CHARACTERIZING THE EVOLUTION OF ACID ROCK DRAINAGE WITHIN AN OVERBURDEN DUMP: LOY YANG, AUSTRALIA

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ABSTRACT

At the Loy Yang Coal Mine in southeast Victoria, Australia, waste material is disposed in a surficial overburden pile where iron-sulphide bearing interseam sediments and inferior coal are encased by a clay-rich overburden which helps to minimize the potential for acid rock drainage (ARD) generation. A combination of geophysics and hydrogeology are used to characterize the ARD generation potential of the west end of the pile. Geophysical results from a TEM survey imply that the presence of acid water is restricted to two distinct sites. Hydrogeologic modeling indicates that the thickest interseam sediments/inferior coal layers are saturated and that the predominant flow path is towards the west end of the pile. The geophysical and hydrogeologic interpretations provide a source and transport mechanism to explain the present day occurrence of acidic seeps on the western batters of the dump.

Key words: hydrogeology, transient electromagnetics (TEM), acid rock drainage (ARD), environmental impact

INTRODUCTION

Appropriate disposal of waste material from open-cut, brown coal mining is a critical consideration in minimizing the potential for acid rock drainage (ARD) generation. Coal mining operations expose iron-sulphide bearing minerals such as pyrite and marcasite (FeS_2) to oxygen and water (Gerke, 1998). This exposure can result in a series of oxidation and hydrolysis reactions that produce sulphuric-acid. With pH values as low as 2, and high concentrations of sulphate and dissolved metals, ARD can be a serious environmental risk to water quality, plants, animals, and humans.

At the Loy Yang coal mine in southeast Victoria, Australia, overburden, interseam sediments, and associated inferior coal are disposed in a 13.5 km^2 surficial dump. The iron-sulphide bearing interseam sediments/inferior coal are encased by the clay-rich overburden thus minimizing the exposure of the iron-sulphides to the atmosphere, and limiting the potential for ARD generation. Despite these precautions, several acidic seeps have developed over the past seven years on the west slope of the dump. Waters from these seeps have pH values as low as 2.8 and exhibit electrical conductivities of 3000-6000 μS/cm.

Given the future detrimental implications that ARD generation within the overburden pile may hold for the groundwater and vegetation around the dump, a combination of geophysical and hydrogeological analyses were conducted over a 1.5 km^2 region at the west end of the dump (Figure 1). This integrated study aims to answer three diagnostic questions: what is the prevalence and distribution of ARD within the overburden pile, what hydrogeologic factors control the distribution of ARD, and how are these factors likely to impact the potential for acid generation and seepage within the overburden dump?

SITE DESCRIPTION AND OPERATIONS

Owned and operated by Loy Yang Power, the Loy Yang mine is the largest open-cut coal mine in Australia. Loy Yang is situated in the LaTrobe Valley (Figure 1), 158 kilometers east of Melbourne, Victoria where it has been operating since 1982. The LaTrobe Valley contains a thick sequence of brown coal seams with an estimated reserve of 168,000 million tonnes (www.loyyangpower.com.au, 2000). Although the brown coal is soft with a high moisture content, it is one of the most accessible and cost efficient fuel sources in Australia.

Current open-cut operations at Loy Yang cover 8 km^2 and have reached a depths of 130m - 170m. 31 million tonnes of coal and 3-4 million cubic meters of overburden are being extracted annually (www.loyyangpower.com.au, 2000). Overburden, inferior coal, and interseam material are excavated separately from the economic coal reserve and transported via conveyor belts to the overburden dump located in a valley south of the mine. Travelling stackers remove the waste rock from the conveyors and disperse it over the 13.5 km^2 surficial pile. The overburden pile is currently comprised of two levels, each 15-18m thick. Deposition of Level 1 occurred between 1982 and 1987 and Level 2 between 1987 to 1995. A third level is currently being deposited over the east end of the pile.

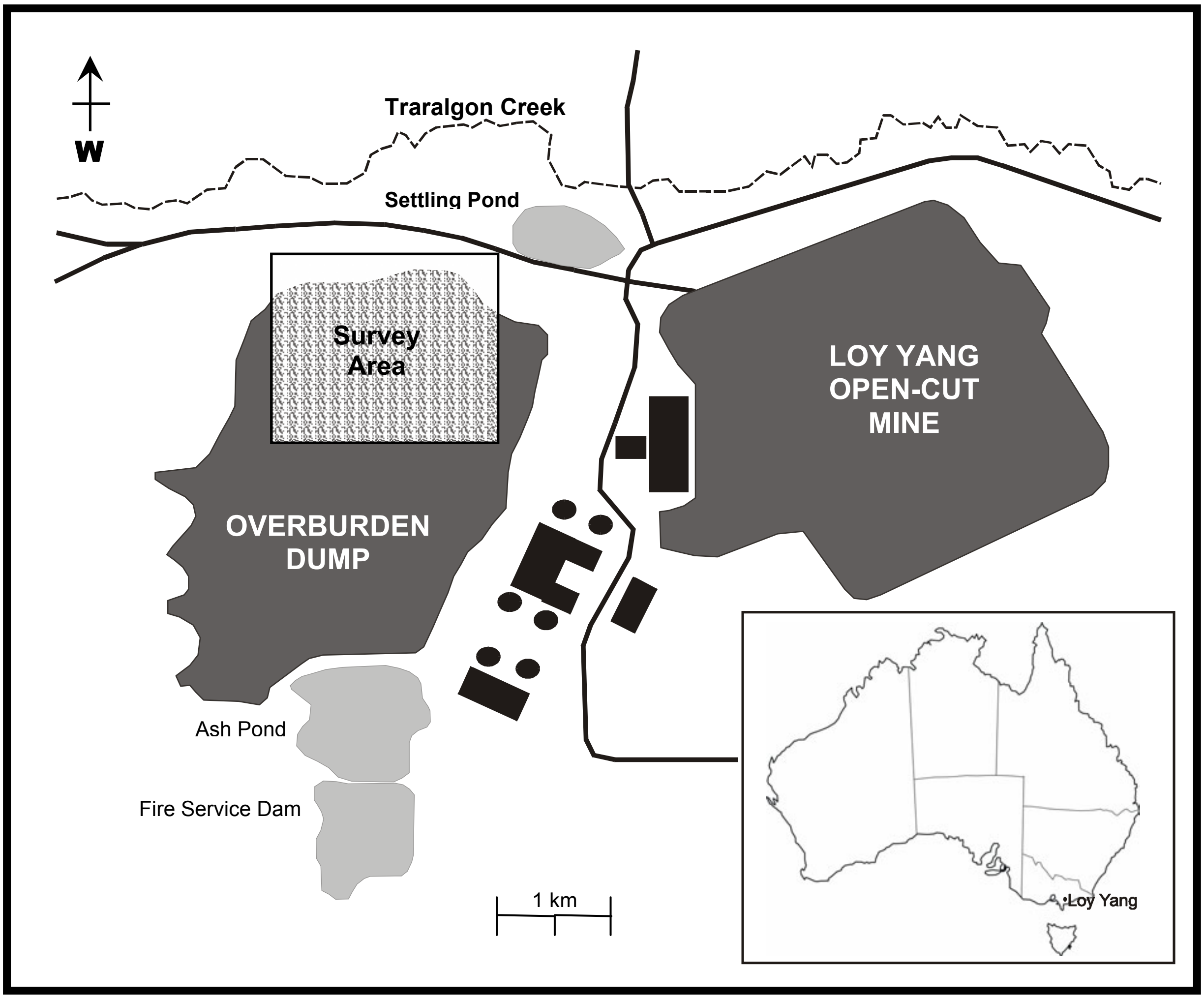

FIGURE 1: Location and site maps.

OVERBURDEN PILE COMPOSITION AND STRUCTURE

The composition, abundance, and disposal mechanism of waste materials have an important influence on the potential for acid rock drainage generation within the dump. Waste materials disposed in the overburden pile at Loy Yang consist of clay-rich overburden, and interseam sediments/inferior coal. During the mining process, these materials are broken down to sizes ranging from fine dust to 300 mm for deposition in the overburden pile.

Within the dump, the interseam sediments/inferior coal are encased by the clay-rich overburden within each of the Levels (Figure 2). The overburden pile is deposited within a valley on the Haunted Hill Formation gravels. Approximately 5m of the clay-rich overburden lines the base of the dump. Within the bottom level (Level 1), 8-10m of interseam sediments/inferior coal overlies the clay. This material is capped by up to 6m of clay-rich overburden both along the berm and down the batters. A second level was subsequently deposited and consists of two 3-5m thick interseam sediment/inferior coal sub-levels separated by 3m of clay-rich overburden material. Level 2 is capped by approximately 3m of clay-rich overburden. The overburden materials are distributed radially over the pile in strips 80m wide. Due to the heterogeneous nature of the material excavated during the mining process, homogeneity of materials within the overburden dump is not expected.

Overburden material is derived from the Haunted Hill Formation that overlies the coal deposits in the LaTrobe Valley. This formation ranges from 5m to 24m in thickness over the

Loy Yang open-cut pit and accounts for 91% of the material disposed of in the overburden pile (Brack, 1998). Sands and gravels with a clay-rich matrix dominate the formation. Quartz, mica and zircon are the predominant minerals of the sands and the clay host consists primarily of montmorillonite and kaolinite with localized areas of ferruginous cementation (Bolger, 1984). The Haunted Hill Formation is intensely oxidized in areas with notable depletion of potassium and magnesium.

Coal at the Loy Yang mine is being extracted from the M1 and M2 seams within the Morwell Formation that immediately underlies the Haunted Hill Formation. Each seam is 30m – 100m thick. These coal seams are separated and subdivided by narrow bands of interseam sediment that consist of thinly interbedded lignite-rich clay, micaceous silt, and quartz sands (Bolger, 1984). Such sediments contain significant marcasite (up to 3.2 wt %) which at times is very fine-grained and reactive when exposed to the atmosphere. Because of its close proximity to the interseam sediments, inferior coal, characterized by its poor quality and high level of impurities, is usually excavated with the interseam sediment. These materials are consequently mixed and disposed of together in the overburden pile. The interseam sediments/inferior coal constitutes 9% of the total waste disposed in the dump and has a theoretical acid generating potential in excess of 1 million tonnes (Brack, 1998).

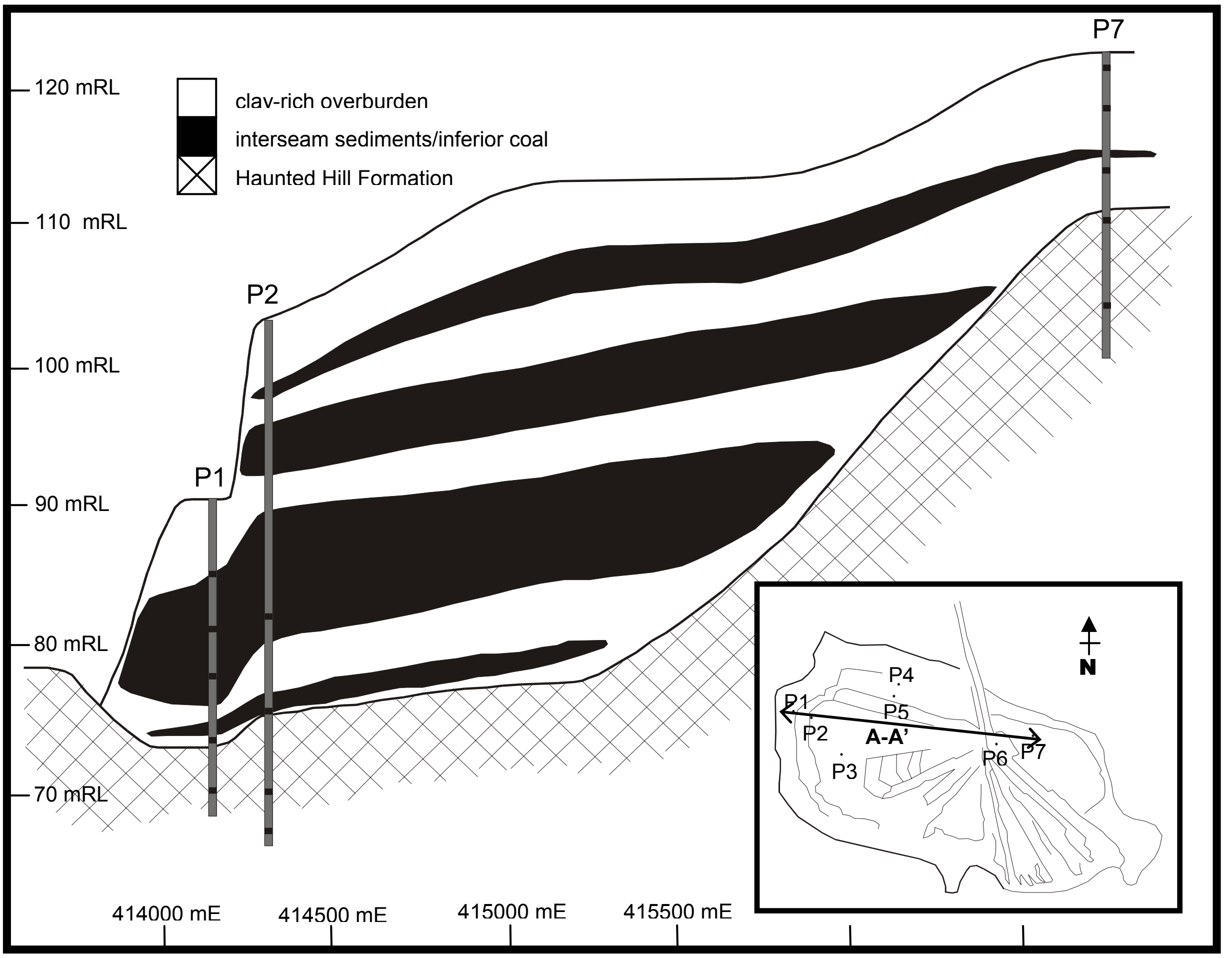

FIGURE 2: Idealized schematic cross-section (A-A') of the distribution of materials dumped in the overburden pile (vertical exaggeration 1:40). The location map identifies the position of piezometers (P1-P7) installed on the overburden dump.

HYDROGEOLOGY

The distribution of water, and direction and rates of flow within the overburden dump can control the generation and migration of acid rock drainage through the pile. In order to monitor these parameters, five vibrating-wire piezometer nests were installed over the west end of the pile after the completion of Level 2 in 1995 (Figure 2). Hydraulic heads from each piezometer have been recorded on a monthly basis since their installation.

Hydraulic head values measured at each piezometer can be considered constant with seasonal fluctuations of the depth to the water table being less than 1m since 1995. Figure 3 depicts a schematic hydrogeologic model of fluid flow for a west-east cross-section through the overburden pile. The three depicted piezometers are located within a single, radial dumping strip. From the hydraulic head information, it is apparent that the water table is positioned 12m-15m below the top of Level 2. This depth correlates with the top of the second interseam sediments/inferior coal layer within this level. Depth to the water table decreases to 3-5 m over the exposed region of Level 1. Due to abrupt variations in surface topography, the water table is situated within 1-2 m of the surface at the contact between the two levels. Saturation of Level 1 occurs below 86 mRL, which correlates to the top of the interseam sediment/inferior coal layer in Level 1.

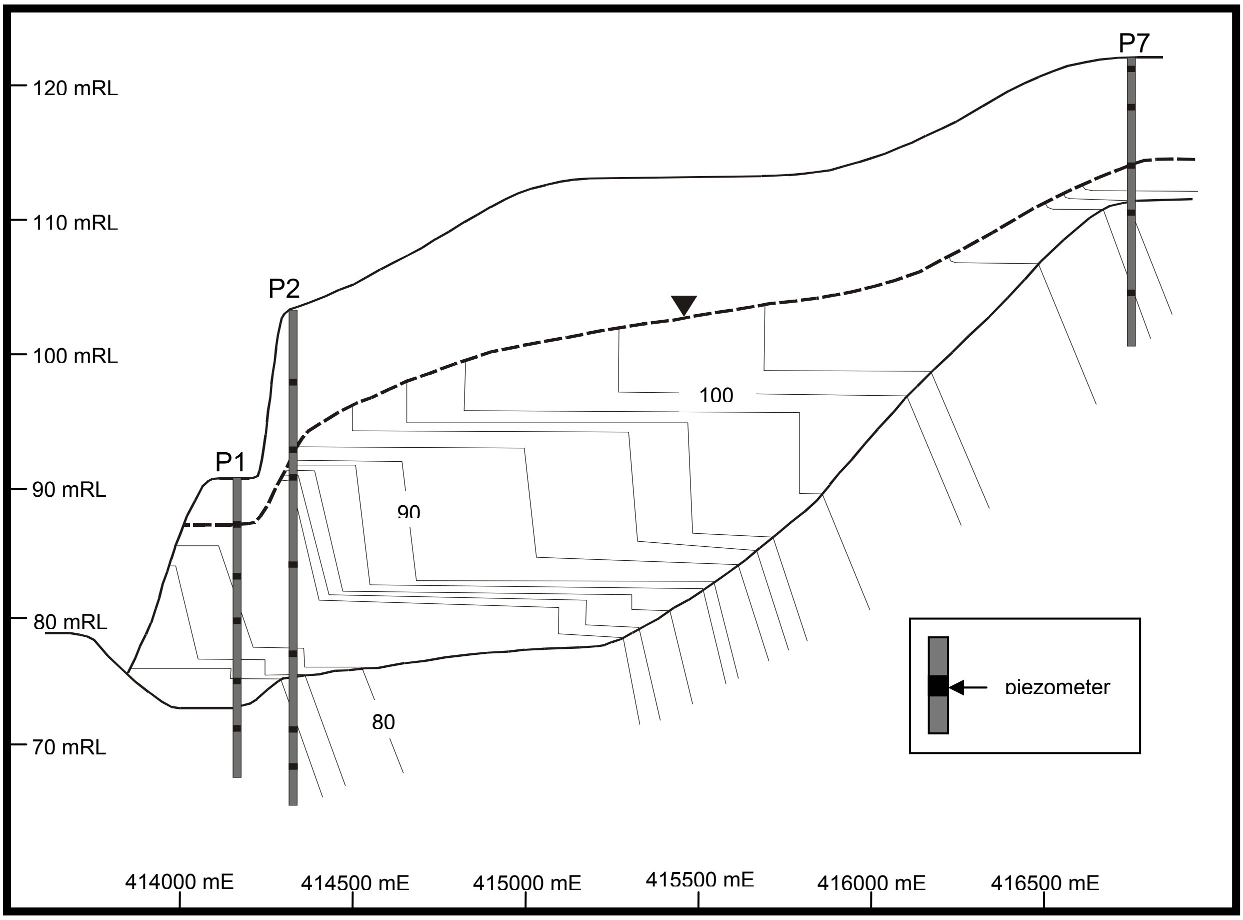

FIGURE 3: Schematic hydrogeological cross-section A-A' (vertical exaggeration 1:40) showing the depth to the water table and equipotential lines for hydraulic head. Assuming isotropic conditions, flow through the pile will be perpendicular to the equipotential lines.

Equipotential lines were contoured on the premise that in hydrogeologic systems with hydraulic conductivity contrasts of two orders of magnitude or more, flow tends to become almost horizontal in the aquifers and almost vertical in the aquitards (Freeze, 1979). In-situ infiltration tests indicate this to be the situation within the overburden dump at Loy Yang with a hydraulic conductivity on the order of 10^{-7} m/s in the clay-rich overburden and 10^{-4} m/s in the interseam sediments/inferior coal layers. Hydraulic gradients throughout the pile are variable with vertical gradients ranging from 1.0 to 8.0 through the clay-rich overburden, and horizontal gradients ranging from 0.002 to 0.1. Modeling indicates that the flow direction is dominantly downward through the clay-rich material and westward through the zones of interseam sediments/inferior coal. These changes in flow direction are critical because they imply that in the absence of a clay cover along the batters, waters within the interseam sediments/inferior coal zones would seep to the surface along the west batters, which is consistent with location of present day seeps.

Rainfall and bound water within the interseam sediment/inferior coal are the primary sources of water within the overburden pile. Average annual evaporation (1109.5 mm) exceeds average annual rainfall (751 mm) with rainfall only exceeding evaporation during the winter months (Bureau of Meteorology, 1998). Based on the estimated hydraulic conductivities and flow paths, the residence time for water entering the pile from the top of Level 2 is estimated to be as long as 6.5 years through the thickest dump sequence. These residence times indicate that oxygen dissolved in the rainwater entering the pile, which acts as the source of oxygen in iron-sulphide oxidation reactions under saturated conditions, can be distributed and replenished within the pile on a time scale suitable for maintaining ARD generating reactions.

GEOPHYSICS

Transient electromagnetic (TEM) methods can effectively distinguish the boundaries between layers of contrasting electrical conductivity. Its application to the detection and delineation of acid rock drainage is two-fold. Because acid waters tend to have a higher electrical conductivity than natural waters due to an increase in dissolved ions, TEM profiling is likely to be effective in identifying regions where acid rock drainage is present. Additionally, inversion of TEM profiles can also provide insight into the depth to the water table and electrically contrasting stratigraphic boundaries (Ladwig, 1983).

Six TEM survey lines were conducted over the west end of the Loy Yang overburden pile (Figure 4). Five TEM lines were extended radially from the Level 2 berm down the batters of the overburden pile to the toe of Level 1. These radial lines targeted regions where surface seepage was visible, as well as regions visually unaffected by groundwater seeps. In order to examine the geoelectric characteristics of a single level within the dump, Line 6 was positioned along the Level 1 berm.

TEM profiles were collected using a single, moving-loop configuration. In this set-up, an alternating current is transmitted through a square loop of wire and voltage measurements are taken in the same loop of wire during the transmitter turn-off times. This configuration is effective in regions where super-paramagnetic materials are absent. In order to electrically penetrate the entire thickness of the overburden pile and still be able to resolve a shallow water table, readings were taken using a 25m x 25m square loop at a station spacing of 25m. High-resolution delay times, ranging from 0.008 ms to 1.709 ms over 25 channels were also used to help delineate the water table depth.

Figure 4 depicts the position of the TEM stations and voltage response from the six survey lines at a delay time of 0.293 ms. Regions of higher conductivity will induce a stronger magnetic field and resulting in a higher voltage response. Consequently, two regions of elevated conductivity are interpreted in the data. A strong anomalous zone (350 uV/A) occurs over a 200m x 150m region in the southwest corner of the survey area. Extensive surface seeps are visible on the Level 1 batters at a position corresponding to the west edge of the anomalous zone. These seeps suggest that the source of the anomaly is acidic water, most likely positioned within Level 1 of the overburden pile. A weaker anomalous zone (240 uV/A) is identified over an area of 350m x 300m along Line 3. Two surface seeps were identified at the toe of Level 2 approximately 6 months prior to this TEM survey. The position of these new seeps correlates with the west edge of the anomalous zone.

In addition to the delineation of the regions of acid water, a layered earth model (Figure 5) of the overburden pile was interpreted from the TEM profiles using standard inversion software (GRENDL). Although the coal/clay layering within the overburden pile could not be resolved due to the heterogeneity and discontinuity of dumped material, a three layer earth model was generated which clearly identified the depth to the water table and the depth to the base of the overburden pile within the non-anomalous zones. These interfaces would be expected to have significantly different conductivities resulting from variations in porosity, composition, and groundwater content of the overburden compared to the original undisturbed ground surface (Buselli, 1990).

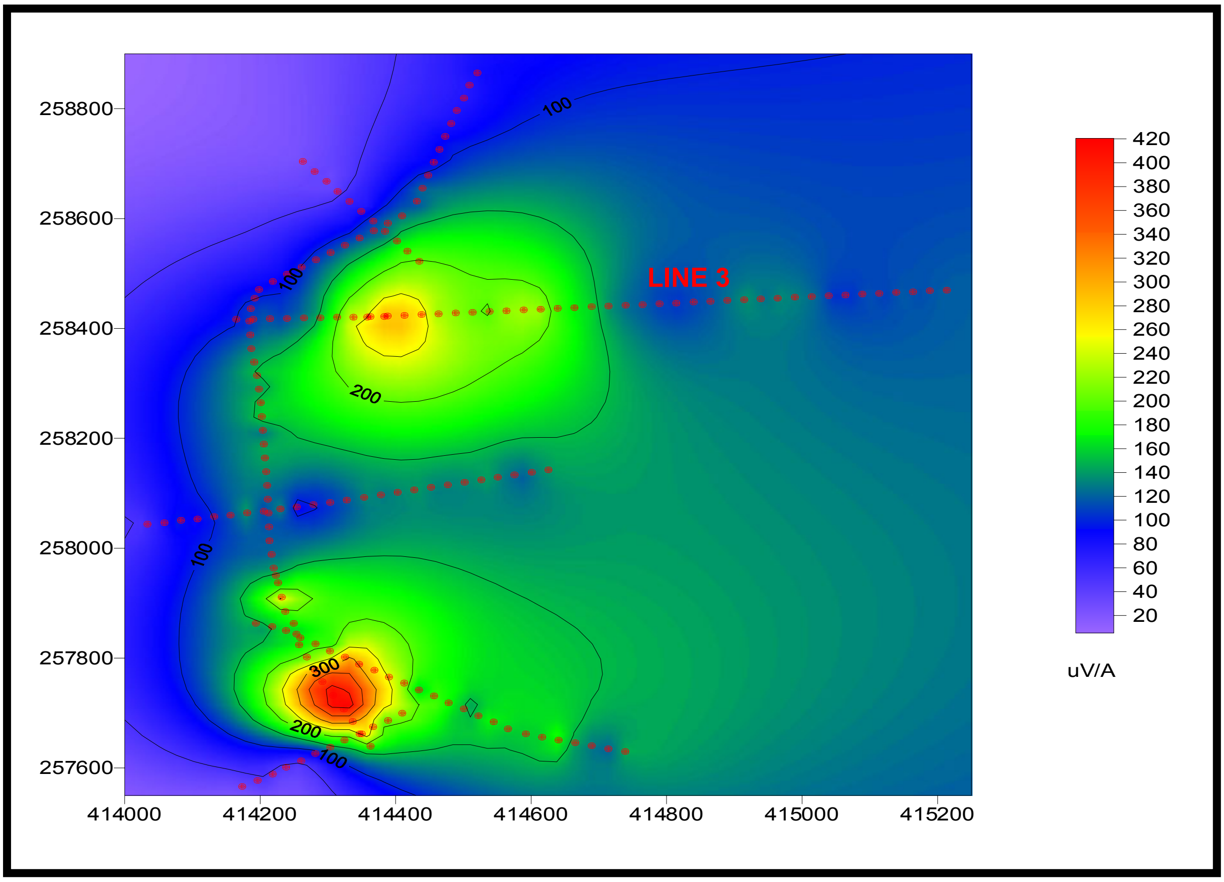

FIGURE 4: Single-loop TEM response for a delay time of 0.293 ms. Regions of high voltage response indicate regions of interpreted acidic water within the overburden dump.

The inversion results for Line 3, which correlates to a portion of the hydrogeologic cross-section A-A', are presented in Figure 5. Since GRENDL is designed for the interpretation of a 2D layered earth, it can be used to remove the background response of the overburden pile thus isolating the response due to ARD. A two step inversion process was used for the generation of the model for Line 3. In the non-anomalous zone between 414775 mE and 415500 mE, layer thickness and conductivity were not constrained thus allowing for a free inversion. The depth to water table and base of the overburden pile obtained from this inversion correlate with the depth to the water table and base of the overburden pile interpreted from the hydrogeologic data. With this in mind, a forward GRENDL model for the anomalous region (414115 mE – 414775 mE) was developed using the water table/overburden thickness data from the hydrogeologic cross-section and the layer conductivities obtained for the non-anomalous portion of Line 3. The residual TEM response, not accounted for by the removal of this layered-earth model, should correlate with the conductivity response from the acid rock drainage (Buselli, 1990). The justification for the background stripping using a layered-earth inversion process is additionally supported by similar results from the GRENDL inversion completed for Line 2 that contained no anomalous regions. In general, the profiles are consistent with an unsaturated zone at the top of the overburden pile (conductivity of 3 mS) underlain by a saturated zone with a conductivity of 180 mS. Layer 3 is indicative of the natural valley surface (Haunted Hill Formation) and has an average conductivity of 2 mS.

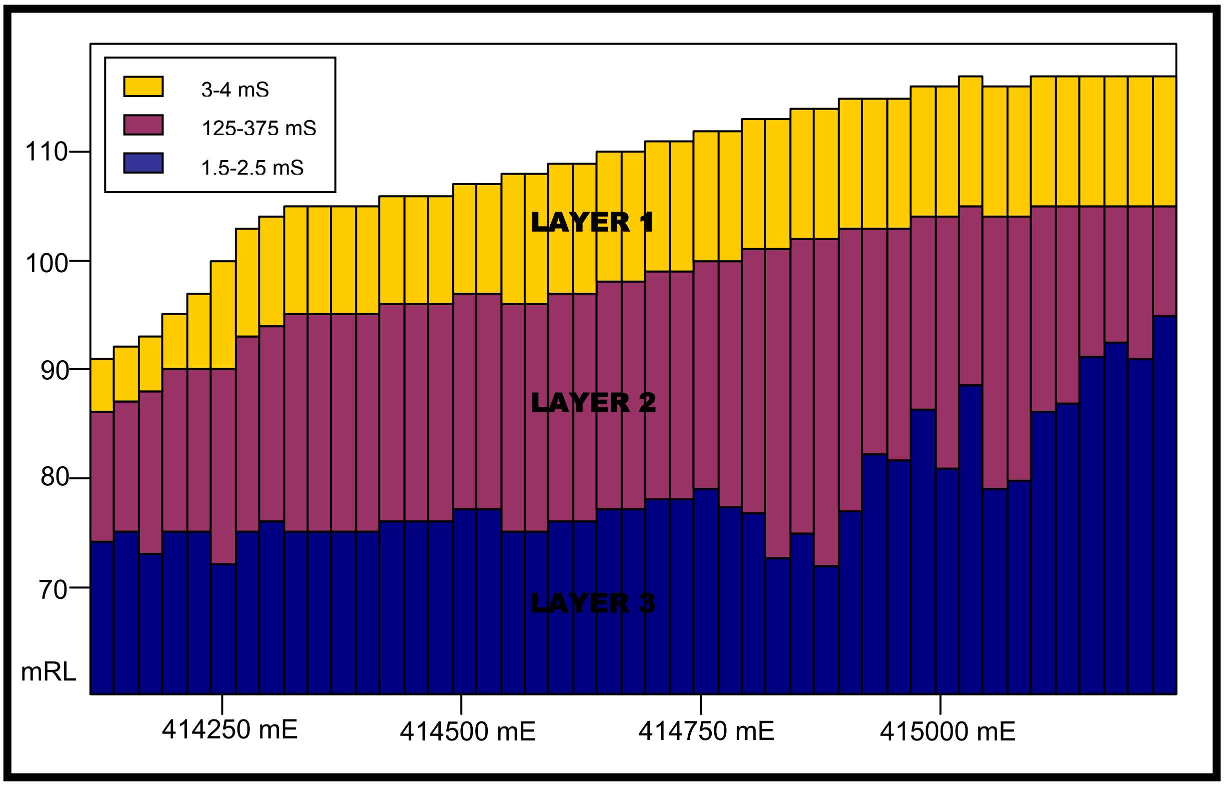

FIGURE 5: Layered earth model for Line 3. The contact between Layer 1 and Layer 2 is interpreted to be the water table. Layer 3 is interpreted to be the Haunted Hill Formation (natural surface).

CONCLUSIONS

Preliminary results from this integrated study provide significant insight into the potential for acid generating processes to be occurring within the Loy Yang overburden pile. The joint interpretation of the electromagnetic geophysical survey and hydrogeologic modeling provides definitive and complimentary results with regards to the distribution and migration of acid waters within the dump.

Results from the geophysical TEM survey indicate acidic water is not prevalent through the west end of the pile, and is instead localized to “hotspots”. The depth of these acid waters is uncertain in the absence of geochemical data. Their most probable location is within the top few meters of the saturated interseam sediment/inferior coal zones in both levels where exposure of the iron-sulphide rich sediments to dissolved oxygen is greatest. The dispersion of the acidic “hotspots” as defined by the TEM anomalies are consistent with the presence of acidic seeps on the western batters and the westward flow path of waters through the interseam sediments/inferior coal zones as identified in the hydrogeologic model. Thinning or absence of the clay-rich material along the slopes may account for the present day occurrence of seeps along the western batters of the overburden dump.

The current steady-state conditions of the water table within the overburden dump imply that buried iron-sulphides would have little opportunity for oxidation. Slight seasonal variations of the water table elevation may account for low levels of ARD generation within the pile, but would not be expected to account for the amount of acid rock drainage required to produce the high amplitude anomalies recorded in the TEM survey. Run-off from the currently exposed interseam sediments/inferior coal zone on Level 3 is highly acidic (pH <3) indicating that during the deposition of each level, iron-sulphides can be exposed to the atmosphere for a long enough period to begin the oxidation/ARD generation process. It is possible that the pH of these waters remains low (<3) after burial and therefore ferric iron is soluble. Ferric iron is capable of driving the oxidation of iron-sulphides under the anoxic conditions associated with burial (Moses, 1987). Another possible explanation for the high amplitude TEM anomalies is that the acidic surface waters are reduced when buried and sulphuric acid is thus converted to H_2S (g). In this case, water within the pile would not exhibit a low pH and acid generation would not occur, but high dissolved metal concentrations would still exist thus accounting for the TEM anomaly.

The hydrogeological and geophysical analysis clearly indicate the abundance, distribution, and migration of potentially acidic waters within the overburden pile. In order to augment the geophysical and hydrogeological interpretation, geochemical analyses of the water and overburden materials at depth throughout the pile are planned. It is anticipated that understanding the composition of the water and sediment will help to determine the mechanisms of localized acid generation as well as the potential for future contamination of the natural aquifer beneath the overburden pile.

ACKNOWLEDGEMENTS

The author would like to acknowledge Loy Yang Power for funding this research and for providing permission to publish these preliminary results. Thanks are given to Ashley Grant, Trudi Hoogenboom, and Simon Baker for their field assistance. Jon Missen, Jeff Taylor, Bear McPhail, and Jim Cull are thanked for their constructive comments.

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