APPLICATIONS OF THE ELECTRICAL RESISTIVITY METHOD FOR DETECTION OF UNDERGROUND MINE WORKINGS

by
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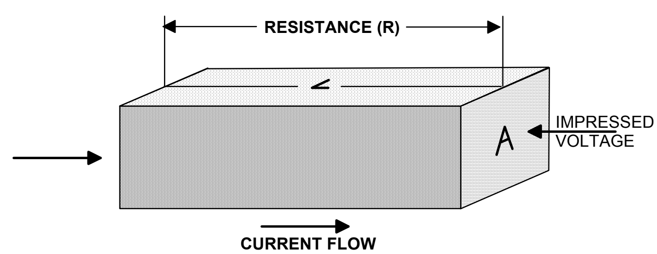
Introduction

The need to understand the location of abandoned workings has recently been highlighted by the failure of the Martin County Coal Corporation tailings impoundment near Inez, Kentucky on October 11, 2000 and the July 24, 2002 Quecreek Mine inundation that trapped nine miners for 77 hours in Somerset County, Pennsylvania. On a more routine basis, subsidence from abandoned mines represents a significant public cost in many states. Just in Pennsylvania, the State has invested over $100 million to address mine subsidence problems and estimates that 200,000 acres of high priority subsidence prone land still remain to be stabilized.

Abandoned mines are often difficult to locate. Detailed mine maps may be unreliable or missing. Conventional exploration (drilling) can easily miss targets as small as a mine entry. Nevertheless, geophysical methods are seldom employed to help map abandoned mines, possibly because geophysics surveys are perceived to be too expensive or will not help to solve the problem at hand. In actuality, there are situations where a geophysical survey can be expected to be effective and other times when the results may be more problematic. This paper reviews both the theoretical and practical aspects of electrical resistivity methods to define abandoned mine workings with the intent of defining conditions where the technique can be expected to produce useful results and the limitations of electrical measurements.

DC Electrical Surveys



Sketch of parameters to define resistivity

The purpose of a DC electrical survey is to determine the subsurface resistivity distribution of the ground, which can then be related to physical conditions of interest such as lithology, porosity, the degree of water saturation, and the presence or absence of voids in the rock. The basic parameter of a DC electrical measurement is resistivity. Resistivity is not to be confused with resistance. Resistance (R), measured in ohms, is the result of an electrical measurement, where according to Ohm's Law:

$$V = I/R \text{ or } R = V/I$$

where V = voltage in volts and I = current in amps.

Resistivity of a material is a fundamental physical property related to the ability of a material to conduct electricity. If R is the resistance of a block of conductive material having length L and cross-sectional area A (see sketch), then resistivity is given as:

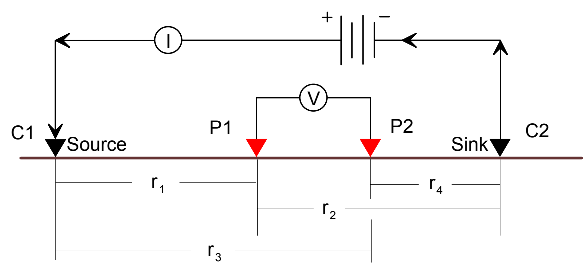
$$\rho = RA/L$$

Resistivity measurements of the ground are normally made by injecting current through two current electrodes and measuring the resulting voltage difference at two potential electrodes. From the current (I) and voltage (V) values, an apparent resistivity (ρ_a) value is calculated.

$$\rho_a = kV/I$$

where k is the geometric factor which depends on the arrangement of the four electrodes.

The "k" value can be calculated for any four-electrode configuration. The "k" value can be calculated for any four-electrode configuration according to the generic formula:

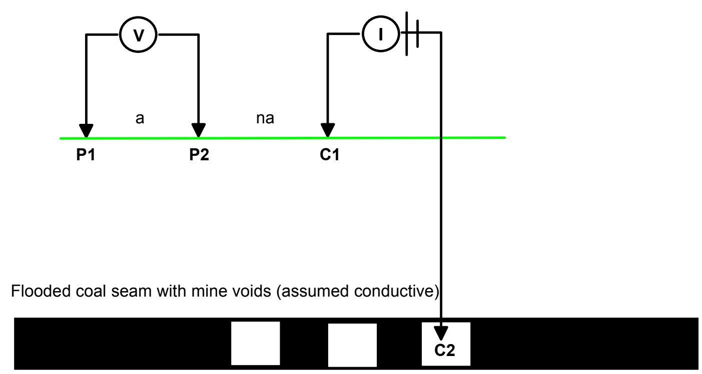


Geometry of generic four-electrode configuration

$$k = 2\pi\,[1/(1/r_1 - 1/r_2 - 1/r_3 + 1/r_4)]$$

where the subscripted "r" values are distances as defined in the adjacent sketch.

Two electrode configurations are most commonly for the mapping of coal mines, the dipole – dipole or the pole - dipole configuration. With the dipole-dipole configuration, two electrodes are separated by a constant spacing called the "a" spacing and are used to inject current into the ground. Two additional electrodes also separated by the "a" spacing are moved along the survey line at distances from the current electrodes that are multiples of the "a" spacing. The pole – dipole configuration is similar, except that one of the current electrodes is sufficiently far from the other three such that it can be considered to be at an "infinite" distance from the other three. In most cases the pole – dipole has proven to be preferable to the dipole – dipole configuration because the depth of penetration is relatively greater for the same "a" spacing and the "noise" level is reduced. Field experimentation has demonstrated that the signal to noise ratio can be further improved with an unconventional pole - dipole configuration where the remote electrode is embedded within the coal mine of interest, should a borehole of opportunity be available.



Setup for unconventional pole-dipole survey

The measured values of apparent resistivity need to be converted to true resistivity for actual conditions in the ground to be interpreted. This is a complex process that restricted the application of DC electrical surveys until the development of software capable of being run on a PC. The conversion of apparent resistivity as a function of electrode spacing to true resistivity as a function of depth can be conducted for 2D profiles with the RES2DINV program published by Loke (2000), who also developed the RES3DINV program for processing 3D blocks of electrical measurements. Another factor that has rejuvenated the application of the DC resistivity technique has been the commercialization of multi-electrode systems. Multi-electrode equipment has greatly improved the efficiency of data acquisition, as measurements can now be made automatically.

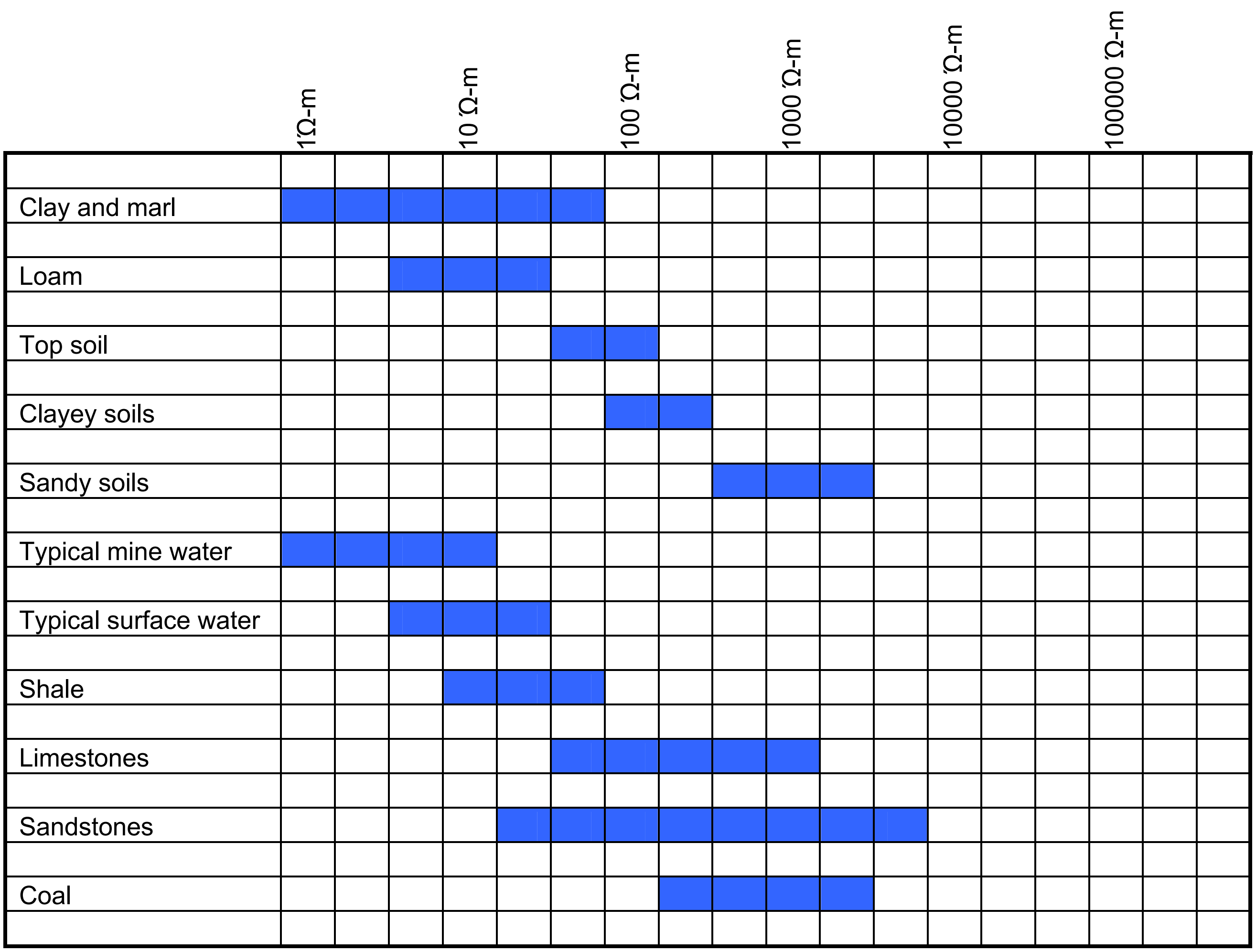
Modeling Coal Mine Workings

The starting point of any geophysical investigation must be basic physics. Geophysics will be effective only if a target of interest has a physical contrast with the surrounding ground. Coal itself usually has a high resistivity compared to other sedimentary rock types. This property has formed the basis for detecting coal from borehole logs and DC resistivity surveying was used as a tool for exploring for coal as early as 1934 (Ewing et al., 1936). The detection of voids depends on whether or not the void has a physical contrast with the surrounding rock. If the void is dry, the void will be difficult to detect with electrical measurements. Air does not transmit an electrical current, but unless the coal is of an unusually low resistivity, it will be difficult to distinguish high-resistivity coal from a void. Fortunately, coal mines are rarely dry and it is not necessary for the mine to contain much water for the mine openings to be detectable.

Mine water with conductivity in the range of typical surface water could be about 500 μS/cm, which corresponds to a resistivity of 20 ohm-meters. If the mine water is more acidic, the conductivity could approach 5,000 μS/cm, which corresponds to a resistivity of 2 ohm-meters. In either case, the contrast between a flooded or even a partially flooded mine compared to a typical coal resistivity of 500 to 1,500 ohm-meters will approach two orders of magnitude.

Forward modeling of coal workings offers the possibility of determining the resistivity measurements that would theoretically be made in the field with different electrode configurations. The means to effectively conduct forward modeling is also a relatively recent innovation. The RES2DMOD program developed by Loke (2002) offers the possibility of calculating theoretical electrical measurements for different subsurface conditions that can then be used as input to the RES2DINV program based on either finite element or finite difference modeling. The results depict what electrical cross sections should look like for different subsurface conditions. These theoretical electrical profiles can then be compared to real-world profiles and facilitate the interpretation of real subsurface conditions. Figure 1 depicts the process of calculating an electrical profile from a theoretical model.

The example depicted in Figure 1 illustrates a model corresponding to a 2-meter (6.6-foot) thick coal seam whose base is at a depth of 10 meters (33 feet). The mine is assumed to be flooded with water of a resistivity of 20 ohm-meters and the coal is assumed to have a resistivity of 1,000 ohm-meters. Surrounding rock is assumed to have resistivity values between 500 and 800 ohm-meters. The mine openings and the pillars separating them are assumed to be 10 meters (33 feet) in width. The resistivity measurements are defined for the pole-dipole configuration with an electrode separation of 5 meters (16 feet). With this typical model, the RES2DMOD program calculates theoretical readings, which in turn forms the basis for the calculation of a theoretical cross section with the RES2DINV program, as depicted on Figure 1.



Typical resistivity range of earth materials in ohm-meters

In the example shown on Figure 1, the mine voids are easy to recognize, as are the pillars separating them. It should be noted that the resistivity profile is not like the model in that the separate layers are represented as transitional changes from one resistivity to another and are not abrupt changes. The coal itself does not stand out as a separate layer, but is in the zone where there is a change in resistivity from the 500 ohm-meter rocks above the coal to the 800 ohm-meter rocks below the coal. If the actual depth of the coal were not known in advance, it would be difficult to precisely define the position of the coal.

In contrast to the coal, the modeling strongly defines the water-flooded mine openings. A problem with the interpretation of the voids is that it is difficult to determine the thickness of the void as the zone of low resistivity appears to extend both above and below its actual position. If the mine is only partially flooded (Figure 2), the results still appear similar to Figure 1, except that the vertical uncertainty in the position of the void increases. Again, a correct interpretation of the model requires that the position of the coal be defined in advance. Fortunately, the question to be resolved is not the exact elevation of the coal, which is normally known in advance, but whether or not the coal contains mine openings, which are obvious from this example.

If the coal is modeled at a deeper depth, resolution quickly decreases, primarily because of the need to increase the electrode spacing to achieve the depth of interest. Figure 3 depicts the variation of theoretical response of the same model shown on Figure 1, but placing the coal seam and voids at increasing depths. With the initial depth of 10 meters (33 feet), the rooms and pillars are easy to resolve, but the deeper models depict only a single anomaly for the mined-out area and it is not practical to distinguish individual rooms and pillars. The anomaly associated with the mine workings at a depth of 18 meters (60 feet) is readily discernable, although it is necessary to know the position of the coal as the resistivity low associated with the mine workings extends many meters above and below the actual voids. The shape of the anomaly for the workings at 28 meters (92 feet) appears similar to the form from 18 meters, but the intensity of the anomaly is significantly less and is only a factor of about three less than that of the background rock. This contrast could be difficult to measure under field conditions if the data are noisy or there are other factors such as variable topography to interfere with the data acquisition. The resistivity contrast associated with mine workings at a depth of 50 meters (164 feet) is less than a factor of two below that of the background rocks. Although theoretically detectable, field conditions would make the detection difficult. The model from a depth of 100 meters (328 feet) is effectively undetectable, even from the theoretical model.

An important practical difficulty defined by the models is the length of the profile necessary to image to different depths. The length of a pole-dipole profile necessary to image a 70-meter wide target at a depth of 10 meters is about 130 meters (425 feet). The length of the line necessary to image to 50 meters would be about 400 meters (1,300 feet), which could be impractical at many locations.

One of the difficulties in detecting deeper mine workings from the theoretical model is that ratio of the depth of the target to the total width of the target (70 meters in the model) increases with increasing depth. The model indicates that reliable results are obtained when the depth/target width ratio is greater than 2. Figure 4 depicts a comparison of the ability to detect two targets at a depth of 50 meters (164 feet), one that is 70 meters (230 feet) wide and another that is 160 meters (525 feet) wide. When the mine workings are 160 meters wide, they are much more easily detectable, although it still necessary to have equipment that will be able to put enough current into the ground such that the workings can be imaged.

Measurements from Actual Coal Mine Workings

Several case histories can be used to compare the theoretical models with actual abandoned mine workings. The details of some of these case histories have been previously presented and are not repeated here (Johnson, 2003; Johnson and Snow, 2002 and Johnson, Snow and Clark, 2002).

Base of Coal at Approximately 10 Meters (33 feet)

A case history depicting conditions where the base of the coal mine workings is at a depth of approximately 10 meters is at the Regency Park Subdivision, Plum Borough, Pennsylvania. The Regency Park subdivision is located over shallow mine workings associated with the Plum Creek Mine operated in the late 19th and early 20th century. The subdivision has been the location of numerous foundation failures over the past several decades since the homes were constructed. The results shown on Figure 5 define a series of resistivity lows that bottom out near the bottom of the Pittsburgh Coal seam at a depth of about 30 feet as known from available mine maps and the results of borings drilled along the profile. Where borings were drilled within 5 feet of the profile, the resistivity lows were found to correspond to mine voids (partially collapsed) and the zones of relatively high resistivity between the lows was found to contain coal. The mine is not completely flooded. Typically, there is no more than about two feet of water in the mine.

Figure 5 compares the actual Regency Park profile with a predictive model of a partially flooded mine. Model constraints indicate that the mine water must be fairly acidic, as a 2,500 µS/cm conductivity, which corresponds to a resistivity of 4 ohm-meters, best fits with a model that is close to the actual results. In both the actual and theoretical models, the electrical measurements exaggerate the thickness of the flooded portion of the mine.

Base of Coal at Approximately 20 meters (66 feet)

A case history that depicts conditions where the base of the coal mine workings is at a depth of approximately 20 meters is from a survey conducted next to a mine tailings impoundment in Jefferson County, Pennsylvania. A single profile was conducted with the pole-dipole technique with a 20-meter electrode spacing over known mine workings at a depth of approximately 20 meters (64 feet). In this case the mine was also known to be fully flooded. The results shown on Figure 6 indicate the presence of a pronounced resistivity low in the area of the known mine entries. The results do not distinguish separate rooms and pillars, as predicted from the theoretical modeling, but the extent of the known mine openings is clear. The results also indicate the probable presence of unknown workings.

Figure 6 compares the actual Jefferson County profile with a predictive model of a completely flooded mine consistent with the known mine workings at this location. Model constraints indicate that the mine water should be close to 1,200 µS/cm conductivity (8 ohm-meters), as this value best fits with a model that is close to the actual results. In both the actual and theoretical models, the electrical measurements exaggerate the thickness of the flooded portion of the mine. The probable unknown mine workings were not modeled.

Base of Coal at Approximately 30 meters (98 feet)

An example from SW Indiana offers the possibility of comparing theoretical versus actual data from a mine near a depth near 30 meters in a complex setting. The property is underlain by two coal seams, the No. 7 seam at an approximate depth of 9 meters (30 feet) and the No. 6 seam at about 27 meters (90 feet). The shallower of the two seams was partially surface mined and the available mine map indicates the presence of some auger workings extending from the former highwall. The deeper seam was mined underground.

In terms of a resistivity target, the deep mine workings represent a much more complicated target than the previous two case histories, considering both depth and the complex conditions above the seam, including strip mining and auger mining of a shallower seam. The survey was conducted with an “unconventional” pole-dipole configuration with an electrode spacing of 10 meters. The pole-dipole survey applied for this survey is considered “unconventional” because the “infinite” electrode was not placed in a remote position on the ground, but was located within the deep coal seam.

The results of the single test line provided two useful pieces of information. The results depict the presence of shallow augering of coal from the former strip mine highwall in an area where it was not known to exist. Also, the existing mine map appears to be a good representation of the deep mine workings. The survey results indicate the presence of a resistivity low across the area where deep workings were known to exist.

Figure 7 compares the actual SW Indiana profile with a predictive model of a fully flooded deep mine that also includes shallow auger workings and mine spoil. Model constraints indicate that the mine water must be very acidic, as a 5,000 μS/cm conductivity, which corresponds to a resistivity of 2 ohm-meters, best fits with a model that is close to the actual results. In both the actual and theoretical models, the electrical measurements do not resolve the vertical extent of the mine voids and the results are useful only in defining the lateral extent of the workings and it is necessary to know the depth of the coal. The mine spoil and the augering of the base of the strip mined seam are well defined.

Base of Coal at Approximately 50 meters (164 feet)

An attempt was made to image mine workings at a depth of 50 meters at a location in Harmar Township, PA over workings of the Harwick Mine in the Upper Freeport Coal. This mine was operated in the late 19^{th} and early 20^{th} century and the entire survey area was essentially mined out except for a 100 x 100 foot block of coal surrounding an old oil or gas well. The purpose of the survey was to determine if this block of coal was still remaining as part of a geotechnical study to evaluate subsurface stability.

The survey was conducted with a pole-pole configuration with a 20-meter electrode spacing, which is different than the previous examples. With the pole-pole configuration one current electrode and one voltage electrode are placed at an "infinite" distance from the survey profile. The other two electrodes are moved along the profile at multiples of the 20-meter spacing up to a factor of 8 (160-meter electrode separation). The pole-pole configuration was used to improve the signal to noise ratio and obtain the maximum depth of penetration, but the drawback to this technique is that resolution is lost. The results of this survey indicate that sufficient resolution was not obtained (Figure 8). The results do not appear to have any relationship to the coal seam, but it is noted that the highest resistivity values are immediately above the anticipated coal pillar. It is speculated that the survey is actually responding a less fractured rock above the unmined coal, which would be expected to have a relatively higher resistivity than the saturated fractured rock over the mined out portions of the Harwick Mine, assuming some mine subsidence has occurred. No attempt was made to model this field survey.

Conclusions

Efforts to delineate underground mine workings typically rely on available maps and confirmatory boreholes and the characterization of regions between boreholes is uncertain. Electrical resistivity measurements can be used to supplement the borehole data and reduce the uncertainty of the interpretation. Furthermore, electrical measurements can be used to optimize the number and locations of the boreholes.

Project experience with DC electrical measurements demonstrates that commercially available technology can be effective, especially for the rapid mapping mine workings at depths up to about 100 feet. For deeper workings, the method has the potential to be effective, but theoretical models and practical experience demonstrate that the target size/depth ratio needs to be favorable and the required length of the resistivity profile to acquire deep images is often limited by surface interference. The method is therefore usually most effective for mine subsidence applications, rather than in evaluating the proximity of relatively deep active mines to abandoned, flooded workings, but local conditions can allow for this technique to be effective for deeper targets.

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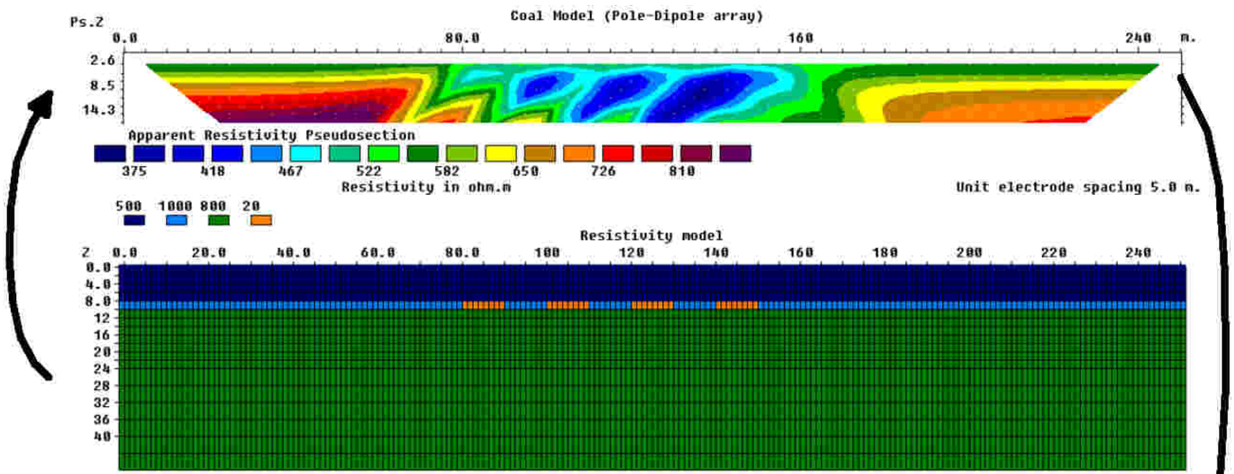
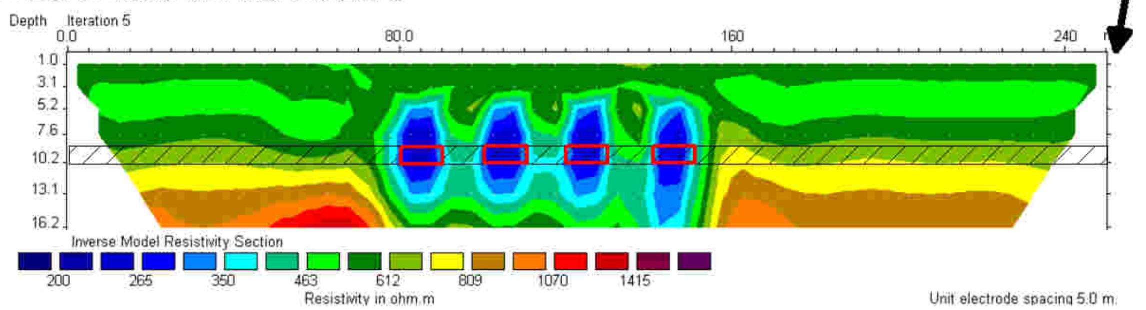


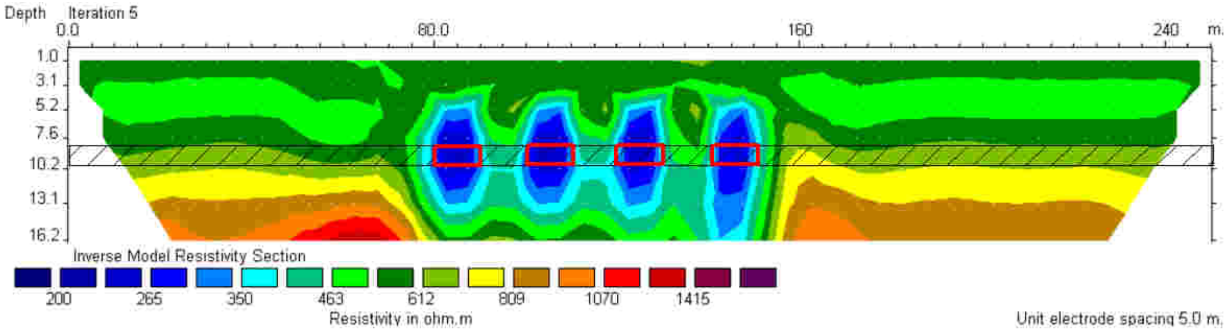
SUBSURFACE MODEL USED AS INPUT TO THE RES2DMOD PROGRAM WITH THE RESULTS DEPICTED AS A CROSS SECTION OF THEORETICAL MEASUREMENTS



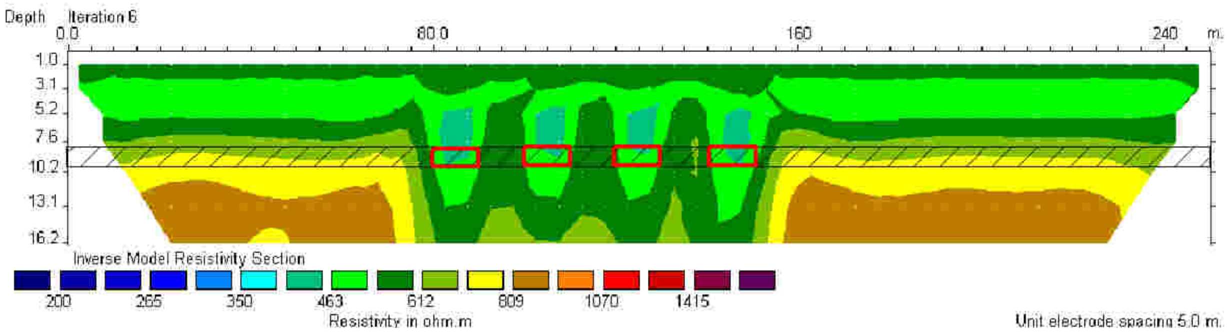
ELECTRICAL CROSS SECTION CALCULATED WITH THE RES2DINV PROGRAM FROM THE RESULTS OF THE RES2DMOD PROGRAM WITH MODEL SUPERIMPOSED ON THE RESULTS

NOTE: The coal is modeled with a resistivity of 1000 ohm-meters, while the mine void is considered flooded with mine water of a resistivity of 20 ohm-meters.

FIGURE 1 - DEPICTION OF MODELING PROCESS FOR THEORETICAL MINE WORKINGS IN A COAL SEAM 2M THICK WITH THE BASE OF COAL AT A DEPTH OF 10M



ELECTRICAL CROSS SECTION CALCULATED FROM THE SAME MODEL AS FIGURE 1 WITH A FULLY FLOODED MINE



ELECTRICAL CROSS SECTION CALCULATED FROM THE SAME MODEL AS FIGURE 1 WITH A PARTIALLY FLOODED MINE

NOTE: The coal is modeled with a resistivity of 1000 ohm-meters, while the mine void is considered flooded with mine water of a resistivity of 20 ohm-meters.

FIGURE 2 - DEPICTION OF RESULTS OF MODELING THEORETICAL FLOODED AND UNFLOODED MINE WORKINGS IN A COAL SEAM 2M THICK WITH THE BASE OF COAL AT A DEPTH OF 10M

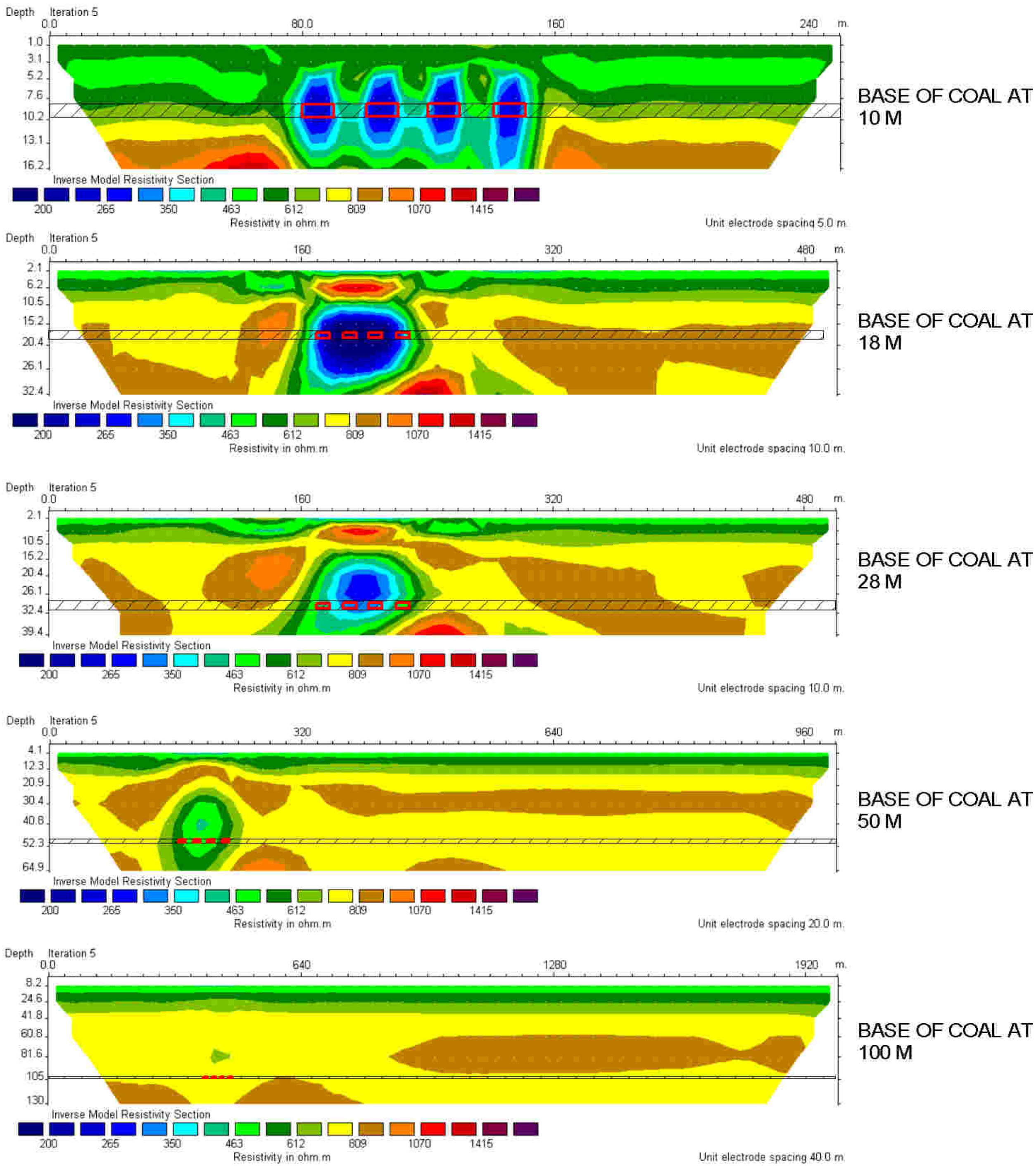
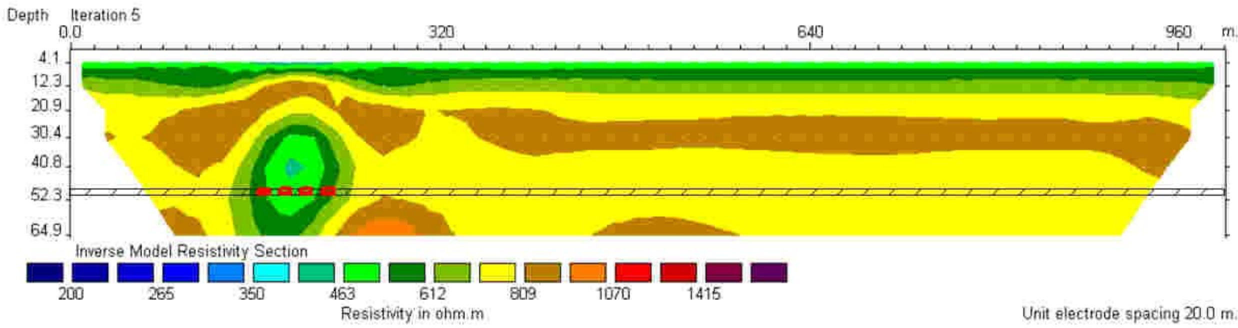
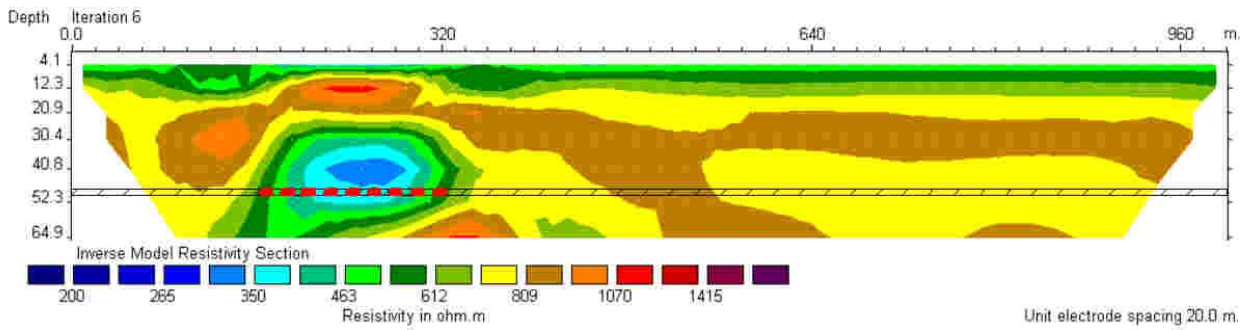


FIGURE 3 - MODEL RESULTS FOR FLOODED COAL WORKINGS AT DIFFERENT DEPTHS (COAL SEAM 2M THICK)



COAL MINE WORKINGS 70 M (230 FT) ACROSS



COAL MINE WORKINGS 160 M (525 FT) ACROSS

FIGURE 4 - MODEL RESULTS FOR FLOODED COAL WORKINGS OF DIFFERENT LATERAL EXTENTS, BOTH AT A DEPTH OF 50 M (COAL SEAM 2MTHICK)

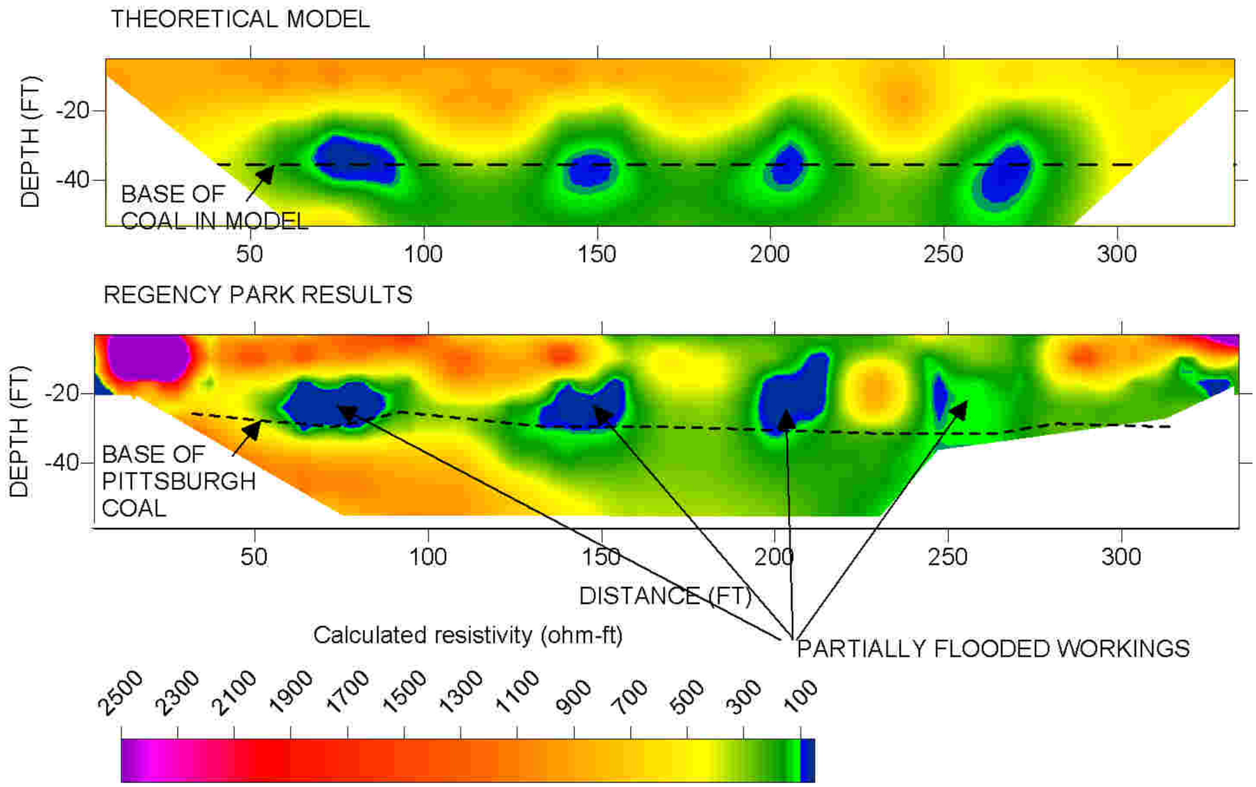


FIGURE 5 - PREDICTED AND ACTUAL RESULTS OF POLE-DIPOLE SURVEY OVER PITTSBURGH COAL SEAM AT REGENCY PARK, PA

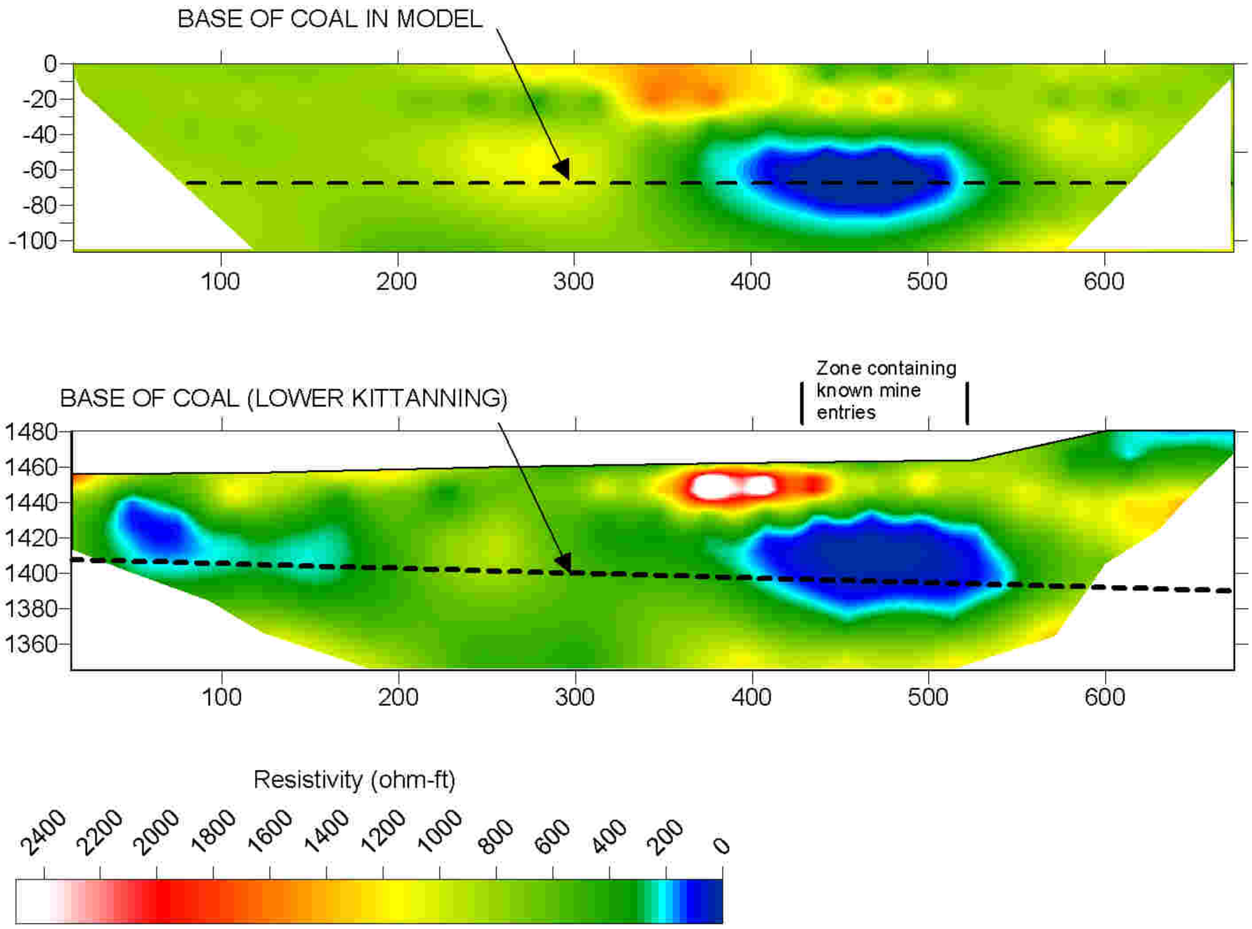


FIGURE 6 - PREDICTED AND ACTUAL RESULTS OF POLE-DIPOLE SURVEY OVER KITTANNING COAL SEAM IN JEFFERSON COUNTY, PA

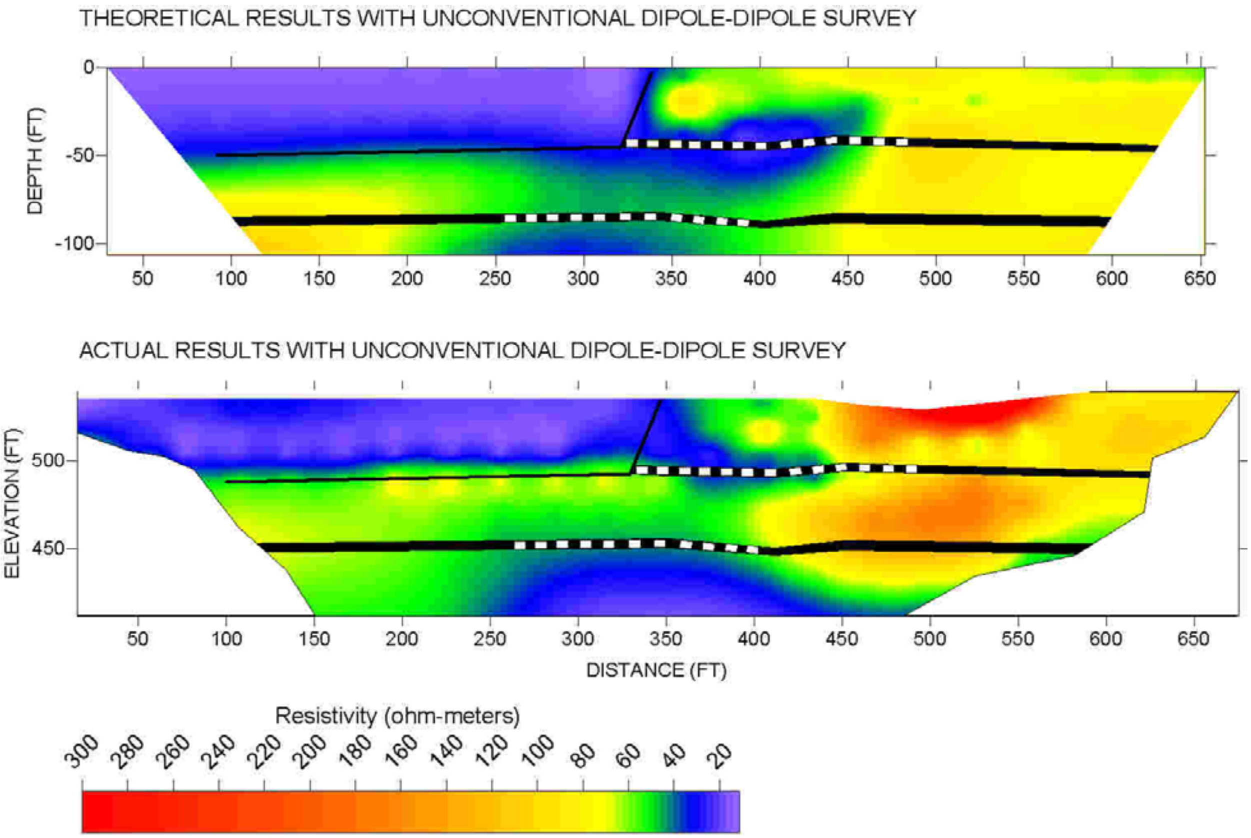


FIGURE 7 - PREDICTED AND ACTUAL RESULTS OF POLE-DIPOLE SURVEY OVER COAL SEAMS IN SW INDIANA

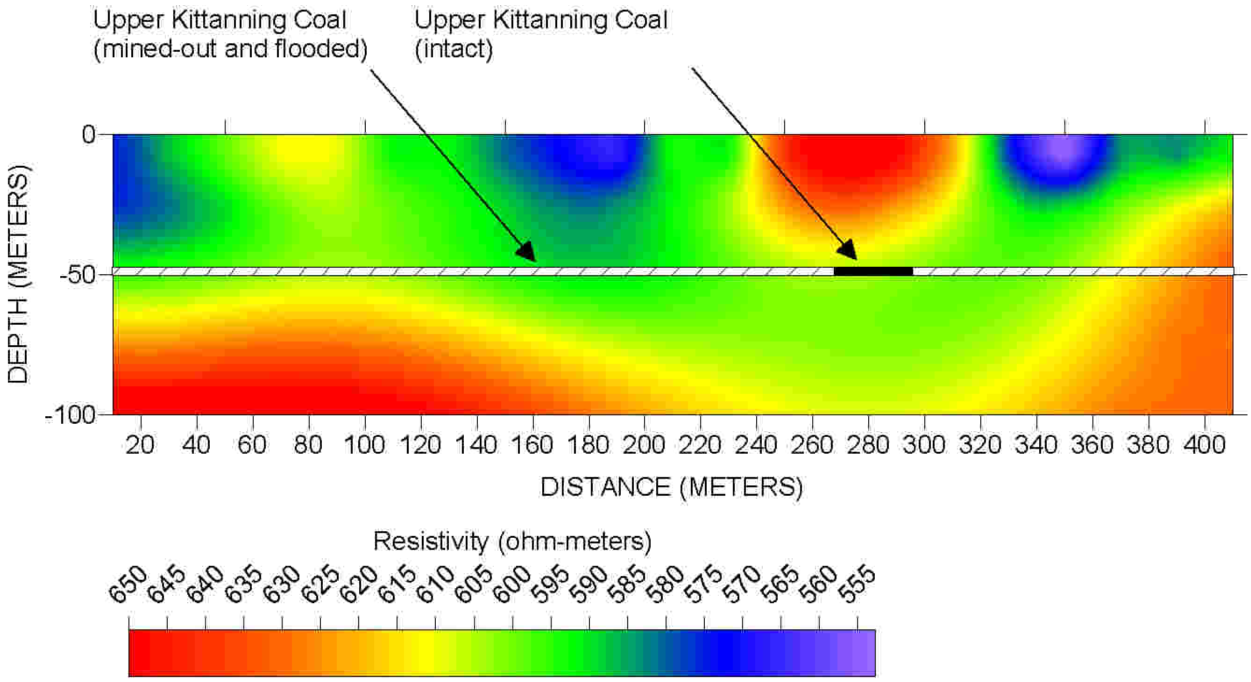


FIGURE 8 - ACTUAL RESULTS OF POLE-POLE SURVEY OVER HARWICK MINE IN HARMAR TOWNSHIP, PA