HELICOPTER FREQUENCY DOMAIN (FDEM) SURVEYS FOR CHARACTERIZING ENVIRONMENTAL PROBLEMS RELATED TO MINING: OBSERVATIONS AND CONCLUSIONS FROM 30 SURVEYS[1]

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Abstract. Since 1999, the National Energy Technology Laboratory has conducted helicopter frequency domain electromagnetic (FDEM) surveys of 30 sites to identify hydrologic problems that have resulted from mining activity. The FDEM data from these surveys was processed to generate conductivity maps and conductivity/depth images (CDI), which together show the lateral and vertical distribution of ground conductivity. This information has been used to determine: 1) the location, depth, and thickness of regional water tables and perched water tables, 2) the location of infiltration zones, 3) the location of pyritic wastes either on the surface or at depth, 4) the location of flooded mine workings (if filled with conductive water and located at depths less than 50 m), and 5) the likely locations for springs or mine discharges. Helicopter FDEM results have been validated using down-hole geophysical measurements, traditional hydrologic measurements from dense networks of groundwater monitoring wells, ground-based electromagnetic surveys, airborne thermal infrared imagery, and field reconnaissance.

Helicopter FDEM surveys cannot be used in heavily populated areas or areas near power lines. The exploration depth will be reduced in areas with conductive cover such as contaminated surface impoundments or clay layers.

Successful and unsuccessful FDEM surveys will be discussed.

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Introduction

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) has conducted helicopter electromagnetic (HEM) surveys of 30 sites nationwide (Fig. 1). Although much work has focused on coal mining areas in West Virginia, Pennsylvania, Ohio, and Maryland, FDEM data has also been collected over an abandoned open pit mercury mine and selected coal bed methane production areas in Wyoming's Powder River Basin (WYPRB). The purpose of these surveys was to determine if HEM can provide hydrologic information that is useful for hazard identification and to aid mine water remediation efforts. In the case of WYPRB, the objective was to determine the fate of water pumped from gas wells to stimulate methane production. Information derived from FDEM surveys could include the location of:

- Flooded mine workings
- Abandoned mine discharges
- Mine water recharge zones
- Paths taken by water through abandoned mine workings and other subsurface features.

In light of the 2002 accident that detained nine miners who were entrapped by water in the Quecreek Mine in south-central Pennsylvania, there is now a heightened awareness of what can happen when mining operations inadvertently encounter water within an incorrectly mapped, abandoned mine. Although the miners were successfully rescued, a nationwide priority to map inadequately documented mine workings has begun.

The Quecreek scenario has also redoubled NETL's efforts to use HEM for detecting mine pools. Generally, pools that develop in underground coal mines are more conductive than the strata above and below the mine, and therefore, offer high-contrast targets for electromagnetic survey methods. However, the mine pool together with the underclay (also conductive) is only about 2 to 4-m thick, and 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 mine pool and the conductivity of the overburden. Forward models performed by Fugro Airborne Surveys suggest that frequency domain HEM can detect a 2-m thick mine pool with a conductivity of 500 mS beneath as much as 50 m of overburden with an average conductivity of

20 mS. The models also indicate that time domain electromagnetic surveys from a fixed-wing aircraft may be able to detect the same mine pool beneath up to 100 m of overburden.

This paper summarizes the results obtained from three out of 30 HEM surveys conducted by NETL in six years. These sites were selected because they represent a diverse set of mining-related environmental problems and help illustrate some of the benefits and limitations of airborne conductivity methods. It is not the purpose of this paper to provide a comprehensive detailed description of the HEM technique and results obtained for each of the study areas, but rather an overview of the results from selected sites and the lessons learned.

General Survey Descriptions

Fugro Airborne Surveys performed the HEM surveys for NETL (Fugro Airborne Surveys, 2003). All surveys were flown using the DIGHEM^{V}, DIGHEM^{VRES} or RESOLVE electromagnetic data acquisition systems. The DIGHEM^{V} system employs 3 pairs of horizontal coplanar transmitter and receiver coils, at frequencies of 900 Hz, 7200 Hz, and 56000 Hz, and two vertical coaxial coil pairs at 900 Hz and 5500 Hz. The DIGHEM^{VRES} is a 5-coplanar system with frequencies of 380 Hz, 1400 Hz, 6200 Hz, 25,000 Hz, and 100,000 Hz. The RESOLVE six channel system consists of five coplanar transmitter/receiver coil pairs operating at frequencies of 393 Hz, 1.53 kHz, 6.20 kHz, 28.2 kHz, and 107 kHz and one coaxial transmitter/receiver coil pair that operated at a frequency of 3.23 kHz. All three systems consist of individually-tuned coils and are designed for mapping conductivity in horizontally-layered geology. The coplanar coil separations for these systems are 7.9 m. In-phase and quadrature electromagnetic data are collected every 3.5 m along flight lines and recorded with locations determined using differentially corrected GPS. The raw data was leveled and smoothed to remove effects of sensor drift and spheric events. Total field magnetics, utilizing a cesium magnetometer, were collected in addition to EM conductivity data. A complete description of the RESOLVE HEM system is available at http://www.fugroairborne.com`/Services/airborne/EM/resolve/index.shtml .

The interline spacing used in all surveys was either 50 m or 100 m (nominally). Tie lines were also flown perpendicular to the normal survey direction. Tie line data are used to correct for instrumental drift and diurnal variation that occurs during the survey. Under ideal conditions, the sensor height should be 30 m above ground level (AGL).

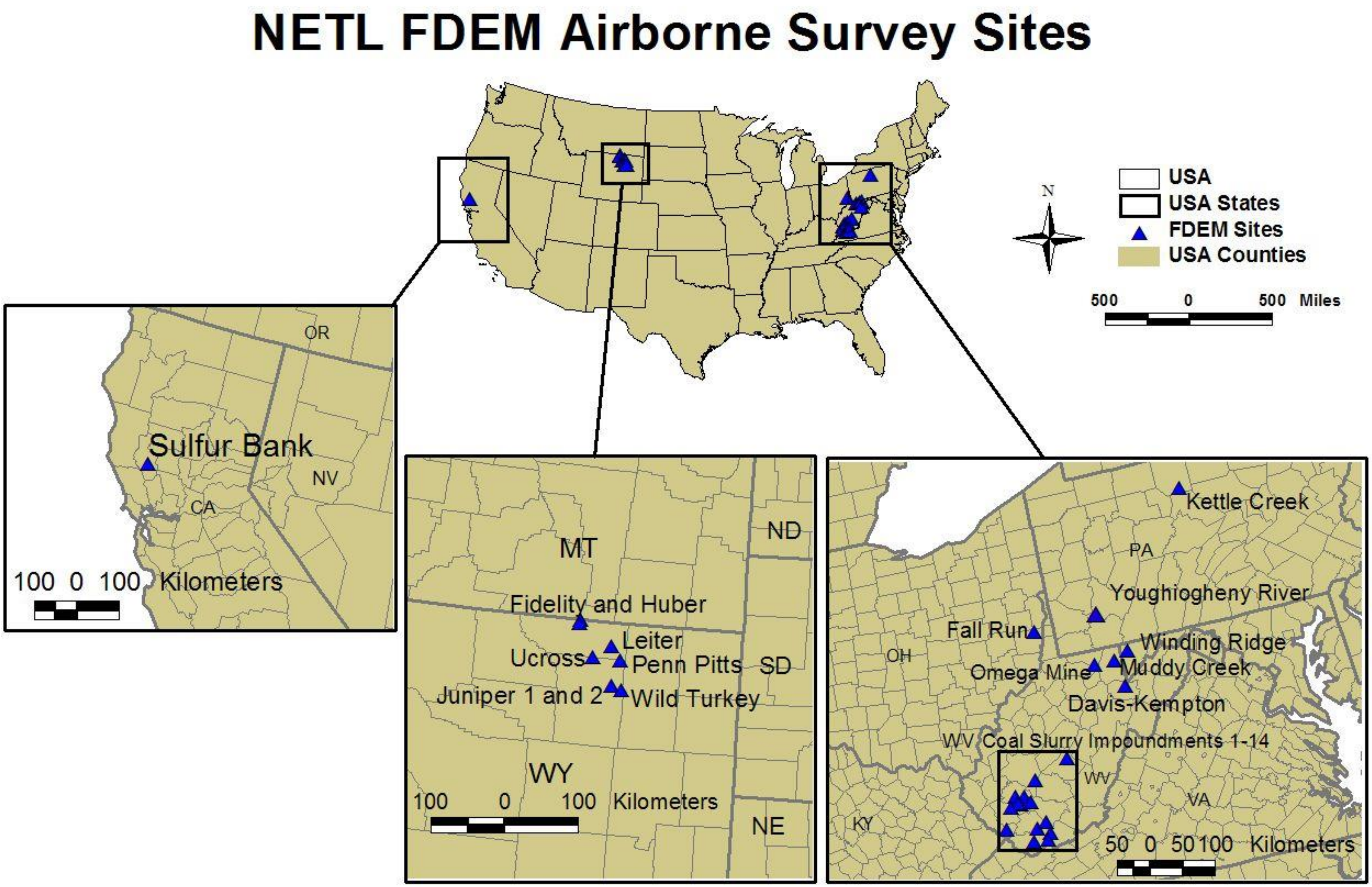

Fig. 1. Locations of airborne HEM surveys conducted by NETL since 1999.

Data Processing and Interpretation

The geophysical data consists of navigational data (GPS, altimetry) along with leveled in-phase and quadrature data for each of the operating frequencies. These data were processed in-house into Conductivity/depth images (CDI) using EM Flow software (Encom Technology, 2001a). CDIs depict a vertical profile of color-encoded conductivity information along the horizontal extents an individual flight line. The surface topography and depth below ground are presented within each profile. The actual processing involves some additional user input parameters describing the data format, transmitter-receiver geometry, transmitter waveform, and recording channels. The software then transforms the input frequency data to the time constant domain (Tau) employing a complex matrix inversion processing scheme that results in a set of basis functions. These basis functions are used in the final deconvolution.

A CDI profile was generated for each flight line and exported to Geosoft database format for further processing in Profile Analyst (Encom 2001b). Profile Analyst facilitates a concomitant comparison between the cursor selection along the flight line traverse superimposed on a geo-referenced base map that may also consist of mine workings, inferred mine pools, and overburden thickness. Additional data sources, such as driller's logs from nearby boreholes may also be compared to the CDIs to determine the accuracy of the EM data and processing. Ground-based geophysical methods were also used for the purpose of validation, or for complementing information sought at various target areas.

Lower Kettle Creek and Cooks Run Watershed, Clinton County, Pennsylvania

Background

In July and August 2002, NETL conducted a HEM survey of the Lower Kettle Creek Watershed in north-central Pennsylvania (Fig. 2) using the RESOLVE system. This survey was funded by the Pennsylvania Growing Greener Program and in collaboration with Trout Unlimited. The targeted site is located in the Kettle Creek Watershed, in Clinton County. This survey benefited from the experience gained from six previous surveys and from the continuous improvement in HEM technology that has occurred since the first survey was flown in 1999. At this site, the mine pool was overlain by 0 to 50 m of cover, and was accurately depicted in a conductivity/depth image (CDI).

Site Description

Kettle Creek Watershed encompasses approximately 245 mi^2 (633 km^2) of the Mountainous High Plateau Section of the Allegheny Plateau Physiographic Province. Elevations range from 229 m in the stream valleys to over 488 m on the highest ridges (Briggs, 1999). Coal has been mined from the Middle and Lower Kittanning Coalbeds within the Kettle Creek Watershed.

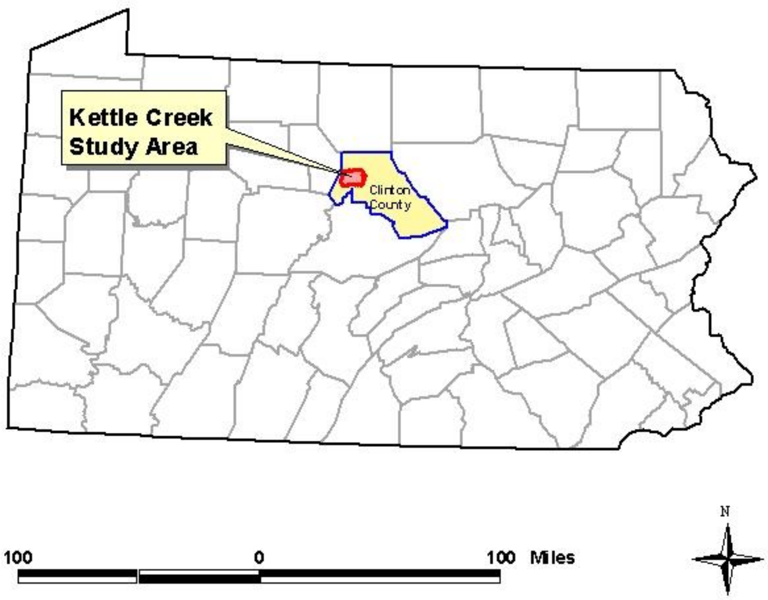

Fig. 2. Location of the Kettle Creek Study Area.

Both coalbeds were surface mined in the watershed from the early 1930's to the 1970's, yet most production was from the Middle Kittanning Coalbed because of shallow overburden. Underground workings were developed in the Lower Kittanning Coalbed in the late 1860's and continued until the 1950's. Following mining, many underground workings filled with water and are now discharging acid mine drainage (AMD) with pH ranging from 1.98 to 4.5.

The survey area west of Kettle Creek contains about 16 underground mines. Mine maps do not exist for the eastern survey area although there is surface evidence of underground mines (Klimkos 2000). One objective of this survey was to provide the location of deep mined areas in the eastern watershed.

Summary of Results

A total of 116 flight lines (~130 km^2) of 6- channel HEM conductivity data were collected using the RESOLVE system. CDI profiles derived from the HEM line data showed clear evidence of flooded mine workings, mine water recharge zones, and paths taken by water through abandoned mine workings (Fig. 3-5). Prior to accomplishing this survey, a thermal infrared (TIR) airborne survey was used to target abandoned mine discharges (AMD) in the same area (Sams and Veloski, 2003). Several of these discharges that were located by TIR and verified in the field, were also observed as prominent anomalies in CDI profiles where the HEM flight line intersected the discharge zone (Fig. 4).

Fig. 5 is a CDI that depicts several thin, conductive anomalies on the surface. These surface conductors always occur within areas that have been disturbed by surface mining activities. However, not all surface mined areas are anomalously conductive. It was postulated that the near-surface conductors indicate the location of mine spoil with high concentrations of weathering pyritic material (Hammack et al., 2003). Reclamation of areas disturbed by strip mining was attempted using rough grading and planting of conifers. However, in areas where infiltration is occurring, the reclamation was not successful. If this can be verified by subsequent ground-based surveys, then airborne FDEM may be a technique to scan large mining regions and quickly target acid-generating material for remediation.

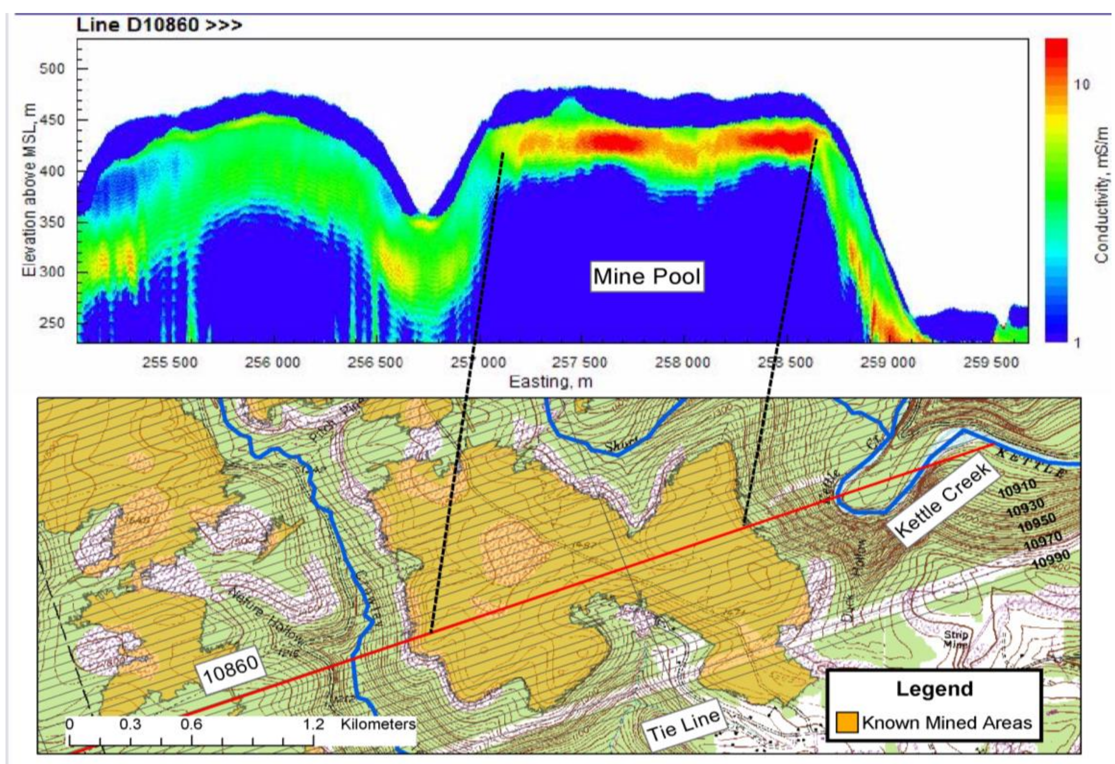

Fig. 3. Inferred mine pools (red and yellow zones) correspond geographically to mapped underground coal mine workings beneath flight line D10860.

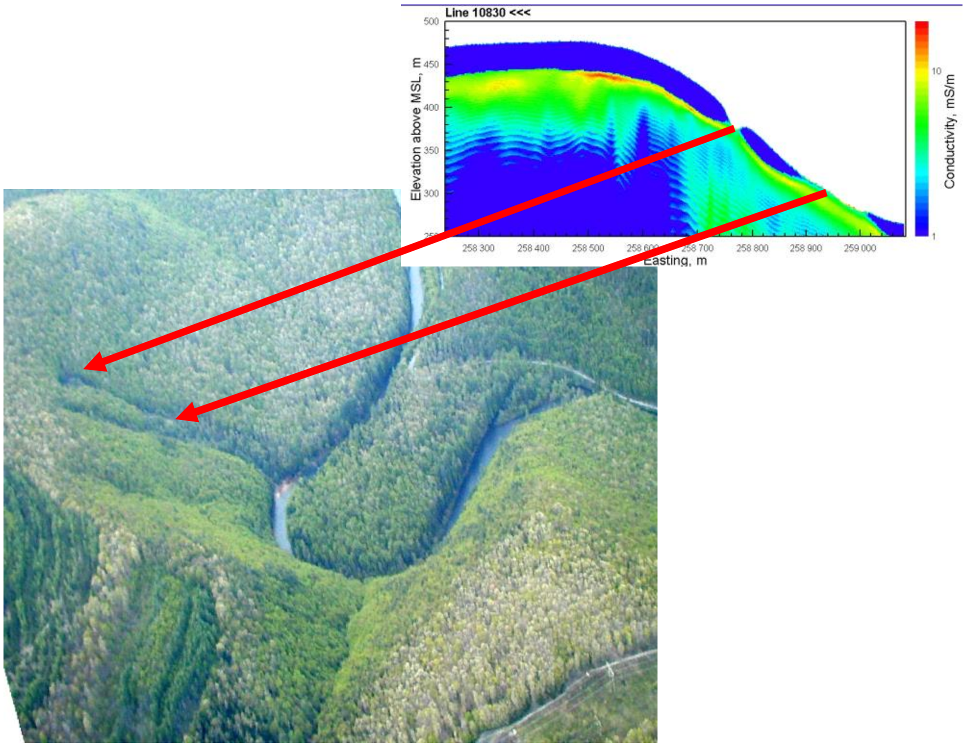

Fig. 4. This air photo shows prominent abandoned mine discharges flowing into Kettle Creek. The CDI inset (upper right) suggests the underground flow paths of the conductive mine water and its surface expression. Warmer colors indicate higher apparent conductivity.

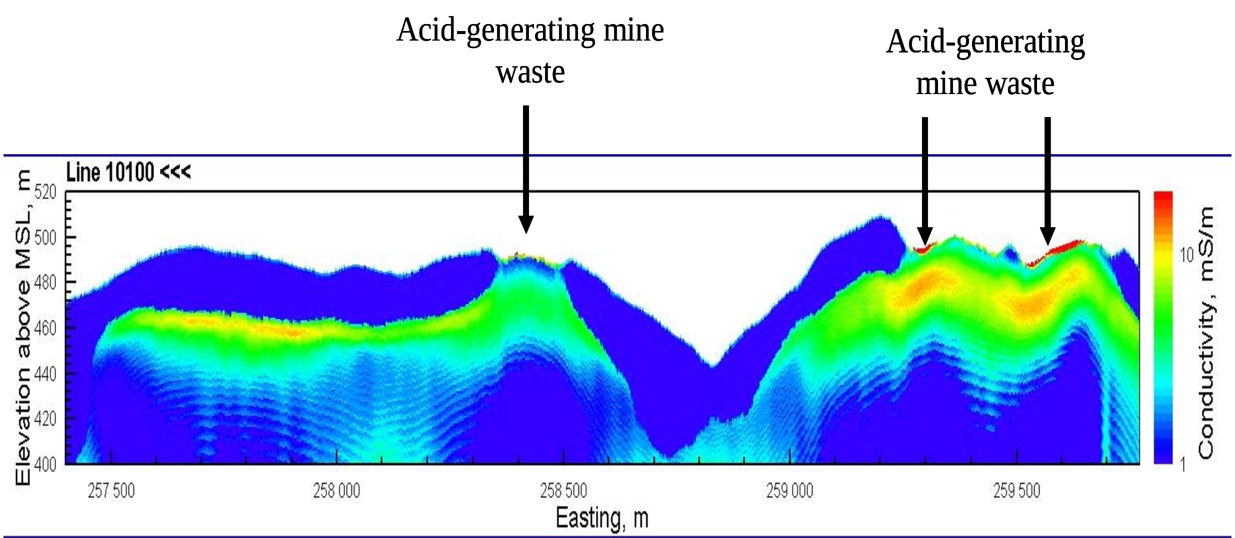

Fig. 5. Acid-generating mine spoils are depicted as highly conductive areas near the surface.

T&T Mine Complex, Muddy and Roaring Creek Watersheds, Preston County, West Virginia

Background

The purpose of this study was to determine the lateral extents of a contaminated mine pool within the study area. Much of the investigation focused on the T&T mine complex (Fig. 5). An HEM survey was conducted using the Fugro DIGHEM^{VRES} multi-coil, multi-frequency system. In addition to EM conductivity, the apparatus was also equipped with a Cesium magnetometer and two-channel VLF (very low frequency) receiver. A total of 124 lines were flown in an east-west direction along with 2 orthogonal tie lines.

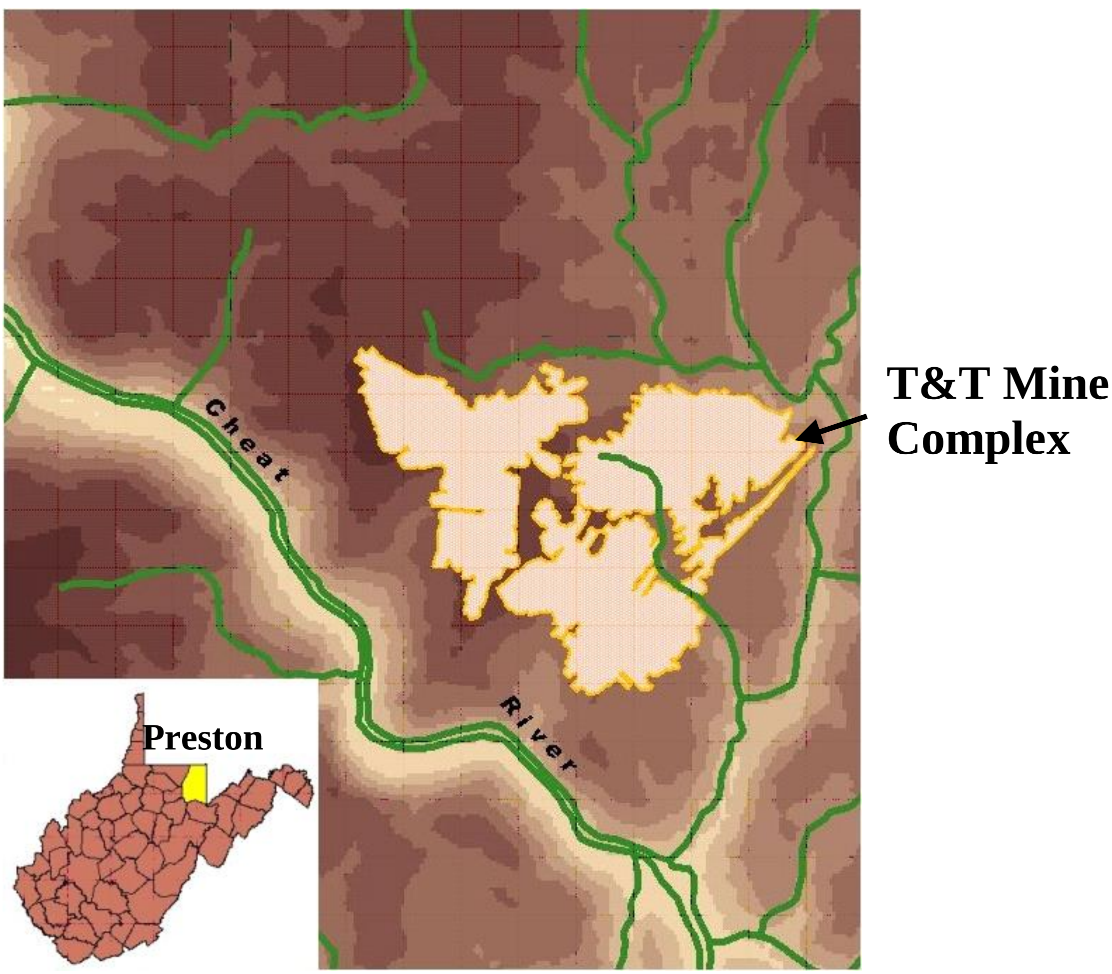

Fig. 5. The T&T Mine Complex is located within the Muddy and Roaring Creeks Watershed, Preston county, West Virginia.

Site Description

Three coal seams underlay the area; the Bakerstown in the Conemaugh Group and the Upper and Lower Freeport seams in the Allegheny Formation (Hobba, 1991). The mine pool is thought to be located at a depth of approximately 300 ft. The study area may be characterized as containing a high density of cultural features that adversely influenced the quality of the geophysical data. Several power lines and substations were present within the survey area.

Summary of Results

Over 145 km^2 of 5- channel HEM conductivity data was collected. The data set was dominated by large cultural anomalies. Numerous power lines induced prominent signals that are most apparent in the low-frequency channels (Fig. 6). Many of these features were confirmed by the fact that they coincided with the precise geographical locations of mapped power lines in the GIS. Other large conductive anomalies were also present and thought to be the result of municipal trash disposal sites and other sites containing a large volume of conductive metallic wastes. Other conductive anomalies coincided with coal refuse piles, and are most likely the result of pyritic oxidation. These areas are manifested as conductive surface anomalies in the higher frequencies (25 kHz and 100 kHz), but may also appear in the midrange frequency data (6.2 kHz), and are probably caused by infiltration of the acidic water. The abundant cultural features complicated the interpretation of the CDI cross sections.

Several ground-based geophysical investigations ensued, focusing mainly on the T&T Mine Complex. EM-34-3XL and 2-D resistivity were used in an attempt to locate the flooded mine pool. Both methods lacked the exploration depth necessary to observe the mine pool. A time domain electromagnetic survey (TDEM) was also attempted; the result of the survey was inconclusive.

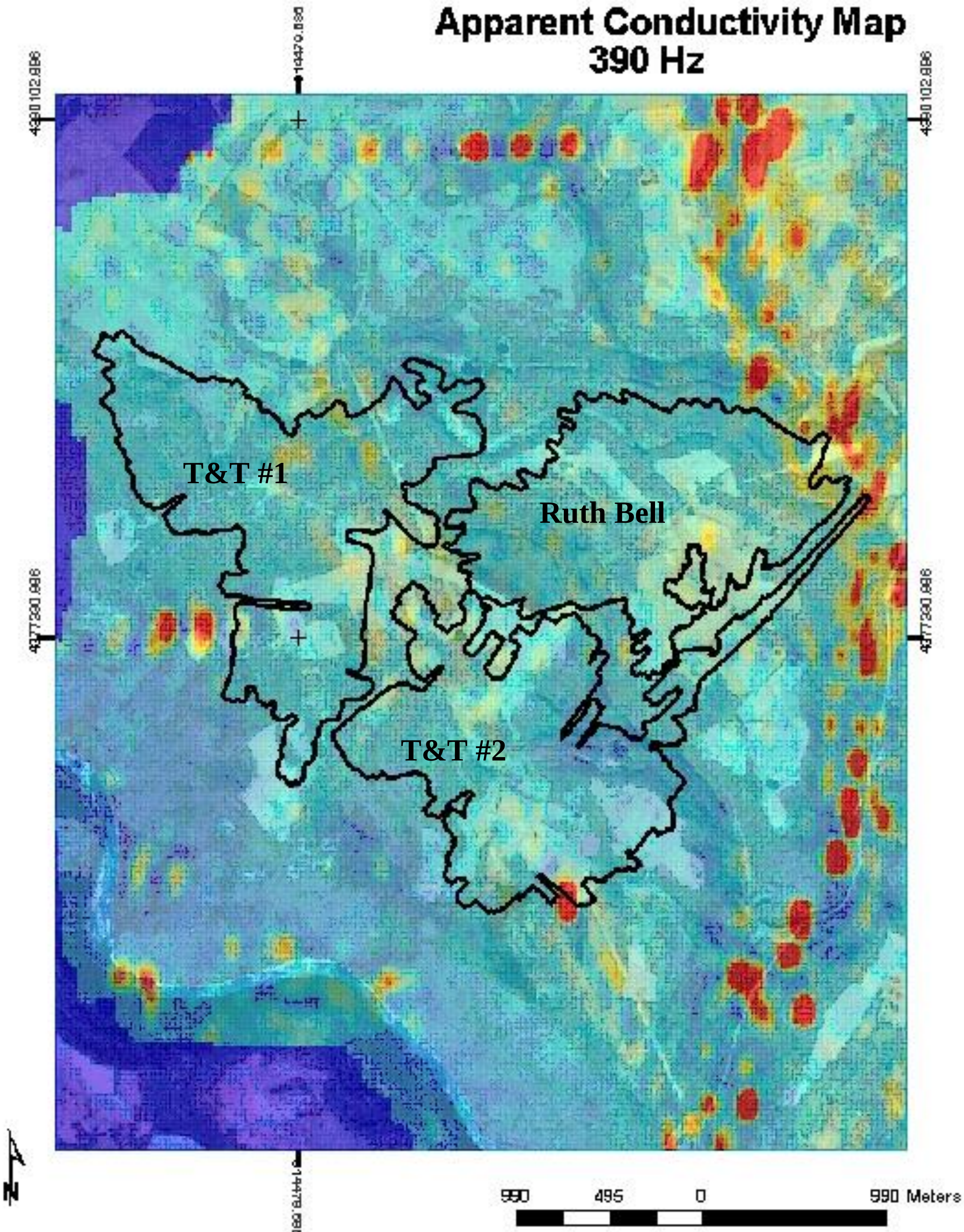

Fig. 6. Subset of the 390 kHZ conductivity map in the vicinity of the T&T Mine Complex. Warmer colors indicate higher apparent conductivities. The orange and red beaded anomalies are power lines.

Lower Youghiogheny River, Fayette and Westmoreland Counties, Pennsylvania

Background

This project was funded by the Pennsylvania Growing Greener Program and in collaboration with the Penn's Corner Resource Conservancy Charitable Trust, Inc. An airborne electromagnetic and magnetic survey was conducted over the Youghiogheny River between Connellsville and McKeesport on July 23, 2002. This survey was conducted by Fugro Airborne Surveys using an Ecureuil AS350-B3 helicopter and a 6-frequency RESOLVE electromagnetic system. Two flight lines were flown; one along each shoreline of the Youghiogheny River. This approach allows the survey footprint to cover the river channel. Navigation was by sight. The helicopter flew at an average airspeed of 97 km/hr with an average sensor height of about 33 m. The total survey consisted of 137 line-km.

Site Description

The Youghiogheny River receives drainage from 1,763 mi^2 in western Maryland, northeastern West Virginia, and southwestern Pennsylvania and is a tributary to the Monongahela River near McKeesport, Pa. (Fig. 7). The basin lies within the Appalachian Plateau Physiographic Province and contains sedimentary rocks of Mississippian and Pennsylvanian age. Approximately 60 percent of the basin is underlain by bituminous coal, a major natural resource for the economy of the basin. Coal has been mined in the basin since the early 1800's from the Pittsburgh, Redstone, Sewickley, Freeport, Kittanning, Bakerstown, and Brush Creek coal beds. The most significant coal bed in the basin is the Pittsburgh coal seam. The 1992 LANDSAT satellite imagery shows land cover in the Youghiogheny River Basin is 68 percent forest, 27 percent agriculture, and 3 percent urban or commercial. The remaining 2 percent of the land area is classified as open water, wetlands, and surface mines or quarries (U.S. Geological Survey, 1998). The 1992 LANDSAT imagery, however, does not accurately represent the extent of mining because many older surface mines are now revegetated and underground mining, as the name implies, takes place below the surface. The Youghiogheny River cuts through the ridges of the Appalachian Mountains, which trend in a southwest to northeast direction. The maximum elevation in the basin is 3,300 ft above sea level at the southernmost end of the basin

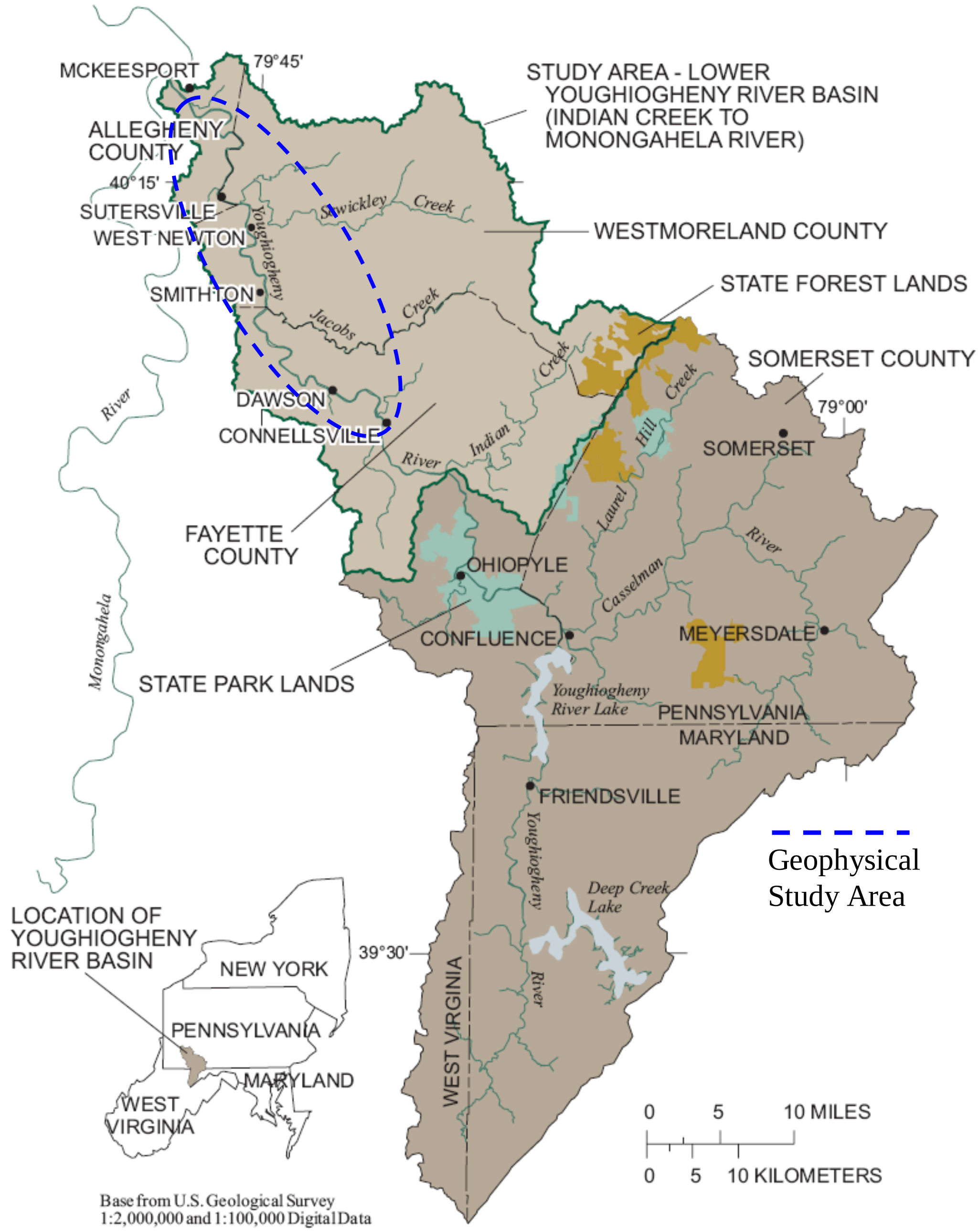

Fig. 7. The Youghiogheny River Basin and location of the study area in Pennsylvania.

drainage divide. The lowest elevation is 720 ft at the mouth of the Youghiogheny River near McKeesport, Pa. About 336,000 people live in the Youghiogheny River Basin; the highest population density is in the lower part of the basin downstream from Connellsville (Palmer, 1984).

Summary of Results

The CDI for the flight line along the west shore of the Youghiogheny River between McKeesport and Connellsville is shown in Fig. 8. Note that the river and underlying strata are especially conductive from McKeesport (Fiducial 0) upstream to about Buena Vista (Fiducial 5000). The source of this unusual conductivity is not apparent. Other conductive areas, especially those areas displaying deep conductivity, are most likely the effect of power line interference. The CDI for the flight line along the eastern shore shows similar trends although the data are noisier due to the proximity to the railroad and utilities. The CDIs must be broken up into smaller segments for interpretation. Fig. 9 is a segment of the CDI near Dawson that shows the river and the aquifer beneath adjacent land areas (red and yellow areas). Note that some parts of the aquifer are more conductive than others. In other coal mining areas, these especially conductive aquifers have been indicative of mine drainage. Likewise, the location where these aquifers approach the ground surface have been found to be favorable sites for mine seeps. Several abandoned mine discharges (AMD) have been located in this area by an airborne thermal infrared (TIR) survey conducted previously by NETL (Sams and Veloski, 2003).

Fig. 10 is another segment of the CDI that shows where the river may be infiltrating into underlying strata. Because there are other explanations for the steeply dipping conductivity patterns, ground-level surveys are needed to confirm this interpretation.

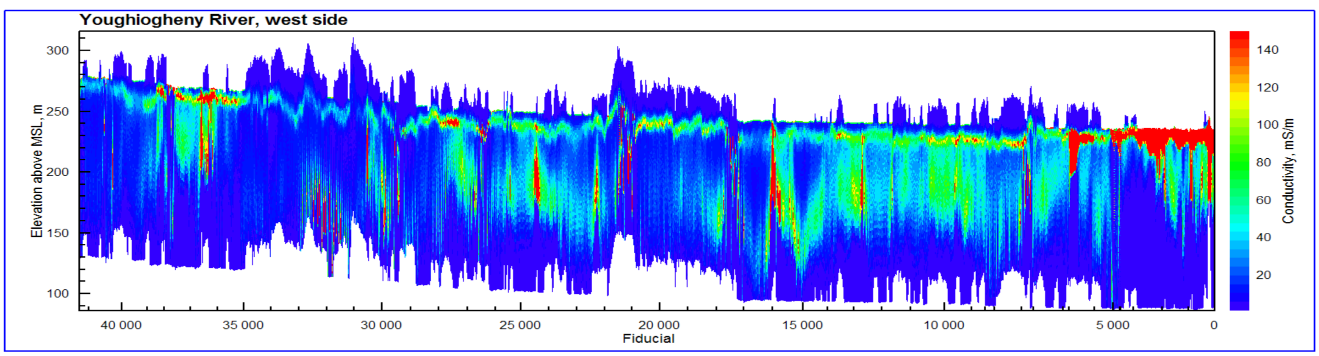

Fig. 8. Conductivity/Depth Image for the west shoreline of the Youghiogheny River between McKeesport (fiducial 0) and Connellsville (fiducial 40000)

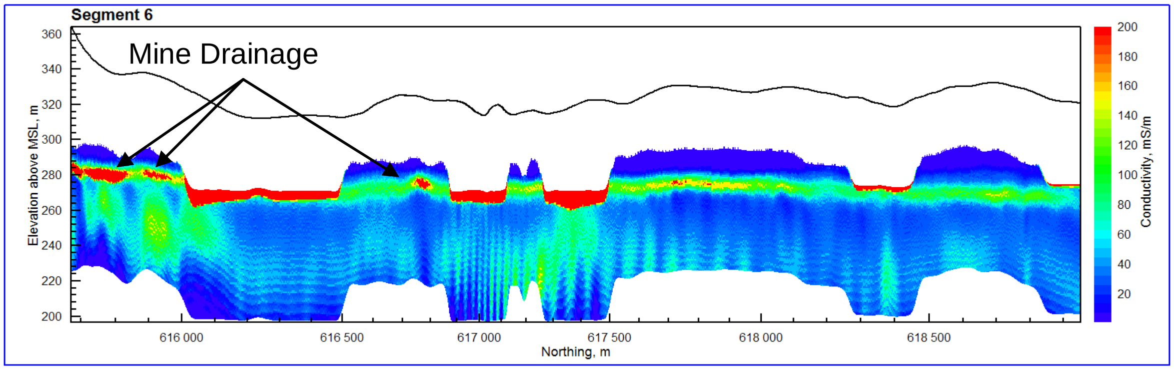

Fig. 9. CDI showing river and adjacent aquifers. Note: conductive aquifers may contain mine water.

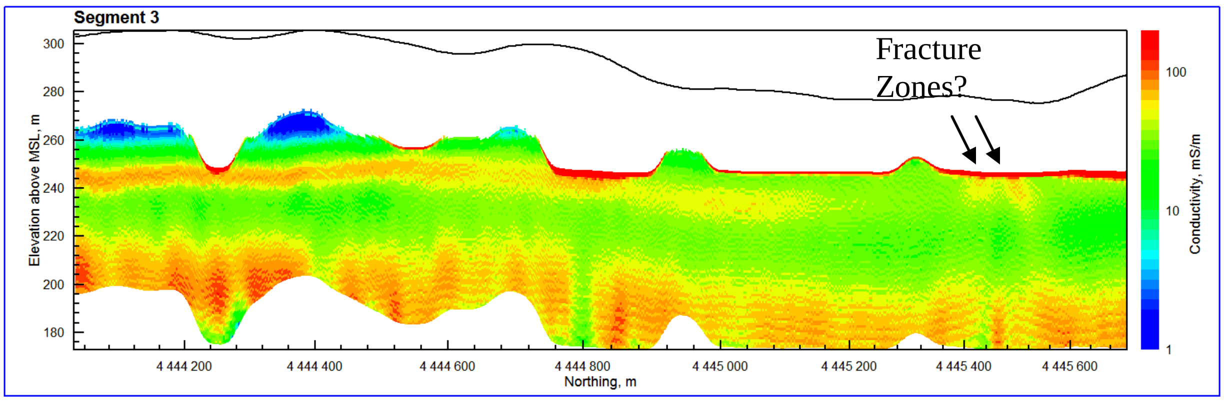

Fig. 10. CDI showing river and possible fracture zones that allow water to infiltrate into underlying strata.

Discussion - Lessons Learned

The success or failure of a project involving the use of FDEM geophysical data sets is largely dependent on several simple factors. Unfortunately, only a few of these are easily predicted. Areas containing a high density of power lines, pipelines, substations, and other electromagnetic cultural interferences should be avoided at all cost. All of these features are capable of producing strong anomalies in the data, particularly at the lower frequencies. Some of these anomalies give rise to prominent and unmistakable features as would be the case for a high voltage transmission power line. However, others are more subtle, and may either be misinterpreted as a geologic feature, or mask the presence of other features of interest. To a certain extent, anomalies produced by 60Hz current can be removed or isolated employing homomorphic or high pass filters. The resulting filtered component of the data may then be subtracted from the original data providing some degree of improvement (Fouzan and Harbert, 2002). Masking the data set in these areas can also be helpful, as this altogether prevents misinterpretation for the areas in question. The masked area should go beyond the geographical extents of the known cultural aberration depending on the strength of the anomaly and the sensitivity of the technique. We have observed the influence of power lines in the data from adjacent flight lines 100 m or more from its origin.

Another important aspect, of HEM survey design involves site selection. The effectiveness of the survey depends on the contrast between target and background conductors. Contrast between conductors constitutes an anomaly. If the overburden is equally or more conductive than any potential targets of interest at depth; these targets will not be observed. The detection of flooded mine workings beneath the river and possible flow paths between the river and these workings was the primary goal of the helicopter EM survey on the Youghiogheny River. However, the water and sediments in the Youghiogheny were found to be more conductive than anticipated, which limited exploration depth and prevented the detection of flooded mine workings beneath the river. It is possible that the site selected to perform airborne FDEM is an area that is uniformly conductive at all frequencies. The target would therefore be indistinguishable from background or geologic noise. This situation could precipitate from the desire to meet economic objectives by reducing the flight areas. It could also result in a near miss scenario where an anomaly that warrants further investigation is identified, but it appears on the edge of the data set, so additional flights may be prescribed at an even greater cost.

All available sources of information should be examined prior to selecting a site. This process begins with the construction of a GIS. Vector and geo-referenced digital raster data layers such as topographical maps, air photos, scanned mine maps, crop lines, structure contours, digital terrain models etc., can improve site selection and reduce costs. Visiting the site or acquiring recent air photos can also be highly beneficial, especially if map resources are out of date. The area may have also sustained changes such as natural resources development which brings with it additional supporting infrastructure (power lines, pipelines etc.).

The local geology should be examined. If the overburden thickness is beyond the exploration depth of the technique, perhaps another is more appropriate. Portable terrain conductivity apparatus such as the EM-34 can be used to ascertain exploration depth by conducting soundings at several locations within the proposed airborne survey area (McNeill, 1980). If known targets cannot be detected in the soundings data, then perhaps the survey should be abandoned or a more appropriate method selected. This technique can also be used to validate post-survey EM results.

A few significant design flaws were overlooked in the case of NETL's Youghiogheny River HEM survey. Data was acquired along two 68 km parallel flight lines that followed the meandering course of the river. It was not determined until the final processing steps that the data could not be effectively modeled using the currently available software. Profile Analyst was primarily designed to model data collected along straight lines in a rectangular survey array. Second, in an effort to minimize costs and optimize coverage, only 2 lines of data were collected, one of which was compromised by the conductive influence of power lines and railroad rails. Finally, data could not be collected over certain areas of interest because of Federal Aviation Regulations § 133.33 rules that prohibit rotorcraft external-load operations in proximity to populated areas.

The pilot selected to perform an HEM survey should be experienced in geophysical data acquisition and understand the importance of terrain conformity. This situation applies almost exclusively to rotorcraft and sling load operations such as the type used in the Fugro DIGHEM and RESOLVE surveys. Both types of instruments have the best overall signal response when carried at 30 m (AGL). Optimally, this height would be maintained throughout the survey. A detailed description of the effects of sensor altitude on sensitivity of HEM systems can be found at http://www.fugroairborne.com/Resources/tn/hem_a-d.shtml .

Departure from the optimum to about 60 m AGL can be tolerated by numerical compensation during post-processing of the data. However, the low-frequency data (400 and 1500 Hz) responses are most affected by excessive altitude. The ground response in the low-frequency data may fall off to the point that it is virtually indistinguishable from noise the when the instrument height increases much above 60 m. Typically, at the beginning of each flight line in a survey, the conductivity apparatus will be carried aloft to about 300 m (AGL) where zeroing and calibration are performed. It may also be necessary to repeat this calibration procedure at various intervals during the course of the survey. The data collected during the recalibration procedure are normally removed. Since the Youghiogheny River HEM survey consisted of 68 km flight lines, this procedure was carried out periodically during the survey. These erroneous data were not excised from the set and were likely incorporated into the CDIs.

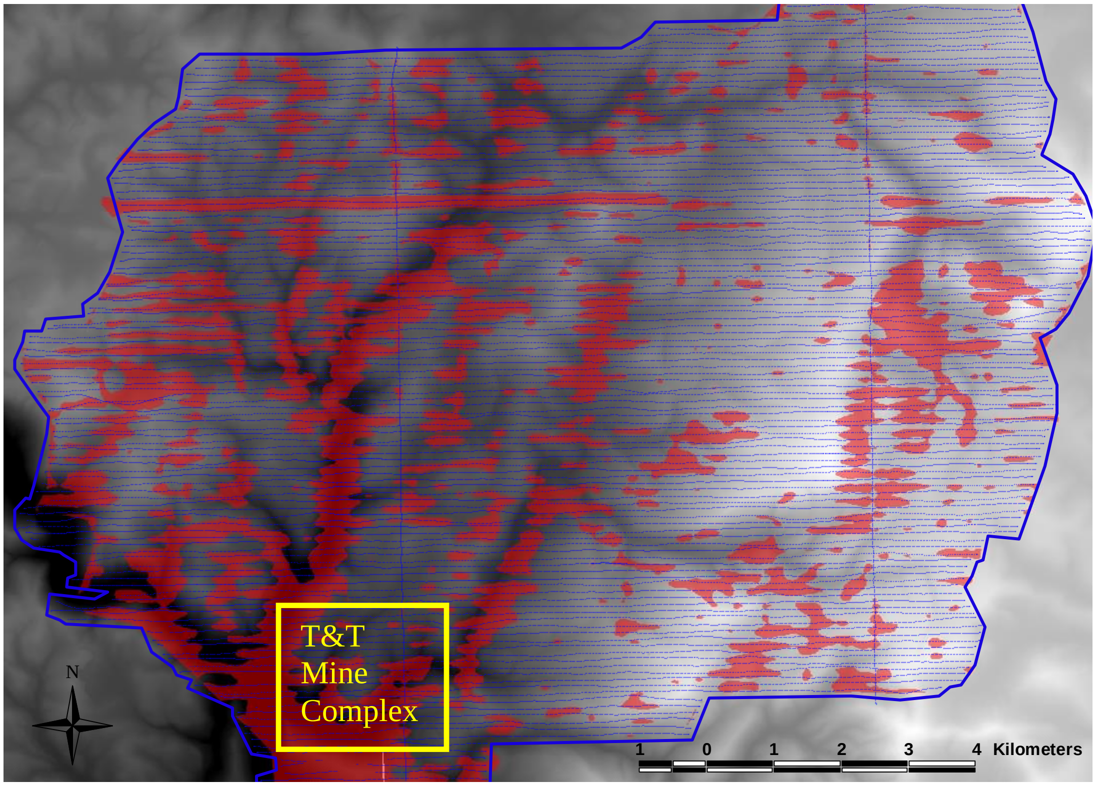

Fig. 11. Flight line map of the Muddy Roaring Creek HEM survey area in Preston County, West Virginia. Flight lines are depicted in blue. Segments along flight lines in red show areas where the sensor (bird) exceeded 60 m AGL. There is a strong correlation between terrain changes in the digital terrain model base map and departures from the proper sensor elevation. Note the location of the T&T Mine Complex.

NETL's Muddy and Roaring Creeks HEM survey demonstrates an extreme example of the terrain compliance issue. Instead of employing Fugro's regular helicopter pilot, a Department of Energy pilot and helicopter was reconfigured from the previous optical remote sensing mission to collect geophysical data. The areas surveyed were situated along ridges having vertical relief in excess of 1000 ft. over relatively short distances. Fig. 6 shows a flight line map detailing the data nodes where the bird altitude exceeded 60 m (twice the optimum height). In comparison, the FDEM survey conducted on the Lower Kettle Creek watershed in Clinton County, PA, (Fig. 7) showed excellent terrain compliance throughout. Less than 1% of the total survey area was affected despite the precipitous terrain. Through experience, the pilot who has engaged in sling load geophysical missions on a regular basis is better able to anticipate, and smoothly compensate for rising or falling terrain, affording better results. Data extracted from the Kettle Creek survey processed with fewer errors and provided generally satisfactory results.

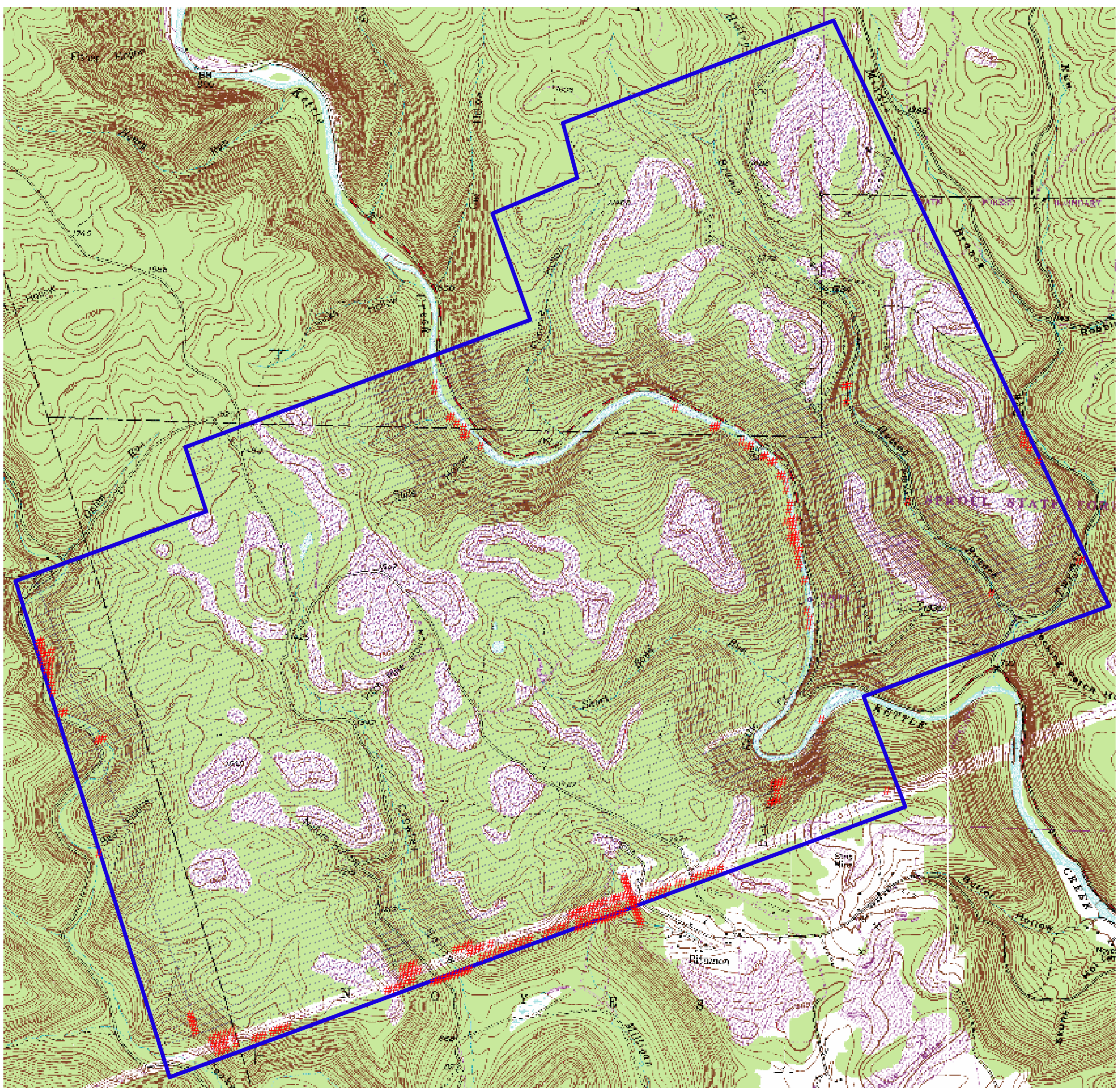

Fig. 12. The Kettle Creek FDEM survey area is outlined in blue. Segments along flight lines in red show areas where the sensor (bird) exceeded 60 m AGL.

Disclaimer

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