powell Mountain TDEM survey was conducted in Lee County, Virginia near the border with Kentucky and about 7 km northwest of the town of Pennington Gap, Virginia (Fig. 6). The surveyed area occupies about 9.2 km^2 of mountainous terrain that is underlain by mines in the Darby and Upper Mason Coalbeds. Figure 6 shows the location of the Thermal Mine (shown in black) and adjacent mines (shown in blue) in the Upper Mason Coalbed. The small abandoned

mines southeast of the Thermal Mine were mined up-dip, which allowed water to drain from them. More recent mines were mined down-dip and are now partly or completely flooded with water. The workings of the recently active Thermal Mine now encircle an older mine (Gregory Coal Corporation Mine) although a pillar of solid coal at least 70-m thick was left as a barrier between the two mines. Both mines are now completely flooded.

Abandoned surface and underground mines in the Darby Coalbed occur about 120 m above the Upper Mason Coalbed. Although no maps exist that accurately depict underground mines in the Darby Coalbed, these mines are presumed to be shallow, less extensive, and older than mines in the Upper Mason Coalbed. The underground mines in the Darby Coalbed probably were mined up-dip and are mostly dry. There are no currently active mines in the Darby Coalbed within the surveyed area. Consequently, the primary targets for the airborne survey at Powell Mountain are the Gregory Coal Corporation Mine and the Thermal Mine, which are flooded with conductive water (100-250 mS/m).

Wet Flats

The Wet Flats TDEM survey area is located in Wise County, Virginia about 8 km northwest of Norton, Virginia (Fig. 7). The surveyed area comprises 14.4 km^2 of hilly terrain. Within the surveyed area, coal has been mined from the Norton, Dorchester, and Blair Coalbeds. Mine workings in the Clintwood Coalbed lie north and south of the surveyed area. Structure contour lines for the Norton Coalbed show a double-plunging, northeast-southwest trending anticline in the eastern part of the study area. The American Energy Mine, an active mine in the Norton Coalbed, is located on the axis of this anticline (Fig. 7). Adjoining the American Energy Mine to the west are the abandoned workings of the Wise Coal and Coke No. 4 Mine and the currently idle Virginia Iron Coal and Coke (VICC) No. 4 Mine. The American Energy Mine, Wise Coal and Coke No. 4 Mine, and the VICC No. 4 Mine are in the Norton Coalbed.

Powell Mountain

Gregory Coal Corp. Mine

0	650	1,300	2,600	Meters

Explanation

Abandoned mineworks in Darby Coalbed

Abandoned mineworks in Upper Mason Coalbed

Thermal Mine, active mine in Upper Mason Coalbed

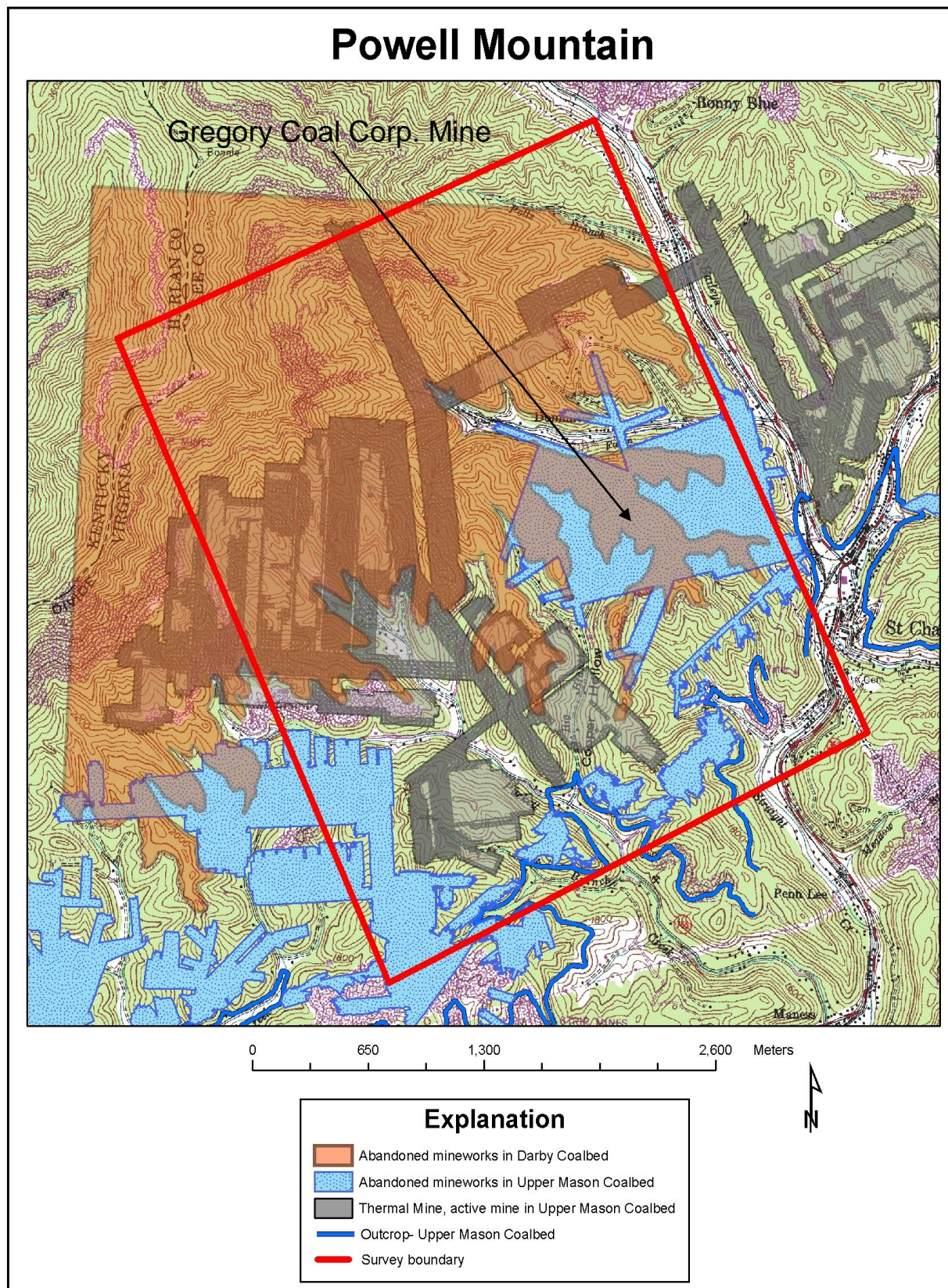Outcrop- Upper Mason Coalbed

Survey boundary

Figure 6. Mine locations at the Powell Mountain Site.

The two other coalbeds of interest are the Dorchester and Blair coalbeds. The Dorchester coalbed is approximately 20 m above the Norton Coalbed. Several abandoned surface and underground workings in the Dorchester Coalbed are in the southeastern part of the study area (Fig. 7). The Blair Coalbed occurs about 35 m above the Dorchester Coalbed, or about 55 m above the Norton Coalbed. The abandoned Sargent Hollow Mine located in the northwestern part of the study area (Fig. 7) is in the Blair Coalbed.

Potential targets for TDEM surveys include mine pools in the northwest headings of the Sargent Hollow Mine, the northwest headings of the VICC No. 4 Mine, and all of the Wise Coal and Coke No. 4 Mine except for the easternmost headings. There may also be some flooding of portions of the American Energy Mine; most likely in headings driven down the eastern and western limbs of the anticline. The Paramount No. 2 Mine in the Dorchester Coalbed is presumed to be totally flooded and should provide a good shallow target. A large mine of unknown name and age in the Dorchester Coalbed occurs in the southeastern corner of the survey. This mine was developed mostly along the relatively flat crest of the anticline but some headings also extend down the more steeply dipping west and east limbs. These headings may also contain conductive pools.
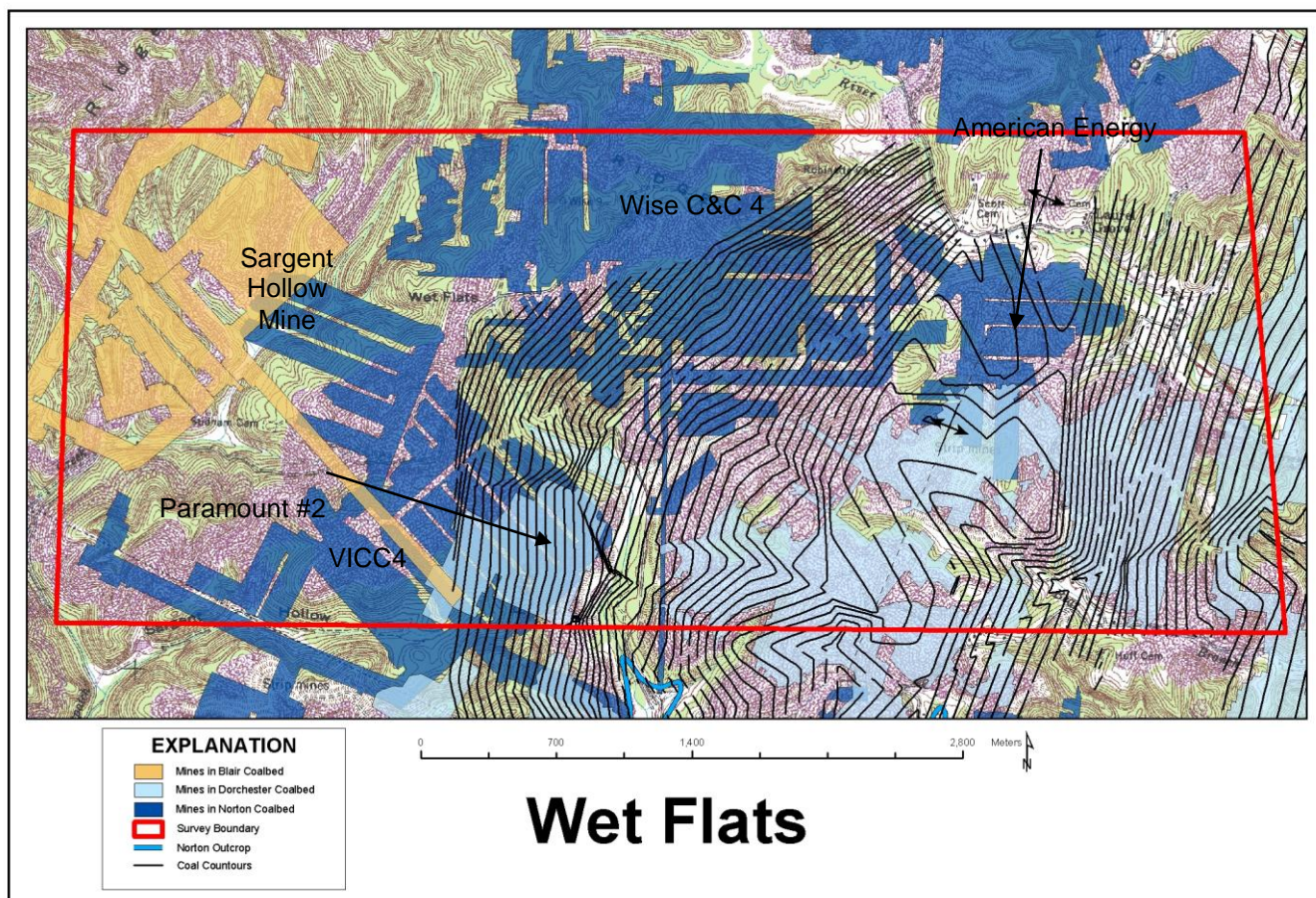

Figure 7. Map of Wet Flats site showing location of mine workings.

Wise Reservoir

Wise Reservoir is the water supply for the town of Wise, Virginia, which is about 4.7 km northwest of the study area (Fig. 8). The surveyed area comprises about 2 km^2, which includes the reservoir and adjacent land.

Coal has been mined from at least three coalbeds within the study area. The most significant mining has been in the White Oak Mine, a large, abandoned underground mine in the Upper Banner Coalbed that underlies most of the study area at an average depth of about 150 m. Although a large pillar of solid coal was left in place below the Wise Reservoir, two headings do underlie the reservoir (Fig. 8). The Norton Coalbed has been extensively surface mined in the area but there are no underground workings. Surface and underground mines in the Lyons and Blair Coalbeds are located near the northern boundary of the study area (Fig. 8).

The objective of the TDEM survey at the Wise Reservoir site was to determine if water from the reservoir is infiltrating via natural or subsidence fractures into the underlying White Oak Mine.

Tom's Creek

Tom's Creek is the site of an active coal slurry impoundment that overlies an abandoned underground coal mine. The survey area comprises 9.2 km^2, which includes the impoundment and surrounding areas (Fig. 9), and is located about 4.1 km NNE of Coeburn, Virginia. The impoundment lies on the axis of a northeast-southwest trending anticline (Fig. 9). Within the study area, coal has been mined from the Upper and Lower Banner Coalbeds although the most development has been in the Upper Banner Coalbed. Extensive workings in the Upper Banner Coalbed underlie the slurry impoundment at a depth of about 100 m.

Because the slurry impoundment is located at the crest of an anticline, it is unlikely that the mine workings beneath it are flooded. Therefore, one survey objective was to attempt to identify conductive water from the impoundment that may be infiltrating into underlying or adjacent strata. A second objective was to detect a mine pool in the Upper Banner Coalbed that has been mapped in a synclinal structure about 2.7 km ESE of the coal slurry impoundment (Fig. 9). The depth of this mine pool ranges from 10 m to about 150 m within the survey area. The water within this mine pool is probably not especially conductive (~50-60 mS/m) based on measurements of water from other mines in the Upper Banner Coalbed.
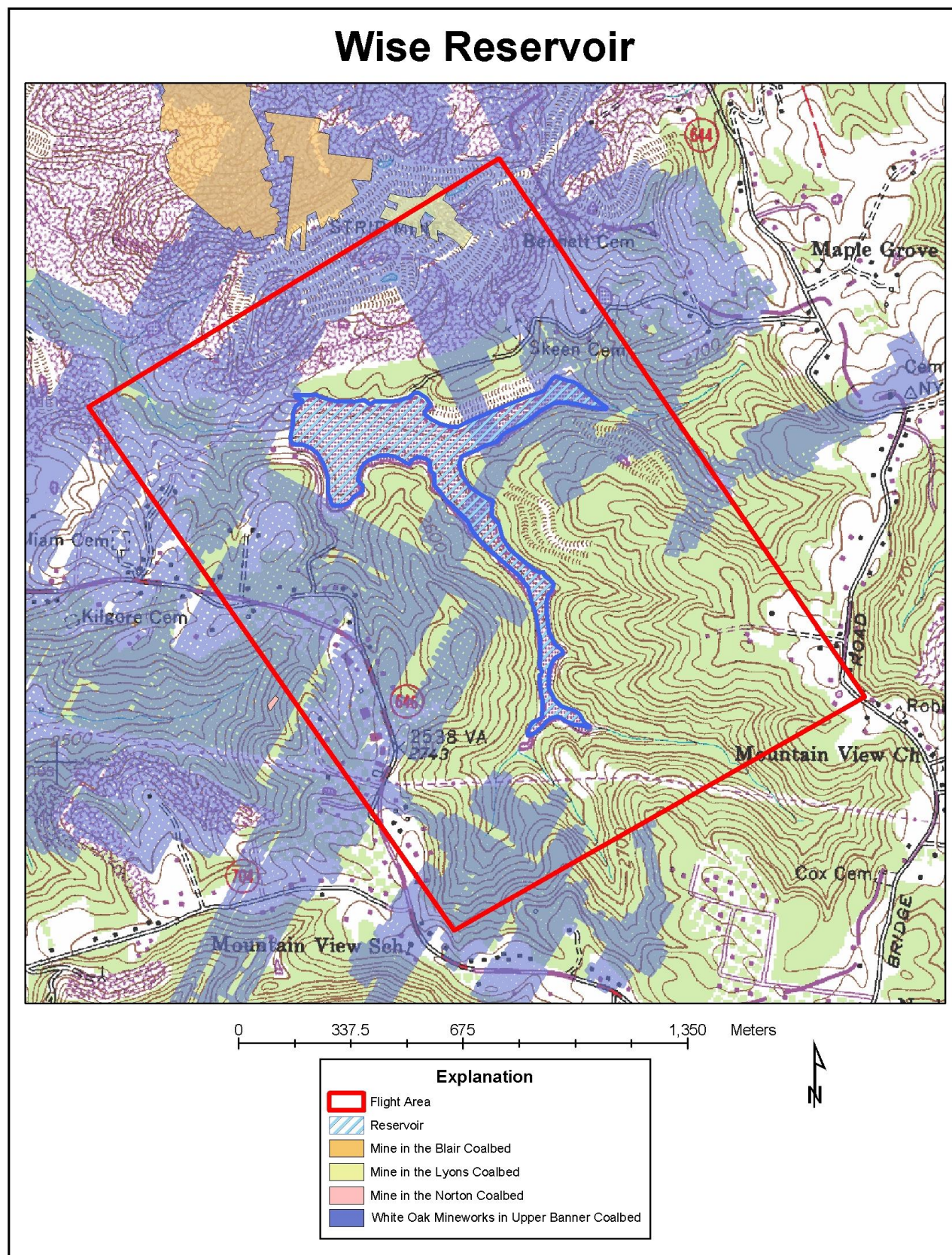
Wise Reservoir

Explanation

- Flight Area
- Reservoir
- Mine in the Blair Coalbed
- Mine in the Lyons Coalbed
- Mine in the Norton Coalbed
- White Oak Mineworks in Upper Banner Coalbed

0   337.5   675   1,350   Meters

Figure 8 Map of Wise Reservoir showing the underground workings of the White Oak Mine.
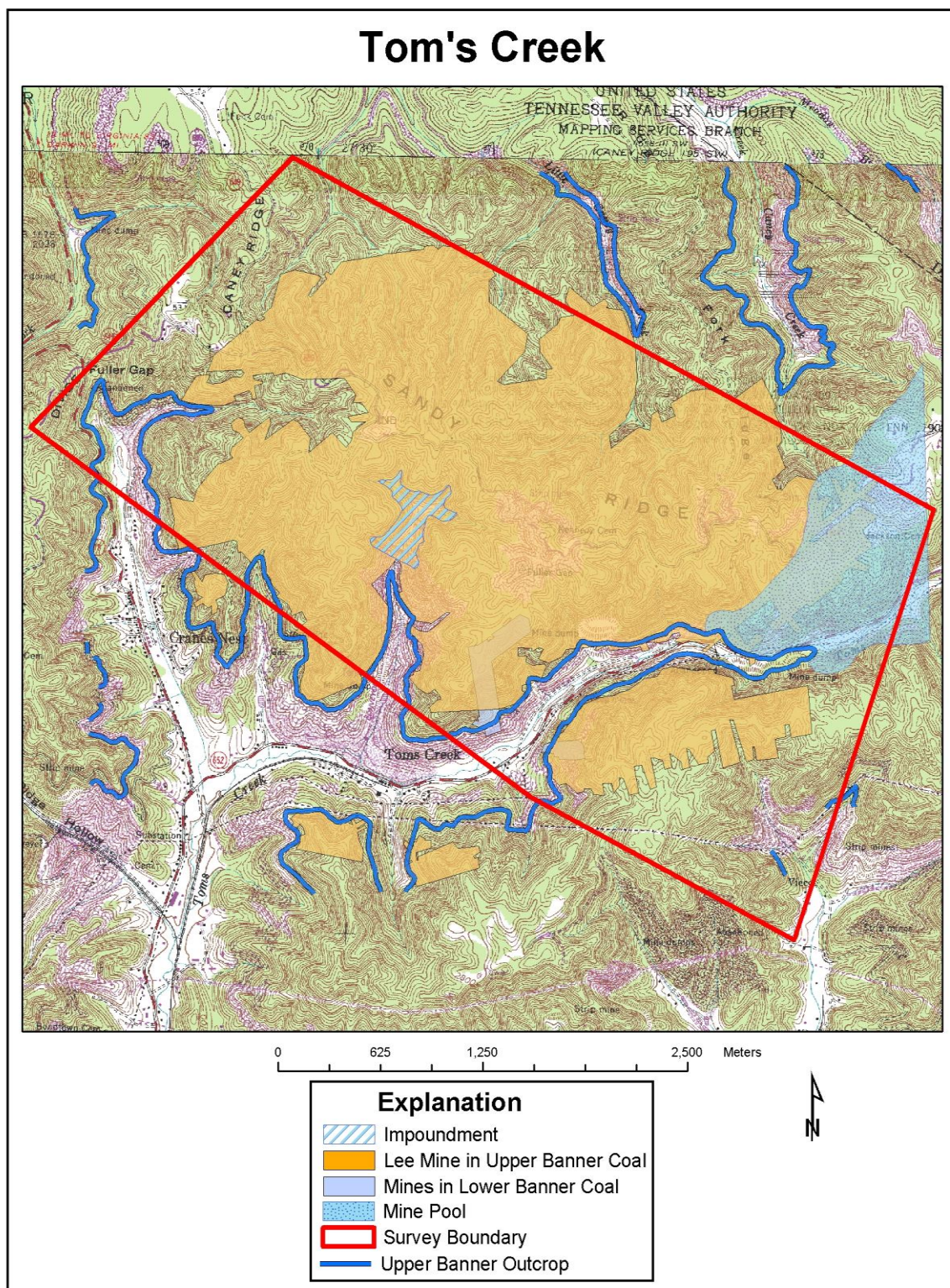
Figure 9. Location of coal slurry impoundment, Lee Mine, and mine pool at Tom's Creek site.

Results and Discussion

EM Flow and Airstem software programs were used to generate conductivity/depth images (CDI), which show the distribution of conductivity with depth along flight lines. The CDIs calculated by the two programs differed substantially although the same raw data was input into each.

Airstem CDIs typically show only one conductor. In some areas, Airstem CDIs indicate a thick, single conductor that extends from the surface to depths of 200 m or more. These thick, deep conductors often coincide with areas of known power line interference. Apparent conductivity values suggested by Airstem CDIs are reasonable based on conductivity information from other data sources. Airstem CDIs have a smooth, visually appealing profile. However, Airstem was not able to discriminate more than one conductor. This capability is needed for flooded mine workings to be identified.

EM Flow CDIs typically show three conductors: a thin surface conductor, a thicker, but less conductive intermediate zone, and a strong and thick deep conductor. The second or intermediate conductor roughly parallels the surface topography and is at the surface in stream valleys. This conductor can reasonably be assumed to be the water table. EM Flow CDIs contained a large amount of vertical striping, and often had an unpredictable response to noisy data. The range of conductivity suggested by EM Flow was about one order of magnitude higher than would be expected for the survey areas. Furthermore, the deep conductor indicated by EM Flow may or may not be real. EM Flow CDIs assume a resistive basement, which may not be valid for sedimentary areas because the basement is often as conductive as near-surface layers. Both programs sometimes indicate a persistent, high conductivity layer at the surface that is geologically unreasonable. Neither program is ideal for this application.

Powell Mountain

Conductivity/Depth Images prepared using Airstem and EM Flow codes showed conductive anomalies in areas and at depths known to contain flooded mine workings (shaded areas of CDIs, Fig. 10). However, the anomalous area extended laterally beyond the known mine perimeter indicating that cultural or geological noise, and not flooded mine pools may be the source of the anomaly. The target mine pool is approximately 1-m thick with conductivity of about 150 mS/m,

which would yield a conductance (conductivity times thickness) of 150 mS. Roof falls that have occurred within the mine pool were expected to result in a thicker layer with proportionately lower conductivity, and only slightly affect the conductance. The Airstem CDI indicates a conductor that is about 100-m thick with a conductivity of about 14 mS/m. This would yield a conductance of 1400 mS or about 10-times the expected conductance of the mine pool. The EM Flow CDI indicates a thinner, more conductive anomaly that is approximately 60-m thick with a maximum conductivity of about 40 mS/m. The conductance of the EM Flow anomaly would be about 2400 mS, or about 24 times the expected conductance of the mine pool. Neither the Airstem anomalies nor the EM Flow anomalies exhibited the dip (towards the right) that the coalbed is known to have. It is obvious that the anomalies depicted by Airstem and EM Flow are not responses to a flooded mine. Rather, these anomalies are due to geologic noise or are an artifact of data processing.

The data from the Powell Mountain Survey contain significant amounts of noise, from both known (power lines) and unknown sources (suspect radio frequency sources). Line 3200, which is shown in Figure 10, is exceptional in that it contains less noise than other lines. The numerous, near-surface conductive anomalies can be attributed to conductors such as weathering mine spoil, saturated areas (flood plains), and metallic objects. The strong conductor at intermediate depth in both the Airstem and EM Flow CDIs (Northing 4074200-4074800, Fig. 10) is from power line interference.

Wet Flats

Survey results for the Wet Flats Area were similar to that for the Powell Mountain Area except that there are even more noise sources in the Wet Flats Area. Figure 11 contains flight line data for line L4110. The locations of known mine pools are shown as shaded regions on EM Flow and Airstem CDIs (Fig. 11). Although the EM Flow CDI indicated the presence of a thick conductor within the target areas, the same conductor was also present in areas without mine workings. The Airstem CDI did not identify conductors in the targeted areas that might represent flooded mine workings. The mine workings in the target areas were approximately 1-m thick and contained water with a conductivity of about 50 mS/m. A 1-m thick mine pool is a very thin conductor when compared to the 100-200 m of strata that overlie it. For the mine pool conductor to be detected beneath such thick overburden, the conductivity of the mine water would have to be several orders of magnitude higher than the conductivity of the overburden strata. The
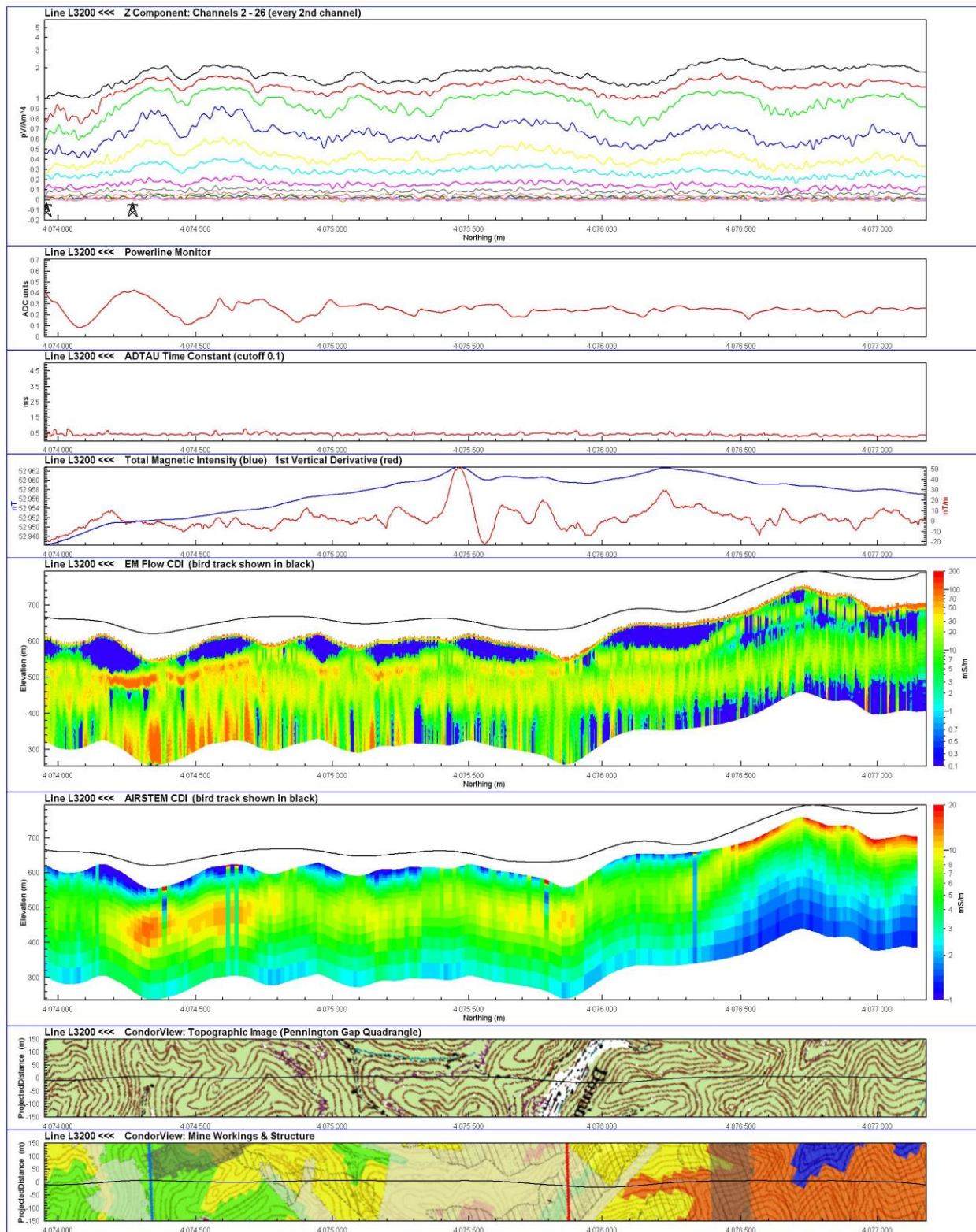
Figure 10 Flight line L3200 from the Powell Mountain Survey showing magnetic and electromagnetic data, EM Flow and Airstem CDIs, and topographic and mine maps. Shaded region on CDIs denote areas containing mine workings known to be flooded.

conductivity of the mine pool is about five times the conductivity of the overburden, which is insufficient for mine pool detection.

EM Flow and Airstem CDIs indicate the presence of a pervasive, relatively thick and strong surface conductor for line L4110. This near-surface anomaly could indicate the presence of conductive spoil from extensive surface mining or it could be an artifact of data processing or inadequate instrument calibration.

Wise Reservoir

The primary reason for the Wise Reservoir Survey was to determine if water from the reservoir is infiltrating into abandoned workings of the White Oak Mine in the Upper Banner Coalbed, approximately 100 m below. Figure 12 contains data from flight line L1090, which is from an area where the impoundment overlies workings in the White Oak Mine. The extent of flooding within the White Oak Mine is not known. Therefore, the mine workings beneath Wise Reservoir may not be flooded and may not provide a conductive target. If the mine was flooded and the survey detected the mine pool, there should be a conductor in the black shaded area of Figure 12. The water within the reservoir is conductive, which limited the exploration depth. No flooded mine workings were detected.

The infiltration of conductive reservoir water would increase the bulk conductivity of the strata beneath the reservoir. The shaded areas of the EM Flow and Airstem CDIs indicate regions where the infiltration would be expected. No anomalies were identified in these areas indicating that either: 1. no infiltration is occurring, 2. infiltration is occurring but it does not increase the bulk conductivity of the strata sufficiently to be detected, or 3. the conductive reservoir water prevents detection of conductors in underlying strata.

Tom's Creek

Figure 13 is a segment of flight line 2180 that crosses a coal slurry impoundment. Mine workings in the 1.7-m thick Upper Banner Coalbed occur about 100 m below the impoundment. The conductivity of water in the coal slurry impoundment is estimated to be about 50 mS/cm based on measurements made in stream below the impoundment. The EM Flow and Airstem CDIs indicate a conductive surface layer at the location of the impoundment. Neither CDI shows conductors beneath the thin, near-surface conductor. Power line interference is more prevalent in

this survey than either the Powell Mountain Site or the Wet Flat Sites. Moreover, extensive surface mining has left conductive cover that limits the penetration depth of electromagnetic energy and reduces exploration depth. A strong magnetic response was observed from the coal slurry impoundment; presumably due to fugitive magnetite (from coal cleaning) that is present in the coal slurry.

Fig. 14 is a segment of flight line 2070 that overlies flooded mine workings at a depth between 200-300 m (shaded area of CDIs). The coal thickness and presumed thickness of mine pool at this locality is about 1.3 m. The EM Flow and Airstem CDIs indicated a conductor east of the mapped mine pool (Fig. 14) but no conductor at the location of the known workings. The Airstem CDI contained a strong surface conductor at this location that would have limited exploration depth. The EM Flow CDI contained a thinner surface conductor but also indicated a conductor that is too deep to represent the mine pool.
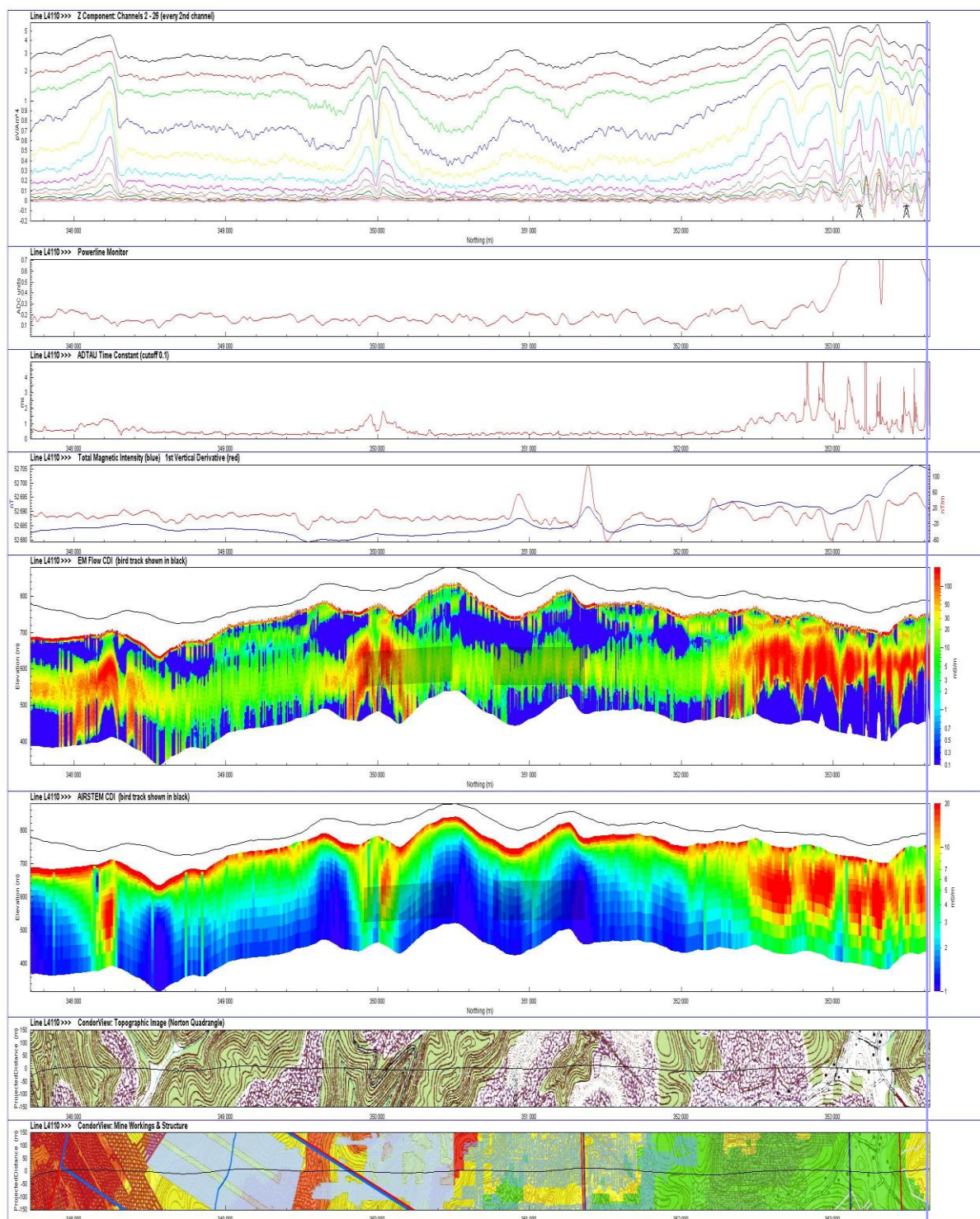
Figure 11 Flight line L4110 from the Wet Flats Survey showing magnetic and electromagnetic data, EM Flow and Airstem CDIs, and topographic and mine maps. Shaded regions on CDIs denote areas containing mine workings known to be flooded.
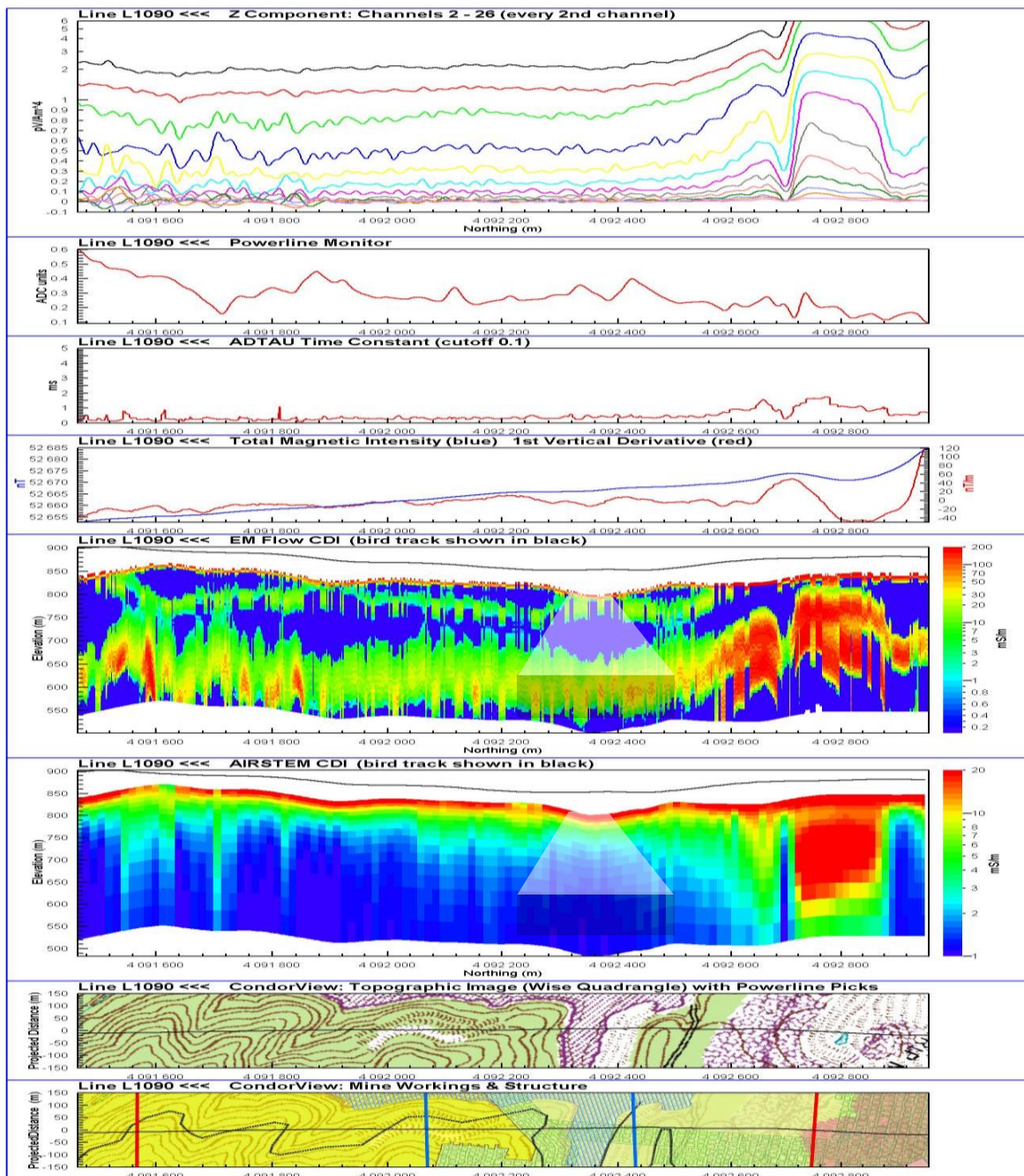
Figure 12 Flight line L1090 from the Wise Reservoir Survey showing magnetic and electromagnetic data, EM Flow and Airstem CDIs, and topographic and mine maps. Shaded white prisms show potential areas for the infiltration of reservoir water into the underlying workings of the White Oak Mine.
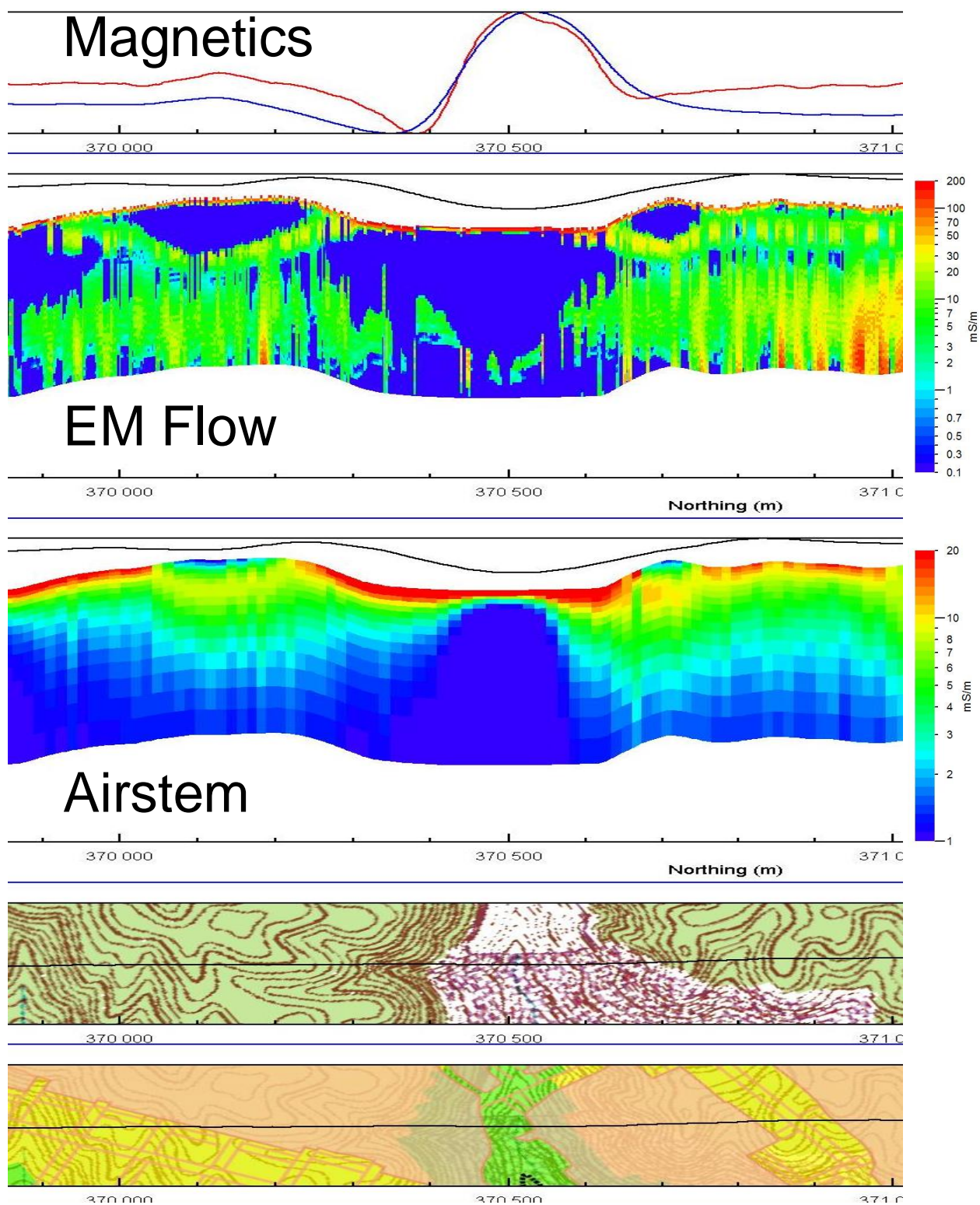
Figure 13 Segment of flight line L2180 where it crosses a coal slurry impoundment. Mine workings underlie the impoundment at a depth of about 100 m.
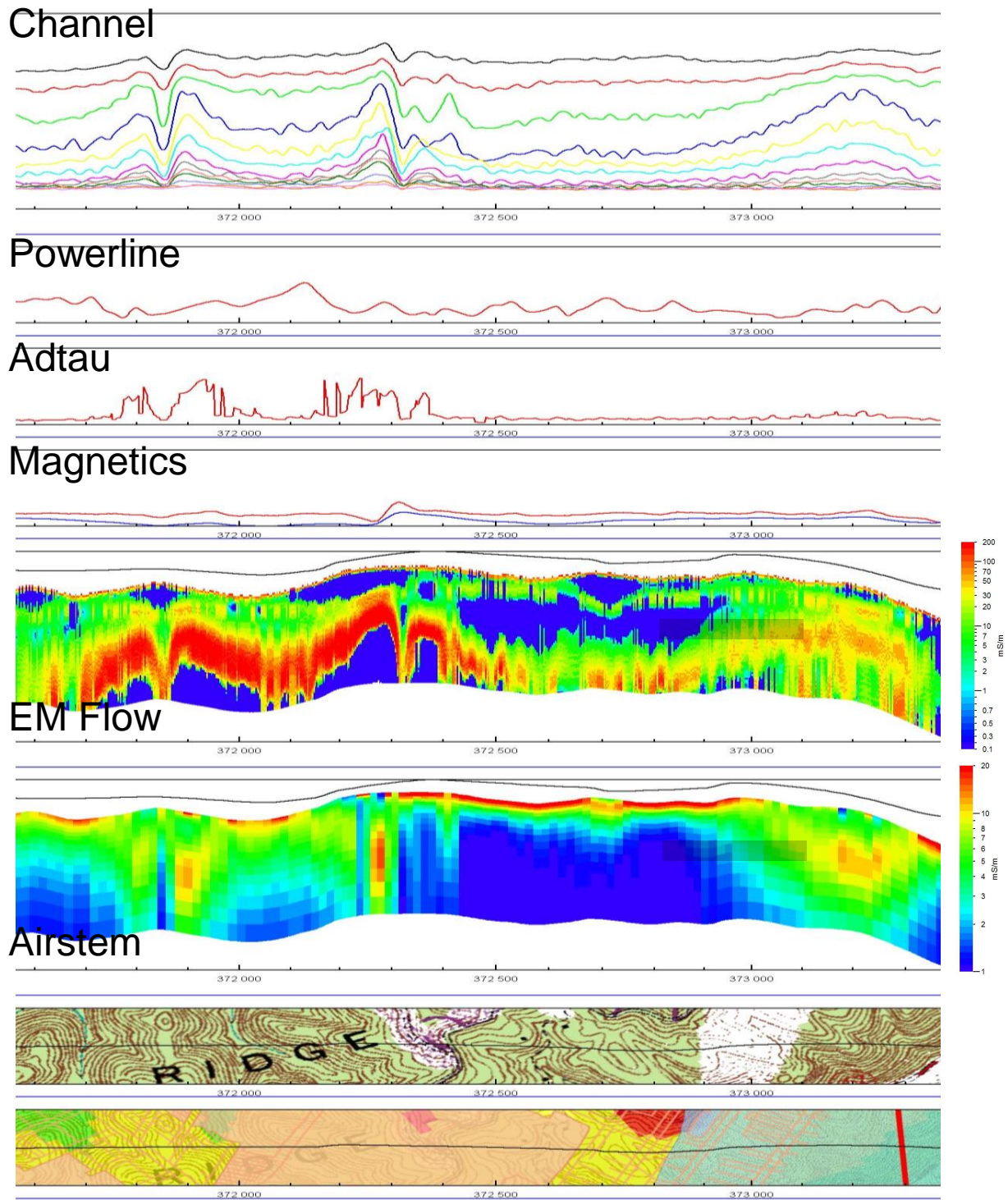
Figure 14 Segment of flight line 2070 over flooded mine pool at a depth between 100 and 200m. Shaded areas indicate the location of flooded mine workings.

Conclusions

The helicopter TDEM surveys failed to achieve the primary objective of this study; detecting flooded mine workings at depths greater than 50 m. Forward modeling performed by Fugro Airborne Surveys prior to this study suggested that their Geotem System could detect a 3-m thick mine pool with a conductivity of 200 mS/m beneath 100-150 m of cover with an average conductivity of 20 mS/m. However, conditions for the four surveys in this paper were less optimal than model conditions. First, rugged terrain precluded the use of more powerful fixed-wing TDEM systems. Second, the coalbed thickness and presumed mine pool thickness averaged slightly more than 1 meter; not the 3-m thickness assumed in the forward model. Third, the conductivity of mine pools in this survey ranged from 30-150 mS/m, less than the 200mS/m assumed in the forward model. Fourth, extensive surface mining in the surveyed areas resulted in a conductive surface layer that decreased exploration depth. The model assumed a uniform overburden conductivity of 20 mS/m and made no provision for a conductive near surface. For a mine pool to be detected, its conductance (conductivity X thickness) must be significantly greater than the conductance of the overburden. For the areas examined in this study, the mine pool underlies a 100-m thick overburden layer with an average conductivity of 10 mS/m. Therefore, the overburden layer has a conductance of 1000 mS. A 1-m thick mine pool with a conductivity of 70 mS/m exhibits a conductance of only 70 mS. Under these conditions, CDIs will not be able to differentiate the mine pool as a separate layer.

Data interpretation was further complicated by selecting areas that contained active mines, idle mines, and abandoned mines of various ages and mine design. These mines were frequently in different coalbeds and would commonly overlie or underlie other mines. Although we were provided access to all known mine maps for the survey areas, it was obvious that maps for some older mines were not available.

A significant amount of noise was observed in all flight lines from all survey areas. This noise was from expected sources, power lines and metallic pipelines, as well as from unknown sources. Noisy conductivity data sometimes had no corresponding response in the power line or the magnetic channels, which excluded power lines and ferrous metal pipelines as potential sources. The unknown noise was accompanied by changes in the ADTAU time constant and occurred at consistent positions on adjacent flight lines. This indicated that the noise source was

from the ground and not internal to the TDEM system or helicopter. For most flight lines, noise rendered 25-50 pct of the conductivity data unusable. The four areas surveyed in this study may have somewhat more cultural infrastructure than typical coal mining areas and therefore, more noise. However, improved noise rejection is needed for helicopter TDEM to be a useful tool in coal mining areas.

Finally, this study was conducted in southwestern Virginia hoping that a successful demonstration in these especially difficult thin, low-sulfur coal mines would indicate that the technology could be applied to virtually any coal mining area. The fact that helicopter TDEM did not work in southwestern Virginia does not imply that airborne TDEM will not successfully identify thicker or more conductive mine pools in other areas.

Acknowledgements

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