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Research Paper

Surface Wave andElectromagnetic Investigation of Abandoned Mine Tunnels

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ABSTRACT: *Abandoned mine tunnels are a concern because over time collapse of the tunnels may lead to surface subsidence. To locate abandoned mine tunnels and help prevent or remediate surface impact it is important to develop non-intrusive methods that can assist in identifying the location of these subsurface voids.*
An integrated geophysical investigation utilizing the multichannel analysis of surface waves (MASW)and electromagnetic methods (EM) was undertaken in an attempt to locate abandoned mine tunnels. To help aid in data acquisition for the surface wave survey a seismic streamer was developed. The seismic streamer has the advantageof increasing the speed at which seismic data may be acquired. Analysis of the seismic data reveals geophysical anomalies that are in agreement with the expected depths and location of the mine tunnels.
An EM survey was also conducted using a multiple coil electromagnetic conductivity meter. The results of the EM survey were compared to the seismic results in an attempt to correlate the existence of the tunnels. While a direct correlation is difficult the results of the EM survey indicate higher conductivity anomalies at the expected depth and location of the tunnels when compared to data acquired over undisturbed land.

Keywords:*abandoned mines, electromagnetic, seismic, subsurface voids, surface waves*

I. INTRODUCTION

Abandoned mine tunnels exist within western Pennsylvania and throughout Appalachia as a result of coal mining operations that have since ceased operation.Underground coal has been mined in Pennsylvania for more than 200 years and mining operations extend throughout 43 of the 67 counties of Pennsylvania [1]. These abandoned tunnels are a concern because they may collapse over time as the ground surface readjusts to the overburden due to failure of underground mine workings. This may give rise to surface subsidence that may have a possible impact on surface structures. Complicating the situation is that many of the historical documents in regards to the location of mine tunnels have been lost, are incomplete or inaccurate, or not documented. Of the 1 million homes in Pennsylvania that sit above underground mines, one in 2,000 insured buildings are damaged by mine subsidence, costing an average of $50,000 per structure [1]. As an example of abandoned mine impact, 10 homes in the Mt. Oliver Borough of Pittsburgh sustained damage from mine subsidence. Also, in Hyde Park, PA the state Department of Environmental Protection implemented a project, at the cost of more than one million dollars,to remediate underground mine voids beneath more than 60 homes. To help prevent or remediate the impact of mine subsidence it is important to develop non-intrusive methods to identify the location of these subsurface voids. Under certain conditions geophysical methods may provide a way to detect these voids andare advantageous because they are non-invasive and can be deployed on the surface of the ground.

Detection of underground voids using surface geophysical methods has a long history and a mixed level of success. Gravity methods have been used with success [2]however the small station intervals required make micro-gravity surveys for void detection a slow task. Ground penetrating radar (GPR) methods [3] have also been used however there is a limitation of depth of penetration because of the high-frequency wavelengths used with GPR. Additionally GPR signal attenuates quickly within clay-rich environments. Electrical methods have also been used within the investigation of subsurface voids [4][5] and have met with some success. Several surface seismic methods have also been employed in an attempt to detect subsurface voids. Seismic reflection

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common mid-point surveying [6] has been used in addition to seismic refraction [7]. Surface wave methods [8] and seismic wave diffraction events [9] have also been used with varying levels of success.

A non-invasive, surface deployed method to detect undisclosed, abandoned near-surface mines would be beneficial as a first step to remediation. For this research the MASW method is used to investigate the shear-wave velocity (Vs) structure of the near-surface to identify shear wave velocity anomalies that may be associated with subsurface voids. EM methods were also used to investigate the electrical properties of the subsurface in an attempt to also identify the location of abandoned tunnels.

Both the MASW and EM surveys took place at Wally Rose field located on the campus of Slippery Rock University in western Pennsylvania (Fig. 1). Wally Rose field is a flat, grassy location that is occasionally used for sporting activities. The site location is ideal in that it has negligible elevation change, is free of cultural noise and allows for an unobstructed area to conduct geophysical surveys (Fig. 2A). The Wally Rose field location is also unique in that there are documented abandoned coal mines beneath the property. Coal from this location was at one time mined to use within the heating plant at Slippery Rock University. Based upon the historical map of the abandoned mines beneath Wally Rose field (Fig. 2B) the mines extend beyond the area that was surveyed for this research (Fig. 2C).

2. Surface Waveand EM Methods

2.1 Surface waves

During a seismic survey several wave modes are created by the source and subsequently recorded as part of the seismic record. Among these various wave forms are direct waves, refracted waves and surface waves. While each seismic wave provides different information about the subsurface each can be used for near-surface investigations. Surface waves, or ground roll, make up as much as two-thirds of a seismic field record [10] and utilizing the record dominating surface waves for analysis provides a method to investigate the subsurface.In general, there are two types of surface waves most widely observed in seismic investigations and earthquake seismology; Rayleigh and Love waves [11]. If a vertical seismic source, such as employed in this survey, is used the type of resulting surface waves are Rayleigh waves.

In a layered medium in which seismic velocity changes surface waves have a dispersive property that is indicative of elastic moduli of near-surface earth materials. Short wavelengths penetrate shallower depths and longer wavelengths deeper depths. The propagation velocity for each wavelength, called phase velocity [12], depends primarily on the shear wave velocity of the medium over the penetration depth and is influenced only slightly by the primary wave velocity, density and Poisson's ratio. Therefore surface wave velocity is a good indicator of Vs. Therefore, by analyzing the dispersion feature of ground roll represented in seismic data, near-surface Vs profiles can be constructed and the corresponding shear moduli calculated.

Surface waves have long been used to study the subsurface and development of surface wave methods date back to the 1950s when the steady state method was first used [13][14]. Spectral Analysis of Surface Waves (SASW), introduced by Nazarian and Stokoe [15] was an advancement of previous methods. The SASW method makes use of the Rayleigh wave dispersion property for the purpose of creating a near-surface Vs profile.

A progression in surface wave methods was the development of the multi-channel analysis of surface waves [16][17][18][19]. One of the main benefits of MASW is that it uses multi-channel acquisition. The focus of surface wave analysis has been the creation of a shear wave velocity profile. That same concept continues through the analysis of surface waves using the MASW method. Surface waves are unique in that they are dispersive. The dispersive nature of surface waves, which body waves lack, allow different wavelengths to penetrate different depths and propagate with different velocities. The corresponding phase velocities then represent the elastic properties within the penetrating depths.

Performing an MASW investigation usually consists of four steps: 1) acquiring surface waves on multi-channel seismic records, 2) generation of a dispersion curve, which is a plot of frequency versus phase velocity, 3) picking the fundamental-mode from each dispersion curve record and 4) inverting the dispersion curves to obtain 1-D Vs profiles. Spatial interpolation is used between subsequent 1-D Vs profiles and each 1-D Vs profile, located in the middle of the receiver spread, is used to create the final 2-D Vs subsurfacecross-section[20].

MASW is an attractive geophysical method because of its efficiency of investigating elastic properties of near-surface materials. In addition, it provides a way of getting subsurface information that may not be available from other methods. In regards to surface waves, the inclusion of waves considered as noise, such as body waves, refracted waves, air waves and higher-modes[21][22][23] ground roll can be identified by its different coherency in arrival times on a multi-channel record.

2.2 Electromagnetic

There are a wide range of EMmethods that have been developed to measure the electrical resistivity of the subsurface [24][25] andEM methods are one of the first geophysical exploration techniques to become widely used [26]. Historically EM methods originated within exploration for hydrocarbons and minerals. Today EM methods are also applied to groundwater and environmental research. EMmethods make use of a time-varying, primary magnetic field generated by a transmitter through which a current is passed to induce electrical currents in the Earth[27]. Frequency domain electromagnetics, commonly referred to as ground conductivity, measures the electrical conductivity of soil and rock by measuring the magnitude and phase of an induced electromagnetic current [28].The electrical conductivity of earth materials can be measured at one or more frequencies to map lateral conductivity variations along a single profile or a grid of profiles.A main benefit of near-surface investigation using frequency-domain electromagnetic instrumentationis that the equipment is portableand easy to operate.

The magnitude of the induced currents depends upon the ability of the subsurface to conduct electricity. The time-varying induced currents of the EM instrumentation interact with subsurface material producing a secondary magnetic field that is recorded with a receiver. EM methods can be divided into several classes and the frequencydomain measurement type makes use of a sinusoidally varying current. Thedata can be analyzed based upon a phase shift between the primary and secondary fields [27]. There are many types of EM systems, some having a single transmitter and receiver separated by a fixed distance while others operate using a multi-coil system which contains several transmitter and receiver pairs separated by fixed distances. By increasing the distance between the transmitter and receiver, and varying the frequency of the transmitter the depth of investigation can be changed. Higher frequencies have less depth of penetration while lower frequencies provide greater depth of penetration.

EM instruments are active instruments that induce an EM field into the ground and measure a response that is attenuated by the underlying soils[29]. Because the electrical resistivity of a rock is closely related to its water content [26]EM methods have been extensively used for near-surface investigations, details of which can be found in a number of publications[30][31][32][33][34][35][36][37][38][26].

II. METHOD

3.1 MASW data acquisition

To aid in acquisition during the MASW survey a seismic streamer was developed. Land streamers are used within surface seismic surveys to increase the speed, ease and efficiency required to perform a survey. Land streamers have gained an increase in use for shallow seismic applications and many researchers have documented the benefits of using a seismic streamer[39][40][41][42][43][44].

The streamer design (Fig. 3A) used for this survey consists of geophones mounted to steel plates which are in turn mounted to a length of fire hose. With the land streamer all of the seismic receivers are moved simultaneously, while maintaining a common separation of 1.0 meters. To advance the streamer during acquisition it is attached to the back of a truck (Fig. 3B). Additionally all of the necessary recording equipment rests on the tailgate of the truck throughout the survey allowing an operator to easily monitor and oversee the operation (Fig.3C). For the survey a 24-channel Geometrics Geode seismograph with 24-bit A/D conversionand 28 Hz vertical component geophones were used. Recording time was 0.5 second with a sampling interval of 0.125 ms.A small sledge hammer struck against a metal striking plate was used to generate the source signal.

During surveying the receiver line was moved at 1.0 meter intervals with a common source-receiver offset of 6.0 meters maintained. A total of 57 source positions were occupied over the course of approximately six hours for a total survey length of 57.0 meters.Processing consisted ofgeneration and picking of dispersion curves for each shot record, inversion of each dispersion curve to obtain 1-D Vs profiles and creation of a 2-D Vs subsurface profile.

3.2 Masw Data Analysis

High velocity geophysical anomalies are interpreted to correspond with subsurface voids. Eleven anomalies are evident across the span of the survey at approximately 7-9 meters depth. Figure 4 shows an example shot record that was acquired during the survey.Each shot record contains several seismic wave modes such as the direct, refracted and surface waves. The dispersive surface waves, as shown by their high amplitude, low frequency characteristics, are the waves of interest when performing an MASW survey.

A dispersion curve (Fig. 5A) and 1-D shear wave velocity profile (Fig. 5B) areshown as example records. As can be seen on the dispersion curves, phase velocities range between ~250-525 m/sec with a frequency range of approximately 12-45 Hz. The 1-D shear wave velocity profile shows that shear wave velocity is not constant with depth and that there is an overall increase in velocity with depth, with velocities in the upper portion of the record at ~275 m/sec and velocities at the bottom of the profile of ~ 500 m/sec. The velocity increase from ~7-9 meters is interpreted to correspond with the expected depth of the tunnels which have been determined to be at a depth of approximately 6.5 meters.

Figure 6 shows the 2-D Vs profile of the subsurface along the survey line. It can be seen that the shear wave velocities range approximately between 200-600 m/sec. The high velocitygeophysical anomalies at approximately 7-9 meters depth are interpreted to correspond with subsurface voids attributed to abandoned mine tunnels. The depth of the anomalies are in agreement with the expected depth of approximately 6.5 meter depth of the mines based upon historical documents. Inspections of the anomalies show that the heights of the tunnels are approximately 2.0 meters tall.

3.3 Electromagnetic data acquisition

Surveying was conducted using a multiple coil electromagnetic conductivity meter (Fig. 7). The device allows for real-time, multi-depth acquisition witheffective depths of 2.2, 4.2 and 6.7 meters. In total, forty-five lines were traversed with 1.0 meter intervals covering the entirety of Wally Rose field. Because the device acquires data in real-time, acquisition is quick and efficient with the total survey only taking several hours to complete.

Processing consisted of organizing the data from the instrument into a format that could be imported into software to thendisplay the data. Because the EM instrument acquires simultaneous data at three effective depths organizing the data into a format that can be used within the display software included creating three data tables, one for each depth, and then adding traverse coordinates to each for both the north-south and east-west directions throughout the surveyed area. The data were then plotted individually to show apparent conductivity for each depth.

3.4 Electromagnetic data analysis

The apparent conductivity plots (Fig. 8) indicate that as the effectivedepth increases potential evidence of subsurface voids also increases. This can be expected as the depths of the tunnels are located at an approximate depth of 6.5 meters.The data shown for all three depths cover the entirety of Wally Rose field and the tunnels are located throughout the left hand area of the data plots. It should be noted that the high anomaly along the right edge of the data plots is the result of a fence. Inspection of the effective depth of 2.2 meters (Fig. 8A)shows that there is little to noevidence of any electrical variation within the subsurface and that apparent conductivity is around 2.0mS/m.At an effective depth of 4.2 meters (Fig. 8B) anomalies start to become evident.Apparent conductivity values range around 5.0 mS/m within the area of expected tunnels and are higher when compared to the data plot from 2.2 meters from the same area. The internal area of the field which, according to historical maps, does not have tunnels underlying, has lower apparent resistivity values of 2.0 mS/m. Inspection of the third data plot (Fig. 8C) shows higher apparent resistivity anomalies at an effective depth of 6.7at the depth tunnels are expected to exist. This depth is just at the limit of the instrument but it does provide evidence that the electrical properties of the subsurface within this area of Wally Rose field differs from that of where tunnels do not exist.While it is difficult to associate the direction of any tunnels with the anomalies they do provide evidence of the general area wherein subsurface voids exist.

III. DISCUSSION

Abandoned mine tunnels are a concern throughout western Pennsylvania and Appalachia. The application of non-intrusive, surface deployed geophysical methods may provide important tools to help aid in the location of abandoned mine tunnels and remediation efforts. Through this research it has been shown that in the appropriate environment, investigation of the subsurface using MASW methods may provide one such method. Using MASW methods we are able to shown that the position, depth and height of subsurface tunnels can be identified. High velocity shear wave anomalies are interpreted to be the result of abandoned mine tunnels at an approximate depth of 6.5 meters. Additionally the heights of the anomalies are approximately 2.0 meters. Both the depth and height of the anomalies are in agreement with information known from historical documentation. While we have had success in this particular research it should be noted that site conditions may play an integral role in the application of the MASW method in the search for abandoned mine tunnels. Within this research the depth of the tunnels is within the range of being able to be imaged using surface waves. If the tunnels were deeper we would have had difficulty imaging them with our equipment. In other locations this could be addressed by using lower frequency geophones, however, there is a maximum depth of imaging using the MASW method and in many locations the depth of mine tunnels may be beyond this range.

This research has also highlighted the benefit of using multi-depth EM instrumentation for rapid data acquisition to identifying lateral changes in ground conductivity. Using multi-depth acquisition we are able to see how the electrical properties of the subsurface change with depth. Data from the shallowest depth of investigation indicate a subsurface with uniform electrical properties and do not reveal any anomalies. However, data from 4.2 meters and 6.7 meters depth indicate anomalies that may be associated with abandoned tunnels.

Electrical variations associated with these anomalies as a result of the abandoned tunnels are found within the southern area of the study site. Inspection of the data also reveals that there is no electrical variation throughout the remainder of the study site, which does not have underlying tunnels, at these depths.

While it is difficult to make a direct comparison of the MASW and EM surveys both indicate an anomalous subsurface where abandoned mine tunnels are expected. The MASW results provide more evidence in regards to the height and width of the tunnels however both methods offer a way to detect the existence of tunnels.

IV. CONCLUSIONS

Research conducted at Wally Rose field demonstrates the utility of MASW and electromagnetic methods for identifying the location of abandoned mine tunnels. A detailed Vs subsurface profile and multi-depth apparent conductivity plots help identify the area where abandoned mine tunnels are located. MASW and EM helps to identify the depth at which the tunnels are located and MASW further helps to identify the width and height of the tunnels. Information revealed through the geophysical results is in agreement with historical documentation in regards to the tunnel locations within the area.

Use of a seismic land streamer was an important aspect of this research. Streamers provide an opportunity to rapidly acquire seismic data to measure site response and map tunnel locations at a rate many times faster than a traditional seismic survey. Fifty-seven shot locations, acquired in one day's time, were occupied, spanning a distance of 57.0 meters. In comparison, performing this survey by manually moving the geophones and seismic equipment and occupying the same number of shot locations without the use of a seismic streamer would likely take several days to complete. While there is a trade-off between geophone and ground coupling and speed of acquisition, with the correct streamer design coupling is more than sufficient to provide for shot records that can be used for analysis.

In appropriate conditions MASW and EM are valuable methods in the detection of subsurface voids such as abandoned mine tunnels. Recommendations for further investigation would include acquiring multiple, parallel, MASW survey lines. This would allow for a comparison of multiple 2-D Vs profiles to map the linear trend of the tunnels at depth. Additionally, a closer grid spacing of the EM traverses is also recommended. EM data can be acquired quickly and collecting data on a 0.5 meter or smaller, traverse interval may help to identify the linear trends of the tunnels at depth and image the extension of the tunnels.

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8. Figures

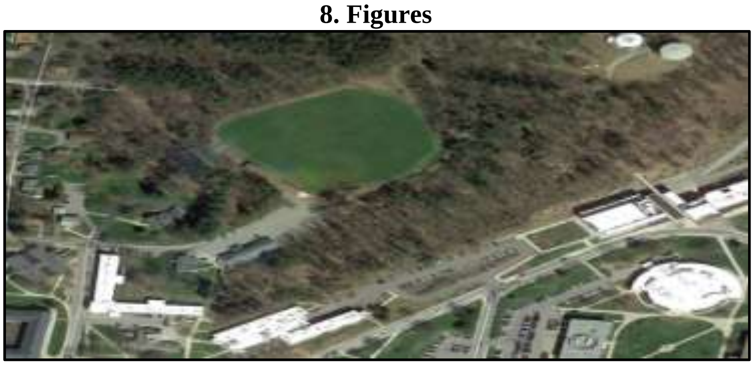

Figure 1. Wally Rose Field survey site (edited from Google Earth).

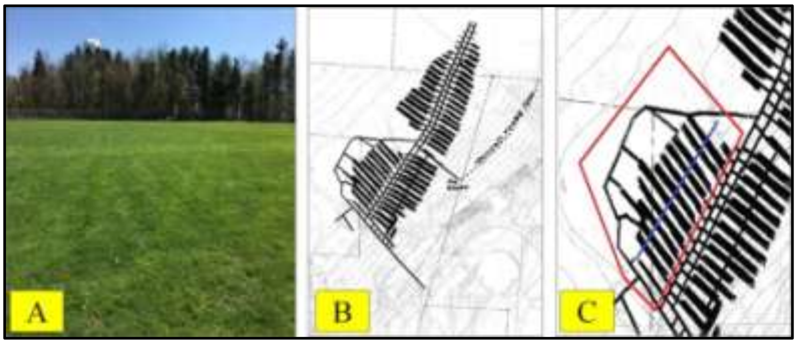

Figure 2. A) Wally Rose Field on the campus of Slippery Rock University, B) Historic map of abandoned coal mines beneath university property, C) Portion of abandoned coal mines beneath the study area. The location of the electromagnetic survey is outlined in red and the surface wave survey line is shown in blue.

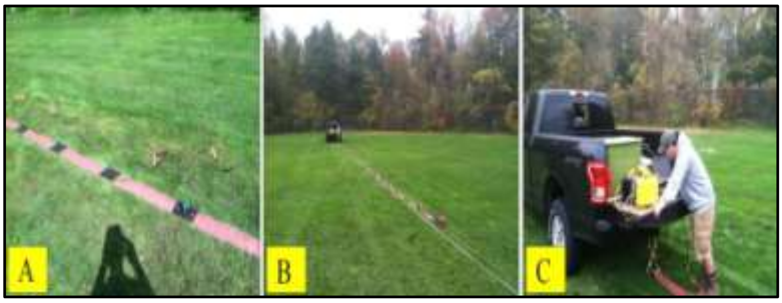

Figure 3. A) Close-up of base plates and geophones, B) The seismic streamer, C) The seismograph and field laptop are carried on the bed of the truck.

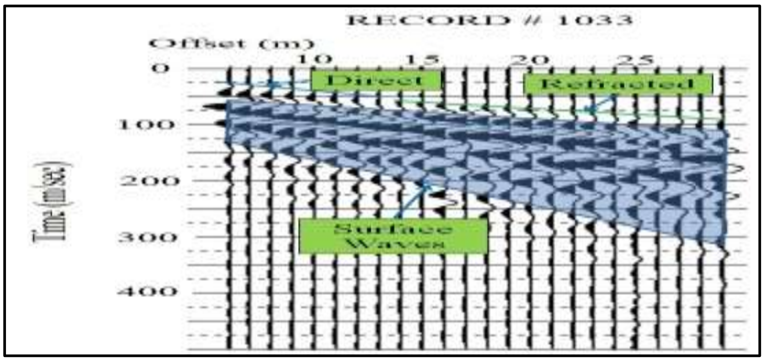

Figure 4. Seismic shot record from surface wave survey.

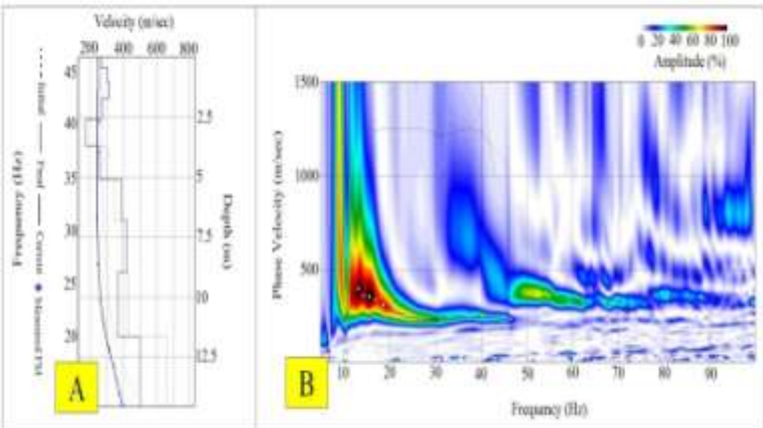

Figure 5.A) 1-D shear wave profile, B) Dispersion curve.

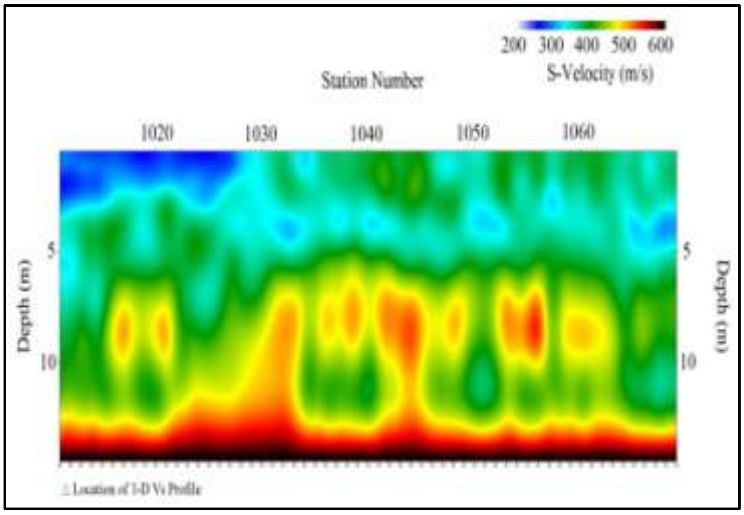

Figure 6.2-D shear wave velocity profile.

Figure 7.EM data acquisition.

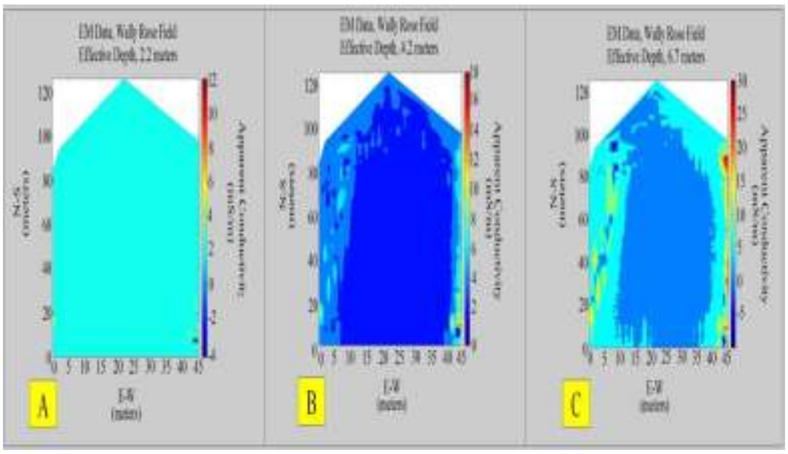

Figure 8. A) EM data effective depth of 2.2 meters, B) EM data effective depth of 4.2 meters, C) EM data effective depth of 6.7 meters.