GEOPHYSICAL INVESTIGATIONS OF NEAR-SURFACE MATERIALS AND GROUNDWATER QUALITY AT ABANDONED MINE LAND SITE NO. 1087, PIKE COUNTY, INDIANA[1]

by

Kevin M. Spindler[2], Greg A. Olyphant[2], and Denver Harper[3]

Abstract. Reclamation of Abandoned Mine Land (AML) Site No. 1087 ("Midwestern") includes extensive use of coal-combustion byproducts such as fly ash and fixated scrubber sludge (FSS) as fill and cover materials. Prior to reclamation, a deposit of coarse-grained pyritic refuse in the central part of the site was the primary source for acidic mine drainage. The FSS tends to have a low permeability, so it was applied over the refuse to serve as a barrier to vertical recharge and thereby inhibit generation and mobilization of additional acidity. Repeated post-reclamation measurements of soil-water content using a neutron moisture gauge provide evidence that vertical recharge is, in fact, not occurring through the FSS. However, a previously existing plume of acidic water extends beyond the area of the refuse into adjacent areas of disturbed overburden (spoil). Electrical resistivity profiles using the offset Wenner method were used to delineate the horizontal extent of the refuse and to quantify spatial variability of groundwater chemistry within the refuse and adjacent spoil. Ground penetrating radar (GPR) was used to precisely determine the thickness and extent of the FSS layer and its relation to the refuse and to the surrounding plume of acidic water. Together, these techniques provide a complete three-dimensional representation of the FSS, refuse, spoil, and plume of acidic groundwater.

Introduction

In recent years, the use of shallow geophysical techniques for site investigations has become more widespread. When elementary knowledge of the conditions in the subsurface is known, these methods can be powerful tools for determining and delineating potential environmental problems that might exist. For example, electrical resistivity can be used to map plumes of groundwater contamination and locate the metallic refuse deposits that can be the source for such contamination (Ebraheem *et al*, 1990; Kelly, 1976; Merkel, 1972; Stollar and Roux, 1975; Warner, 1969). Ground penetrating radar (GPR) can accurately measure depth to, and thickness of, most geologic materials, and neutron moisture gauges provide good estimates of soil moisture content (θ) (Greaves *et al*, 1996; Kramer *et al*, 1992). When combined with additional knowledge of the site obtained through drilling logs and monitoring wells, these geophysical techniques can provide a detailed picture of the subsurface which can be valuable to hydrologic investigations of near-surface aquifer materials.

The purpose of this paper is to describe geophysical investigations that were conducted at an abandoned mine reclamation site, where a plume of acidic mine water exists within a deposit of pyritic coal-preparation refuse that has been covered with an impermeable cap. The geophysical investigations were designed to (1) better define the extent and location of the cap material, the refuse, and any resulting contaminant plumes; and (2) to evaluate the effectiveness of the cap material in reducing infiltration into the refuse.

Site Description

The study area is Abandoned Mine Land Site No. 1087 ("Midwestern"), located in the uplands of the Patoka River watershed, in Section 22, T. 2S, R. 7W, Pike County, Indiana. During surface mining of the Springfield Coal, widespread layers and ridges of overburden spoil were deposited. In addition, pyritic coal-preparation refuse was deposited over approximately 7.9 acres in the central part of the site (Figure 1). When the site was abandoned, the highwall pits filled to form a series of ponds on the periphery of the site. Rainfall infiltration resulted in the generation of acidic

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[2]Kevin Spindler, Research Assistant, and Greg Olyphant, Associate Professor, Dept. of Geological Sciences, Indiana University, Bloomington, IN 47405

[3]Denver Harper, Senior Scientist, Environmental Geology Section, Indiana Geological Survey, 611 N. Walnut Grove, Bloomington, IN 47405

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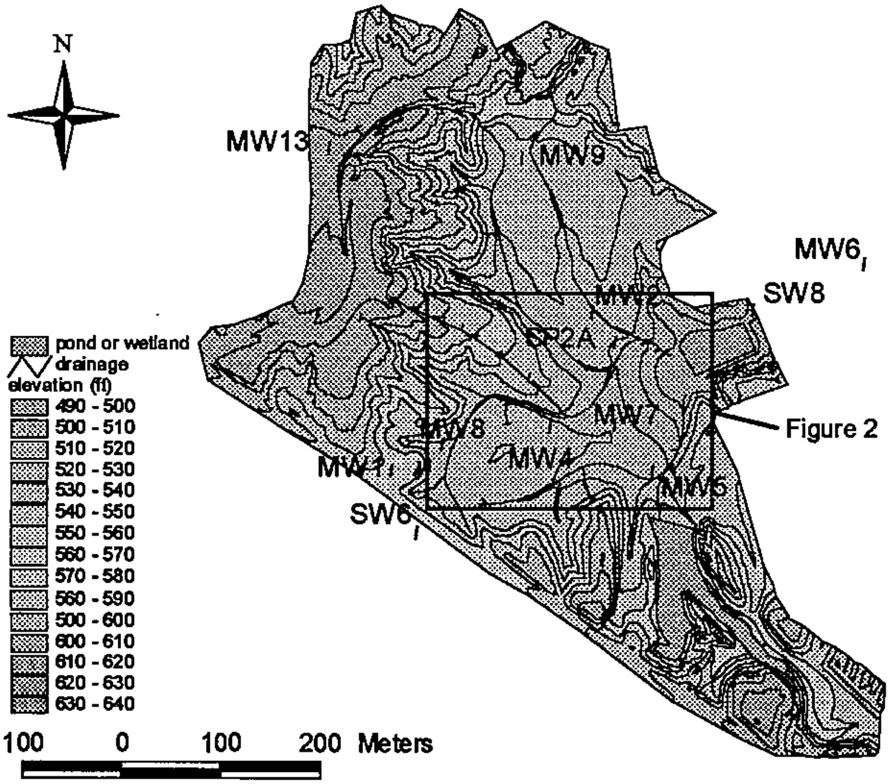

Figure 1 Map of study area showing topography and selected monitoring sites. Area in box is enlarged in Figure 2.

groundwater (from pyrite oxidation), which was discharged into a central trunk stream as baseflow. Water from the flooded workings of adjacent, abandoned underground mines discharges through a spring (SP2A) located in the central area of the study site. This water was also contributing to acid mine drainage from the site (Harper *et al*, 1995).

Reclamation of the Midwestern site began in early 1995. Reclamation activities throughout 1995 and 1996 included the draining of the highwall lakes and backfilling of these and other low areas with fly ash. Fixated scrubber sludge (FSS), a mixture of fly ash, gypsiferous flue-gas desulphurization sludge, and agricultural limestone, was used as a capping material over the pyritic refuse. Based on laboratory experiments, FSS has a very low saturated hydraulic conductivity (10^{-6} and 10^{-9} cm s^{-1}) and, therefore, should prevent percolation of infiltrated rain water into the refuse deposit. By preventing the vertical recharge of the refuse, the quantity of AMD discharging from that deposit would presumably be reduced. The entire central lowland area of the site was capped by a layer of soil material removed from the surrounding spoil ridges.

Geophysical Methods

Electrical Resistivity

Typically, contaminant plumes in coal-preparation refuse have a relatively high specific conductance when compared with naturally occurring waters. This high conductance will express itself as a low resistivity layer in the subsurface, which can be detected by introducing a current into the ground and measuring the resulting potential at various spacings (called *a-spacings*). For this study, two different survey methods were performed. The first of these, vertical electrical sounding (VES), was used to determine the thickness and resistivity of layered earth materials. In the other, the electrode spacing was fixed as survey lines were traversed. By using VES, it was possible to construct one-dimensional resistivity curves for the five locations identified in Figure 2. These locations were

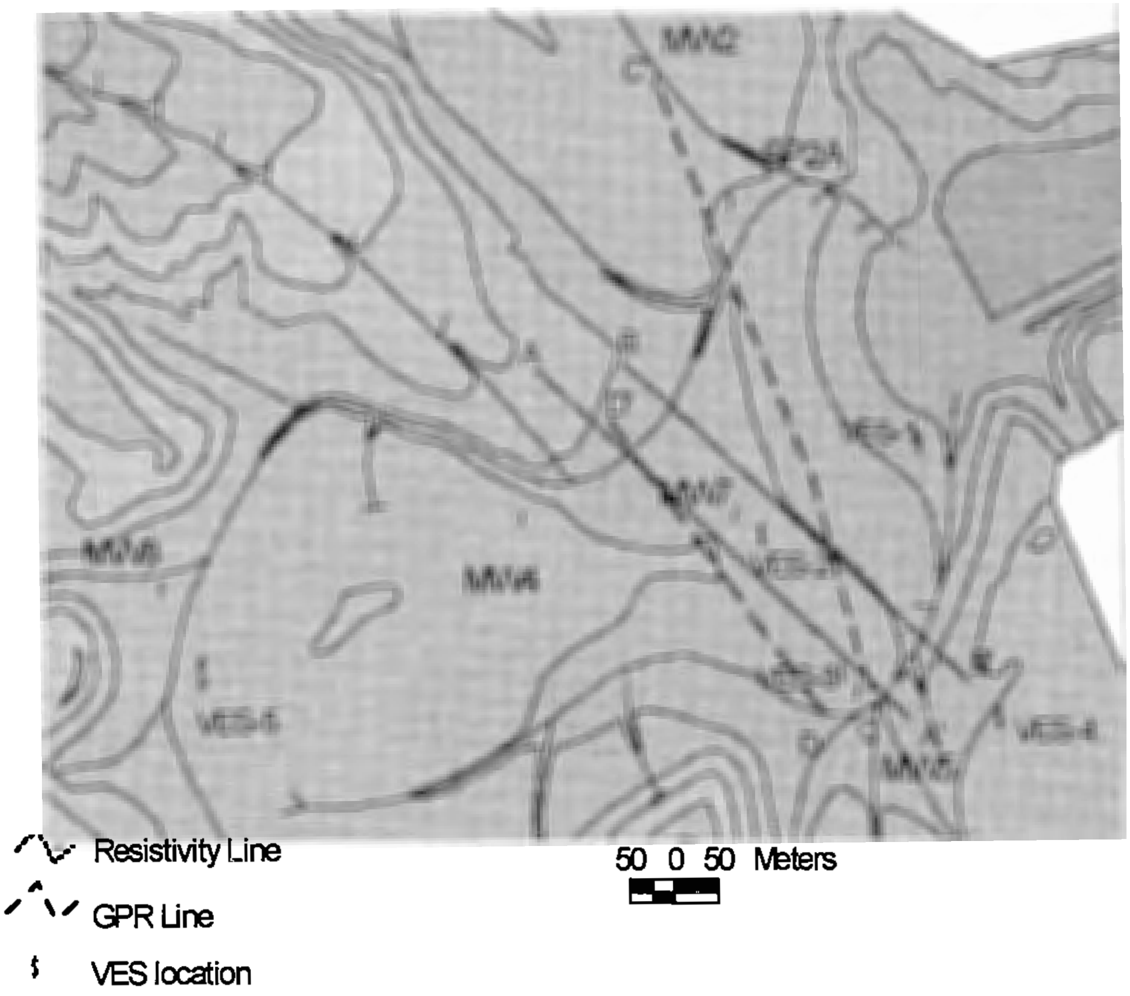

Figure 2 Map of central lowland area showing location of geophysical lines and vertical electrical sounding points.

chosen because they are near monitoring wells where drilling records and gamma ray logs provide information about the subsurface, so that the resistivity effects of the various subsurface materials could be determined. The VES surveys were performed using the Bison Offset Sounding System (BOSS), which employs the Offset Wenner method to provide a more accurate measure of apparent resistivity (Barker, 1981). Curve-fitting software was used to estimate resistivity profiles at these locations. Inverse modeling of the VES data from these areas gave results that are consistent with the known geology to a high degree of accuracy. Figure 3 shows the data from VES-2 and the curve generated from the inversion program, which agree within an RMS of 6.0 percent, which is a very good fit for these conditions. The data from the five vertical soundings is plotted together on Figure 4, in which the trend in the resistivity profiles can be seen. Table 1 shows a summary of the models obtained and the corresponding earth materials beneath each sounding. Note that at spacings greater than 10 meters, the soundings that were not performed on the pyritic refuse material (VES-4 and -5) have consistently higher apparent resistivities than surveys that were known to be over refuse. This demonstrates that a sufficient resistivity contrast exists between refuse and non-refuse areas for fixed traverses to be able to detect the pyrite-rich layers. Because this effect is more pronounced at wide spacings, an *a-spacing* of 16 meters was chosen for the fixed surveys. Two fixed traverses were run across the central lowland area at an interval of 10 meters (see Figure 2 for locations). The apparent resistivities are plotted versus position in Figure 5. In

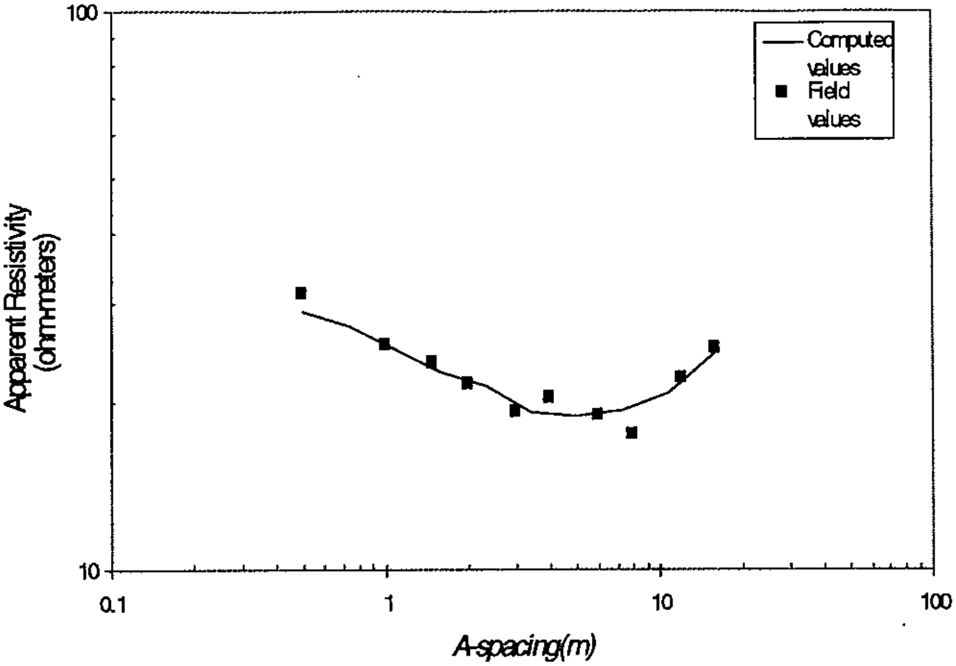

Figure 3 Vertical electrical sounding obtained near MW7 showing correlations between raw data and a curve obtained from data inversion.

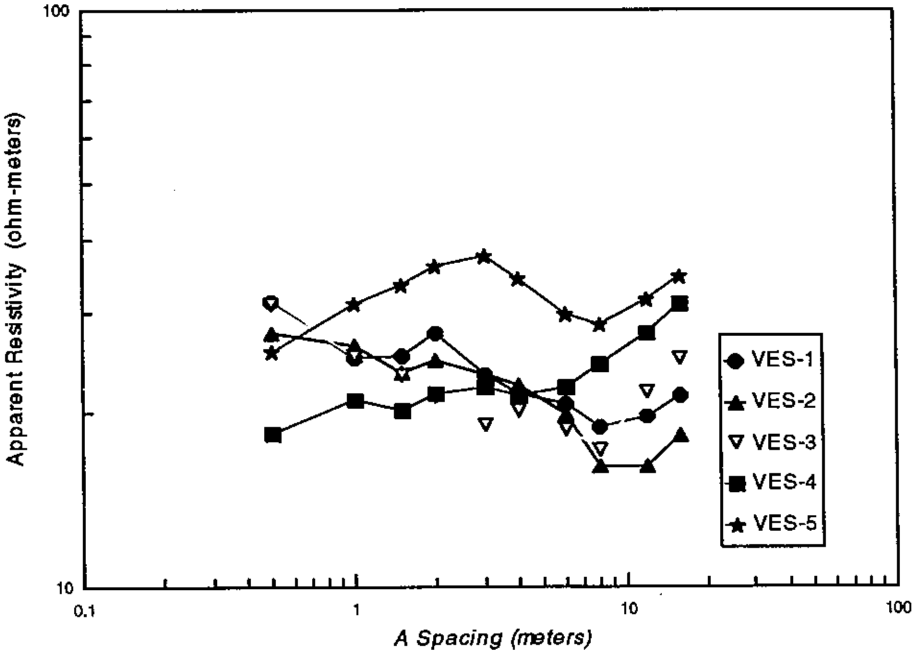

Figure 4 Results of the vertical electrical sounding (VES) surveys. VES-1 and -2 are known to be over the pyritic refuse deposit, which causes low apparent resistivities at large *a-spacings.*

Table 1 Summary of vertical electrical sounding data.

	Model Depths (meters)	Model Resistivity (ohm-meters)	Geologic Materials	RMS (percent)
VES-1	0 to 1.1 1.1 to 1.45 1.45 to infinity	28.3 28.35 19.5	Soil FSS Refuse	6.28
VES-2	0 to 1.1 1.1 to 1.5 1.5 to infinity	26.89 24.85 16.13	Soil FSS Refuse	6.01
VES-3	0 to 0.7 0.7 to 17.4 17.4 to infinity	30.14 18.07 251	FSS Spoil Sandstone	4.50
VES-4	0 to 15 15 to infinity	20.8 200	Soil Sandstone	5.6
VES-5	0 to 3.8 3.8 to 8.8 8.8 to infinity	31.6 27.5 39.0	Soil/FSS Ash fill Lake bottom sand	11.1

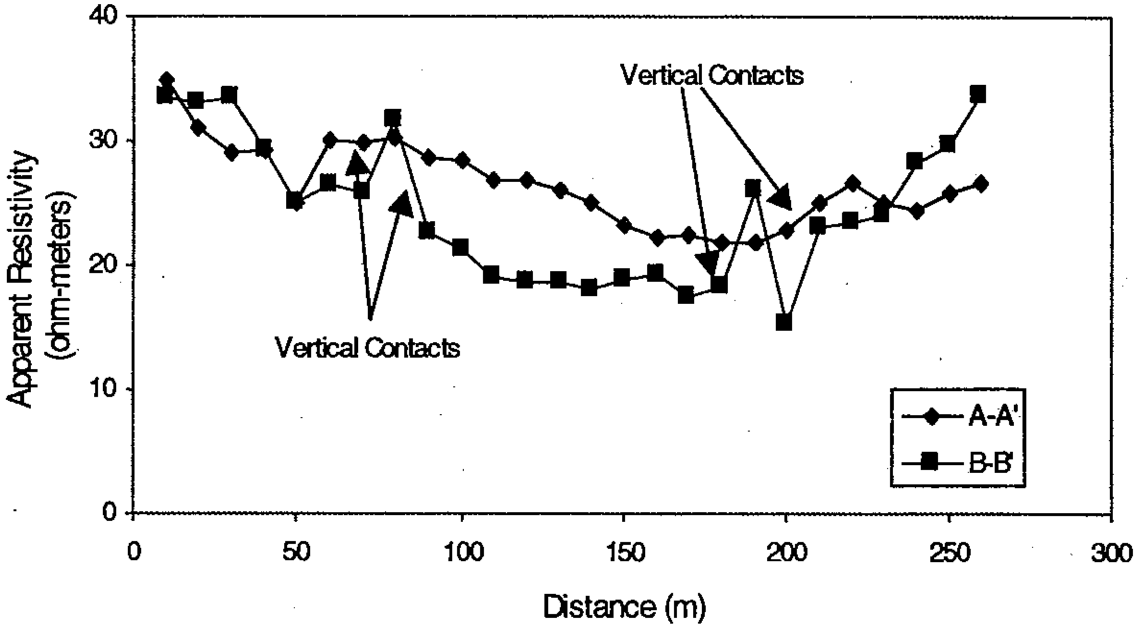

Figure 5 Fixed resistivity traverse along the lines A-A' and B-B' (see Figure 2 for locations). The shapes of the curves suggest a vertical contact between high and low resistivity materials.

both plotted transects, the north ends have apparent resitivities around 33 to 35 ohm-meters, which is within the range of both the soil material and the FSS layer. As the line extends over the area of the refuse, however, the apparent resistivities become smaller due to the existence of the pyritic refuse and acidic pore water. Note the shapes of the curves as they encounter the edge of the refuse. A slight increase in apparent resistivity occurs just before the gradual drop-off takes place. Such a response is indicative of a vertical contact in the subsurface (Telford, 1990). In this case, the vertical contact can be interpreted as either the edge of the pyritic refuse deposit or the adjacent plume of AMD. This edge effect occurs because the pyritic coarse refuse is so conductive that no current can pass through it, so the entire subsurface acts as separate, low resistivity body.

Ground Penetrating Radar

In ground penetrating radar, an emitted electromagnetic pulse travels through the subsurface and is partially reflected by materials of contrasting electrical impedances, such as layered geologic materials. The timing of the returns from the reflectors provides information about the depth to, and thickness of, geologic materials in the subsurface, or other features such as the water. In this investigation, a bistatic, 100 MHZ *pulseEkko* system was used to record two profiles across the site (see Figure 2 for locations). The lines were gathered with a one-meter antenna separation and a one-meter step size. Because the material used as soil cover at the survey site is rather high in clay content, a gain was applied to amplify returns that were reduced due to attenuation. The Spreading and Exponential Compensation (SEC) gain was chosen, because it compensates for spherical spreading loss (Sensors and Software, 1996). Individual traces were adjusted to an arbitrary zero point to correct for time-zero drift inherent in the equipment. Since pulse systems such as the one used in the present study transmit a time-domain signal, returns are plotted as a function of two-way travel time. The time scale can be converted to depth in two different ways. If a good estimate of the velocity of an electromagnetic wave through the earth material is known, then the depth scale can be easily calculated. Most geologic materials have velocities that fall within a specific range of values that can be determined in a reference table. However, since the materials found at the study site are uncommon, a common midpoint (CMP) was performed in order to calculate velocity. The transmitting and receiving antennas were moved progressively farther apart at equal intervals. The slope of hyperbolic returns is related to the velocity of the subsurface layers. The CMP's indicate that the velocity of the cover soil material is 0.08 m ns^{-1}, which is intermediate between the reported values for clay and shale. Another method for converting travel time to depth involves finding a reflection on the GPR record of known origin and adjusting the velocity in order to match it up with the depth of a known feature (the water table in this case). The velocity determined in this manner is also 0.08 m ns^{-1}, which is the same value obtained from the CMP. Thus, it is assumed to be accurate. Figure 6 shows the interpreted radar profile along the line C-C', which clearly shows the FSS layer beginning at trace 19 at a depth of approximately 1.3 meters. Note that according to the GPR, the thickness of the layer is somewhat variable, but on average, is greater than a meter thick. Although it is not possible to see direct reflections from the refuse layer, multiples can be seen between traces 60 and 140 at travel times of 150 to 280 ns. Profile line C-C' also crossed a passive anoxic limestone drain (PALD) that is used to treat outflow from spring SP2A. The blocky nature of the alkaline material acts to scatter the radar pulse and results in many multiples for those traces. This effect can be seen between traces 215 and 255, where many strong reflections can be seen at long travel-times. The survey also crossed two rip-rap-lined channels that were installed to prevent erosion because of surface runoff. Here too, the records are distorted because of multiples and point scattering and were only used as a reference point. Similar features can be seen along the line D-D' (Figure 7). The surface of the FSS appears to be fairly irregular here as well. It is interesting to note however, that reflections off of the water table do not have a consistent amplitude, indicating that the contrast between the electrical properties of the groundwater and the surrounding aquifer material is not as sharp as in some places on the record. Note that around trace 143, the reflection at approximately 3.0 meters depth abruptly disappears. This has been interpreted as the edge of the refuse layer.

Evaluation of FSS as a Cap

In this study, a neutron moisture gauge was used to evaluate soil moisture changes in the FSS, the underlying pyritic refuse, and the overlying spoil material. The probe was lowered into the subsurface through a stainless steel access tube that was emplaced to a depth of 3.35 meters at site MW7 (see Figure 1 for location). The probe contains an americium/beryllium source that emits fast neutrons into the soil material. The neutrons are slowed by collisions with hydrogen atoms that are found in the soil water and deflected back to the probe. Repeated measurements are used to calculate changes in the moisture content within the soil.

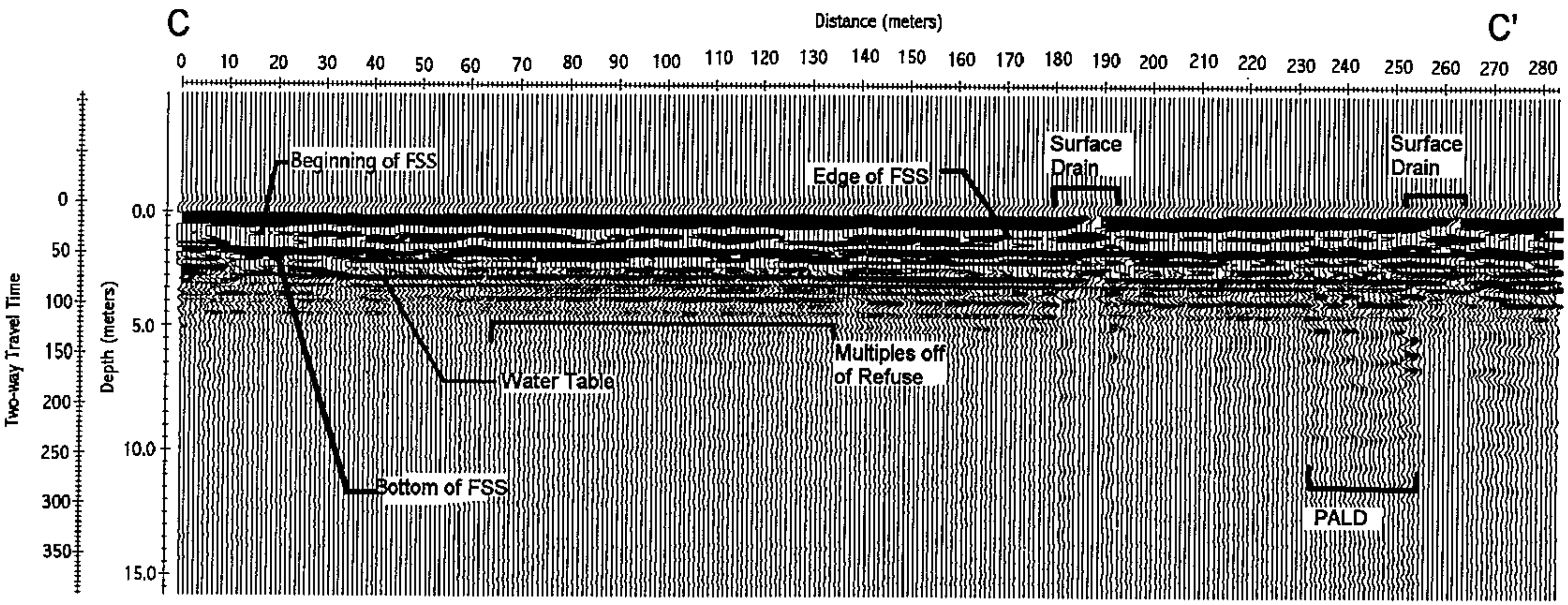

Figure 6 Interpreted GPR cross-section from C to C' (see Figure 2 for location).

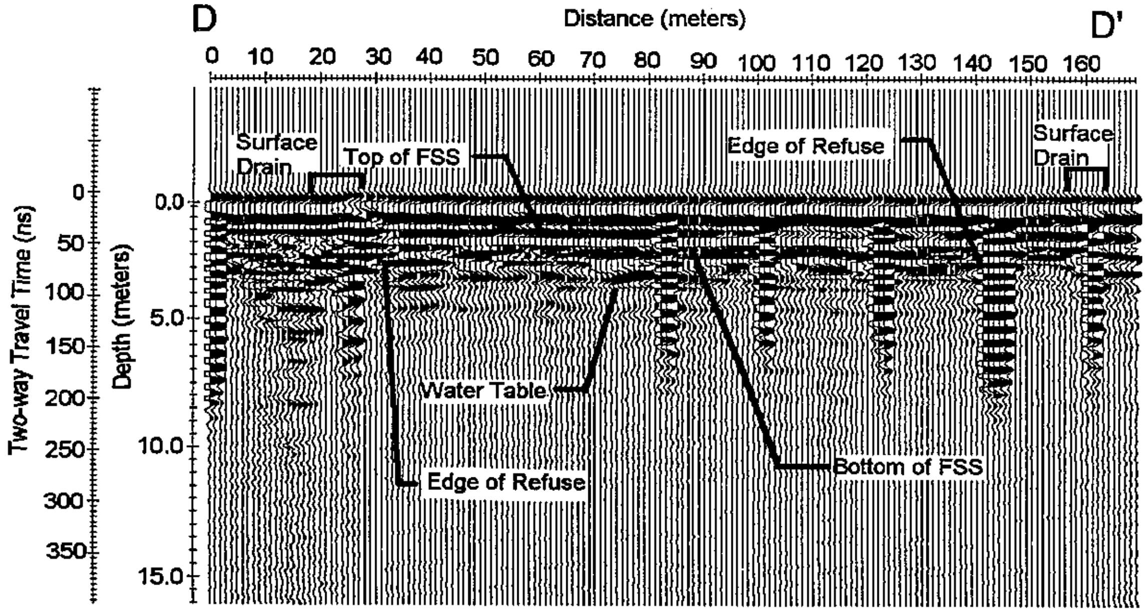

Figure 7 Interpreted GPR cross-section from D to D' (see Figure 2 for locations).

The neutron moisture gauge readings were made at an interval of approximately two weeks between June and November, 1997. Measurements were made at 30 cm intervals to a depth of 3.35 meters. The FSS layer lies at a depth of approximately 1.2 meters beneath the ground surface at MW7 and is approximately 1.2 meters thick. Reworked spoil was used as a final cover material, due to the lack of topsoil in the area. Figure 8 shows the wettest and driest profiles that were measured. In the spoil layer above the FSS, a large range in moisture contents occur due to the storm infiltration of rain water and extended periods of evapotranspiration. An analysis of the measured moisture contents indicated that fluctuations are virtually nonexistent within the FSS layer. Table 2 shows that variances calculated for the measured depths in the FSS layer are an order of magnitude smaller than for the layers in the overlying spoil. The greatest variance is associated with measurements made immediately below the surface, where the effects of infiltration and evapotranspiration are much more pronounced. In contrast, the change in soil moisture content within the FSS is so low that it is within the range of errors associated with the neutron gauge. Therefore, the FSS is probably functioning to prevent infiltration into the pyritic refuse.

Variations in the moisture content of the refuse were detected by the neutron gauge. The seasonal raising and lowering of the water table associated with these moisture changes must be a result of lateral inflows and outflows, unless there are local leakages in the FSS cap.

Conclusions

The results of the ground penetrating radar investigations at Site No. 1087 verify that the FSS was laid down as a continuous layer and currently exists at approximately 1.3 meters below the ground surface. The FSS has variable thickness, but is at least one meter thick on average. Buried pyritic refuse underlies the FSS at a depth of nearly three meters. The FSS layer reaches beyond the extent of the refuse in the area of the two survey lines, indicating that none of the refuse is left exposed to recharge from the surface. The horizontal electrical resistivity profiles indicate that a vertical contact between a high and a low resistivity material

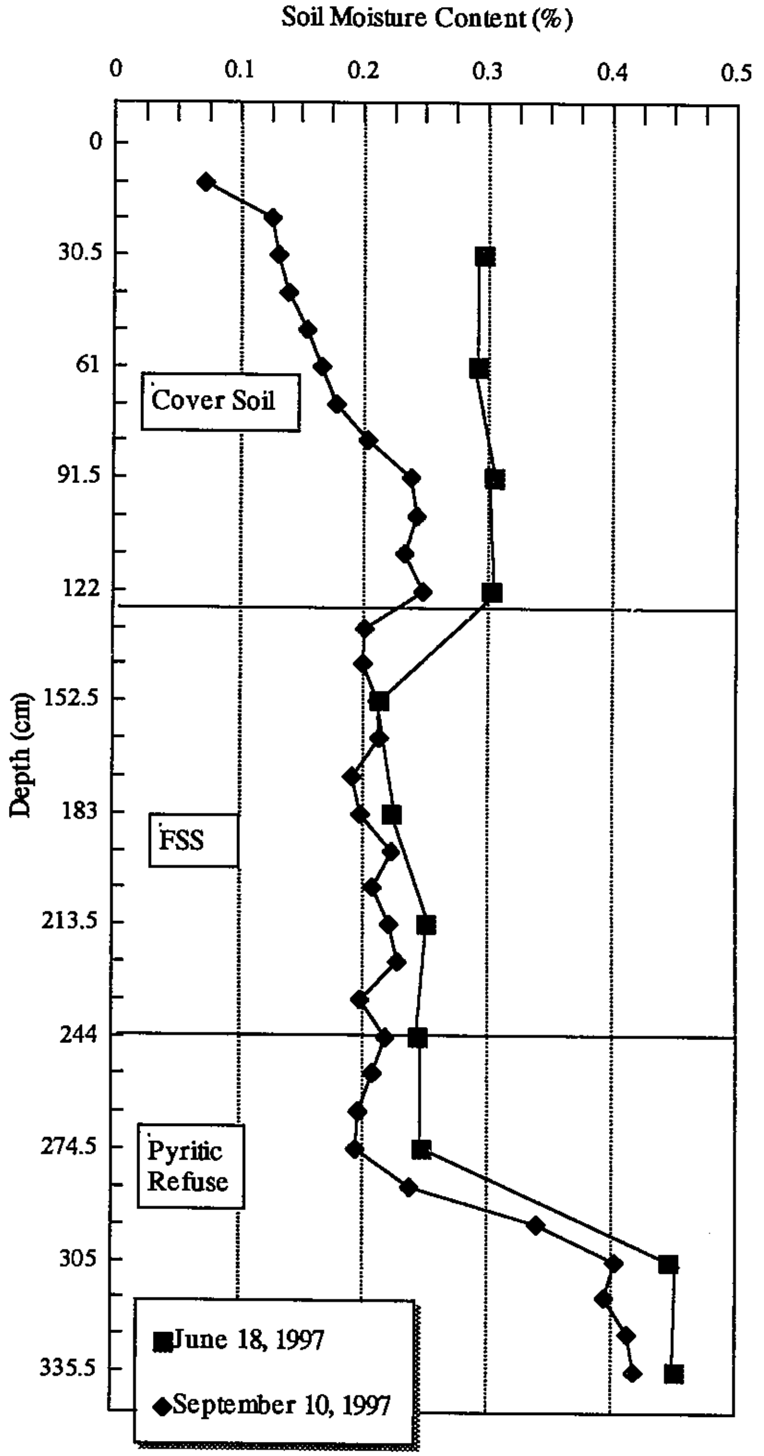

Figure 8 Soil moisture profiles for the wettest (June 18, 1997) and driest (September 10, 1997) measured days during the study period. Note that the range of values in the FSS is much lower than in the overlying soil layer.

Table 2 Statistical analysis of neutron moisture gauge data

	Depth (cm)	Min. θ	Max. θ	Avg. θ	Variance in θ
Cover soil	30.5	0.1259	0.2968	0.1790	3.12E-03
	61	0.1540	0.3005	0.2081	2.62E-03
	91.5	0.2317	0.3086	0.2618	8.25E-04
	122	0.2435	0.3095	0.2724	4.15E-04
FSS	152.5	0.2022	0.2244	0.2122	3.46E-05
	183	0.1918	0.2229	0.2075	9.09E-05
	213.5	0.2113	0.2515	0.2270	1.58E-04
	244	0.2040	0.2443	0.2230	1.15E-04
Pyritic Refuse	274.5	0.1790	0.2472	0.2173	5.65E-04
	305	0.3900	0.4475	0.4148	3.00E-04
	335.5	0.4152	0.4522	0.4307	1.25E-02

exists in the vicinity of the refuse deposit. By comparing resistivity data with GPR data from the same area, it can be seen that the vertical contact is approximately 15 meters beyond the extent of the refuse deposit. This would may be indicative of a plume of acidic groundwater that extends beyond the edge of the refuse but still beneath the FSS layer. Repeated neutron moisture gauge readings show that little or no changes occur in the moisture content in the FSS layer, indicating that the FSS is preventing infiltrated rain water from percolating into the pyritic refuse.

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