MAPPING A PALEOCHANNEL SYSTEM CONTROLLING CONTAMINANT MIGRATION AT A WOOD-TREATING FACILITY USING ELECTROMAGNETICS

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Abstract

A wood-treating facility, located near Sheridan, Oregon, has been the focus of a groundwater contamination investigation. A geophysical survey was conducted in April, 2000. Objectives of this geophysical survey included detection and delineation of coarse-grained channel-type deposits in the unconsolidated section above bedrock. These deposits constitute preferential pathways for groundwater flow, and hence contaminant migration through the subsurface. Contaminants consist of petroleum-based creosote and pentachlorophenol (PCP) solutions. Dissolved phases of these contaminants comprise the groundwater contamination expected, and the delineation of the extent of this contamination was the overall objective of the investigation. In addition, dense non-aqueous phase liquid (DNAPL) contamination was expected in accumulations in topographic lows of the bedrock surface near the source area. Therefore, another objective of the geophysical survey was to investigate any topography on the bedrock surface.

In this preliminary phase of the investigation, geophysical methods used consisted of transient electromagnetic (TEM) soundings, a resistivity sounding, and an extensive terrain conductivity (EM-31) survey. Due to the extensive sources of cultural interference at the site (buildings, fences, railroad tracks, etc.), the geophysical survey was limited. Three profiles of 20-m central-loop TEM soundings were obtained, along with some isolated soundings where it was thought that cultural interference could be avoided. TEM approximate depth sections clearly identify the paleochannel system in cross-section. Correlation with terrain conductivity response provides confidence in the terrain conductivity interpretation of the paleochannel system in areas where only that type of data were obtained. One resistivity sounding, and an adjacent TEM sounding, were modeled simultaneously to the same layered-earth in order to test the idea of improving the resolution of the interpretation. This proved valuable in delineating an electrical equivalent of the working model of the hydrogeological section based on nearby drilling information.

Introduction

A geophysical survey was employed at an active wood-treating facility, located near Sheridan, Oregon (Figure 1). This facility consists of above ground storage tanks, a retort area and drip pad, a non-contact cooling water spray pond, a laboratory, treated wood storage areas, white wood storage areas, and a shop. The treatment plant conditions and pressure-treats wood products with preservatives to prolong product life. Wood products treated include lumber, poles, pilings, posts, ties, crossarms, and occasionally plywood. Treating operations began in 1966, and preservatives include petroleum-based creosote and pentachlorophenol (PCP) solutions.

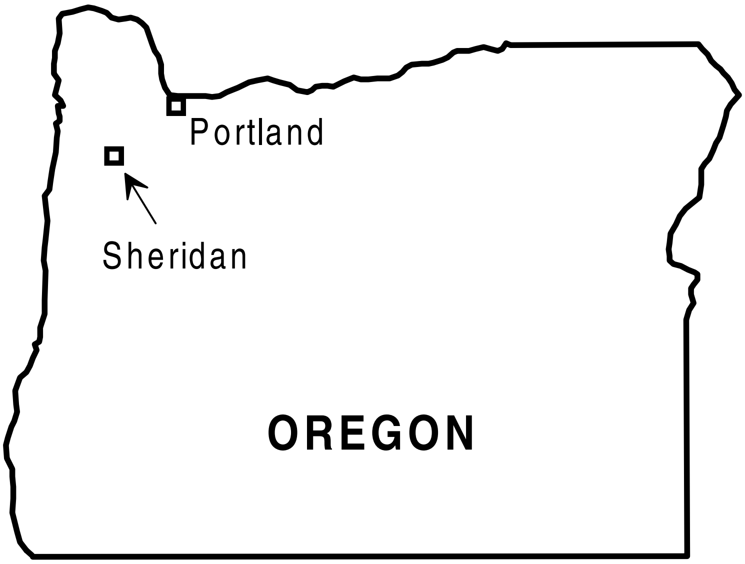


Figure 1. Location map showing the site location near Sheridan, Oregon.

A groundwater contamination investigation was initiated by the United States Environmental Protection Agency's Environmental Response Team Center (U.S. EPA/ERTC) who were assisted by Lockheed Martin's Response, Engineering, and Analytical Contract (REAC). As part of this investigation, a geophysical survey was conducted in April, 2000. Objectives of the geophysical survey included detection and delineation of coarse-grained channel-type deposits in the alluvial unconsolidated sediments above bedrock. These deposits constitute preferential pathways for groundwater flow, and hence contaminant migration through the subsurface. Dissolved phases of the wood preservatives comprise the groundwater contamination expected, and the delineation of the extent of this contamination was the overall objective of the investigation.

In addition, dense non-aqueous phase liquid (DNAPL) contamination was expected in accumulations within topographic lows of the bedrock surface near the source area. Therefore, another objective of the geophysical survey was to investigate bedrock topography.

Site Geology and Hydrogeology

The site is underlain by up to 5 feet of fill, consisting of silty clay to gravelly clay, and road gravel. Below the fill is alluvial material (Quaternary alluvium and lower river terrace deposits) from approximately 10 to 20 feet thick. This alluvium consists of yellowish brown and/or gray deposits of fine-grained mottled or silty clay and/or clayey silt in the upper portion, and sandy silt and silty sand which may grade to poorly sorted, silty sand and sandy gravel in the lower portion. Underlying the alluvium is a greenish gray, fine grained, and moderately to very hard siltstone of the Tertiary Yamhill Formation.

Groundwater in the alluvium is semiconfined or confined by the overlying fine-grained silty clay alluvium, with the water table typically from 4 to 20 feet below ground surface. Groundwater in the saturated portions of the underlying siltstone is confined or semi-confined, with potentiometric levels typically ranging from 2 to 8 feet below ground surface. The siltstone is massive and is not thought to exhibit significant primary or secondary permeability.

Methodology

In this investigation, geophysical methods used consisted of transient electromagnetic (TEM) soundings, a resistivity sounding, and an extensive terrain conductivity (Geonics EM-31) survey. Due to the extensive sources of cultural interference at the site (buildings, fences, railroad tracks, etc.), the geophysical survey was limited. A brief description of these methods is presented in the following sections.

Transient Electromagnetic (TEM) Sounding

The TEM sounding method consists of transmitting current through a large square transmitting loop on the ground surface, abruptly terminating this current, and then sampling the resulting scattered magnetic field at the center of the loop. This scattered magnetic field arises due to eddy currents flowing within conductive strata below the loop. These currents decay with time according to the conductivity (resistivity) and geometry of the strata. A receiver coil is placed at the center of the transmitting loop, in the central-loop configuration, to detect and record the magnetic field resulting from these eddy currents. The acquired data can be modeled to produce thicknesses and conductivities (resistivities) of subsurface layers.

As shown in Figure 2, three profiles of 20-m central-loop TEM soundings were obtained, along with some isolated soundings where it was thought that cultural interference could be avoided. A total of 39 TEM soundings were collected, including one 40-m sounding as indicated at the western end of the site in Figure 2. The Geonics TEM-47 transmitter was used along with a Geonics PROTEM receiver. Data were obtained using the 285, 75, and 30 Hertz (Hz) base frequencies at each sounding location. Since the objective of the survey was to investigate the shallow alluvial section, modeling and analysis was confined to the 285 Hz dataset. The other base frequencies were used only qualitatively to indicate data quality (presence or absence of metallic interference).

TEM data were processed by initially producing apparent resistivity versus sample time using the so-called all time (ramp-corrected) apparent resistivity formulation; these values were calculated using the computer program RAMPRES2 (Sandberg, 1990). Approximate depth versus resistivity was calculated using a relationship between apparent resistivity and diffusion depth (Meju, 1998). This approximation produces a relatively sharp upper boundary for a couductive layer at depth, and a diffuse lower boundary of that layer. To improve the depth resolution, one-dimensional layered-earth modeling was employed using a non-linear least squares iterative algorithm to fit field data with theoretical data calculated from specific layered earth parameters. We used an updated version of the EINVRT program (Sandberg, 1990; 1995) to solve for the thickness and resistivity of each layer in a specified model.

Resolution of layered-earth parameters can be improved by combining TEM and resistivity sounding data obtained at the same location in a simultaneous inverse model (see for example, Sandberg, 1993). This technique was used to model data collected at one location toward the western end of the site (Figure 2).

Variations in resistivity mapped using these soundings are due to lithologic variability within the fluvial depositional system at the site; specifically, bedrock channels and coarse-grained river channel deposits would respond as resistivity highs. The coarser-grained material is higher in resistivity than the finer-grained material, and a greater thickness of sediments yields a higher resistivity from surface measurements. The underlying siltstone is a low resistivity unit, as are fine-grained (clay and silt) alluvial deposits.

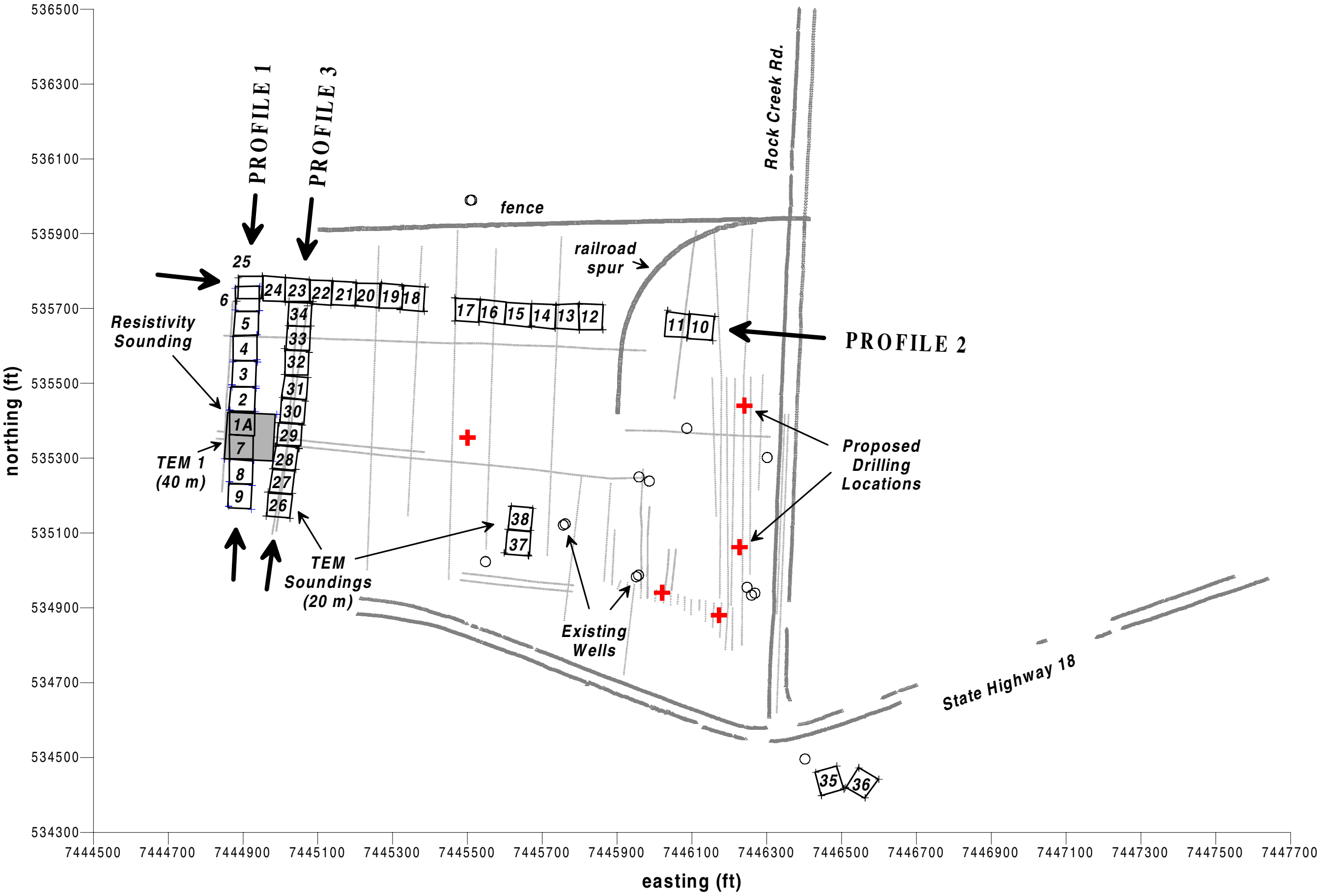


Figure 2. Site map showing locations of the geophysical lines, TEM profiles, and TEM sounding numbers.

Resistivity Sounding

In the electrical resistivity method, electrical current is injected from a transmitter into the ground through a pair of current electrodes (usually steel stakes), and the distribution of the resulting electrical potential at the ground surface is mapped by using another pair of electrodes connected to a sensitive voltmeter. For the survey described here, a digital voltmeter was used as a receiver, and a Phoenix IPT-1 geophysical transmitter was used to supply the current. From the magnitude of the current applied and knowing the distances between the respective electrodes, inhomogeneities within the subsurface are inferred because they deflect the current and distort the resulting electrical potentials on the ground surface.

Data were collected using the generalized Schlumberger array where the distance between the potential electrodes is small compared to the distance between the current electrodes. The Schlumberger array is a symmetric four-electrode in-line array in which the voltage at the inner electrodes is measured as a function of the separation of the outer (current) electrodes as this separation is sequentially increased. The unit of electrical resistivity is the ohm-meter (ohm-m). Computer modeling was employed to match resistivity data to a layered-earth model. Software used was an upgraded version of the nonlinear, least-squares simultaneous inversion program EINVRT (after Sandberg, 1990; 1995).

Terrain Conductivity

Terrain conductivity is an electromagnetic method in which a low frequency current is induced to flow into the ground due to a changing magnetic field resulting from current flowing through a transmitting loop antenna or coil at the ground surface. A secondary magnetic field, generated by this current which is channeled through conductive material, is detected by a receiver coil spaced a known distance from the transmitter coil. The strength of the secondary current is proportional to the bulk conductivity of the subsurface beneath the two coils to some given depth, depending on coil spacing and frequency of operation. In the profiling method, the spacing between transmitter and receiver coils is held constant and lateral changes in conductivity are mapped along a set of traverses or across a grid.

The magnetic field detected at the receiver coil is a combination of inphase and out-of-phase components. The out-of-phase or quadrature signal is usually most indicative of lithologic or water quality changes while the inphase signal is most indicative of buried metallic objects. Lateral variations of electrical conductivity can be due to conductive contaminant plumes in the groundwater, shallow clay and silt horizons, disturbed or filled areas such as buried trenches, and buried metallic objects such as drums, tanks, or utility lines.

Anomalies expected from a confined conductive target, such as a metal drum, buried cable, pipe, or narrow conductive bedrock fracture (narrower than the coil separation of the instrument), are U-shaped for a loop-loop (slingram-type) vertical dipole (horizontal configuration) electromagnetic system such as the Geonics EM-31. The distance between inflection points on the inside of this U-shape is equal to the coil separation of the instrument and has little to do with the target geometry.

In this survey, EM-31 data were obtained along most available roadways through the site as shown in Figure 2, using a station spacing of 2.5 feet. Differential GPS was used for locational control mostly at 50-foot intervals along profiles, and intervening data locations were interpolated between these points.

The interpretation of terrain conductivity data most often involves plotting and contouring instrument readings taken over a geophysical grid. Conductivity profiles or cross-sections can be used for interpreting lateral contrasts.

Results

EM-31 Results

EM31 data were obtained on 41 profiles as shown in Figure 2 by the grey-scale lines, and in Figure 6 by the plus (+) symbols alligned along profiles in black. EM31 terrain conductivity and inphase data along profiles corresponding to PROFILE 1, PROFILE 2, and PROFILE 3, as indexed in Figure 2, are presented above TEM approximate depth sections in Figures 3, 4, and 5. EM31 terrain conductivity data from all data collection points are contoured and plotted in Figure 6.

TEM Results

TEM soundings were collected at the locations shown in Figure 2, and numbers correspond to individual sounding numbers. There were a total of 39 TEM soundings, 38 of them were 20-meter square transmitter loop soundings, and one was a 40-meter loop, as drawn in Figure 2. In addition, some tests were performed on 10-meter transmitter loops in which transmitter effects contaminated the measurements and were therefore not included in this paper.

TEM approximate depth sections are plotted in Figures 3, 4, and 5, corresponding to PROFILE 1, PROFILE 2, and PROFILE 3, respectively. Apparent resistivity values shown are “all time” values as

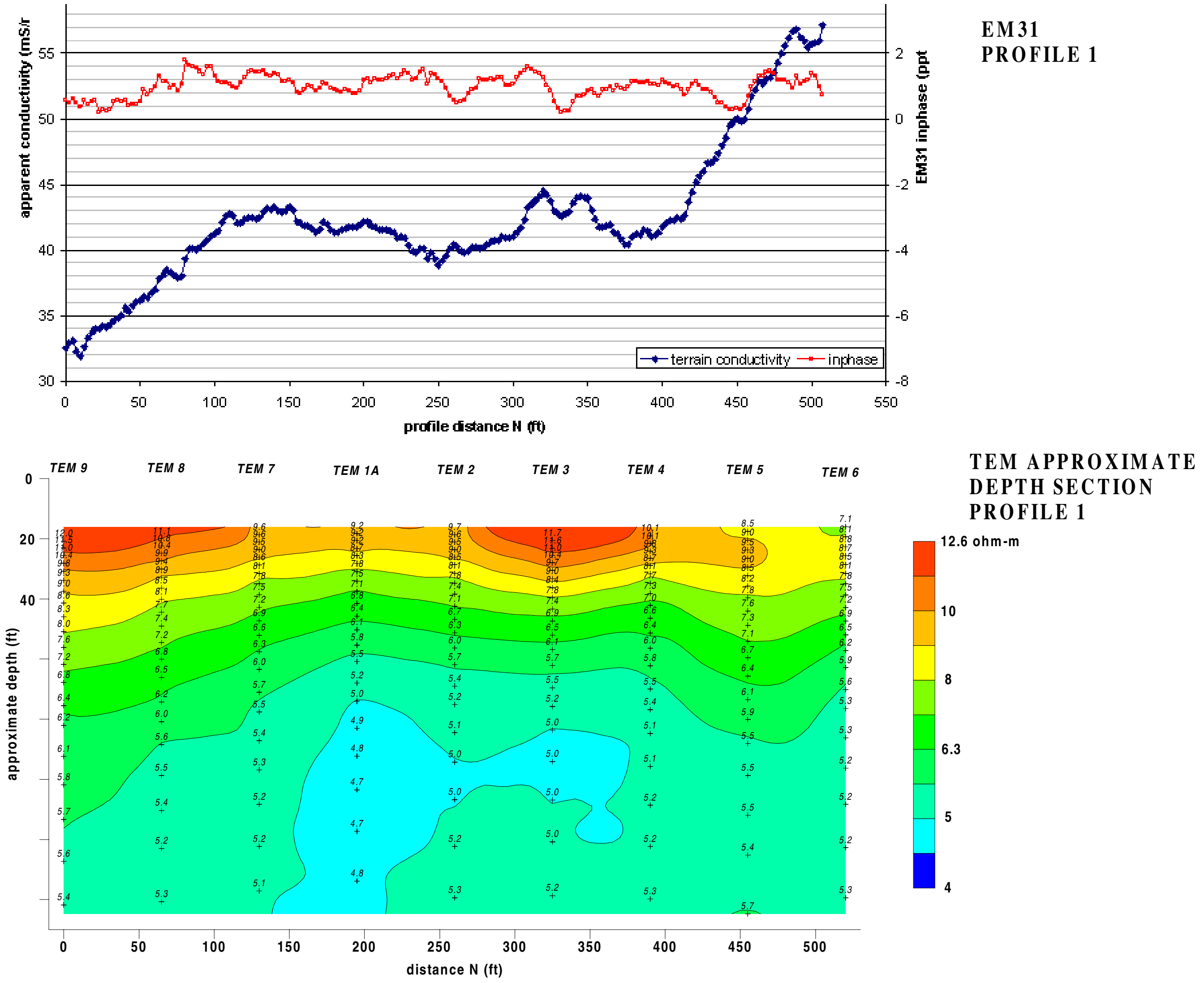


Figure 3. EM-31 data plot and TEM approximate depth versus resistivity section along PROFILE 1.

described in the methods section. The depths that these values are posted at are from the diffusion depth relation described in the methods section. TEM apparent resistivity curves are presented along with model-derived data for TEM 1A and TEM 11 in Figures 7 and 8, respectively. Modeling data-fit curves show apparent resistivities from field data versus model-derived data using the asymptotic apparent resistivity definition as described in Sandberg (1990). Note, for example, that field data calculated using the two definitions can be compared in the two graphs in Figure 8; the asymptotic apparent resistivities in the modeling data fit plot are a bit higher in magnitude at early time than the “all time” values.

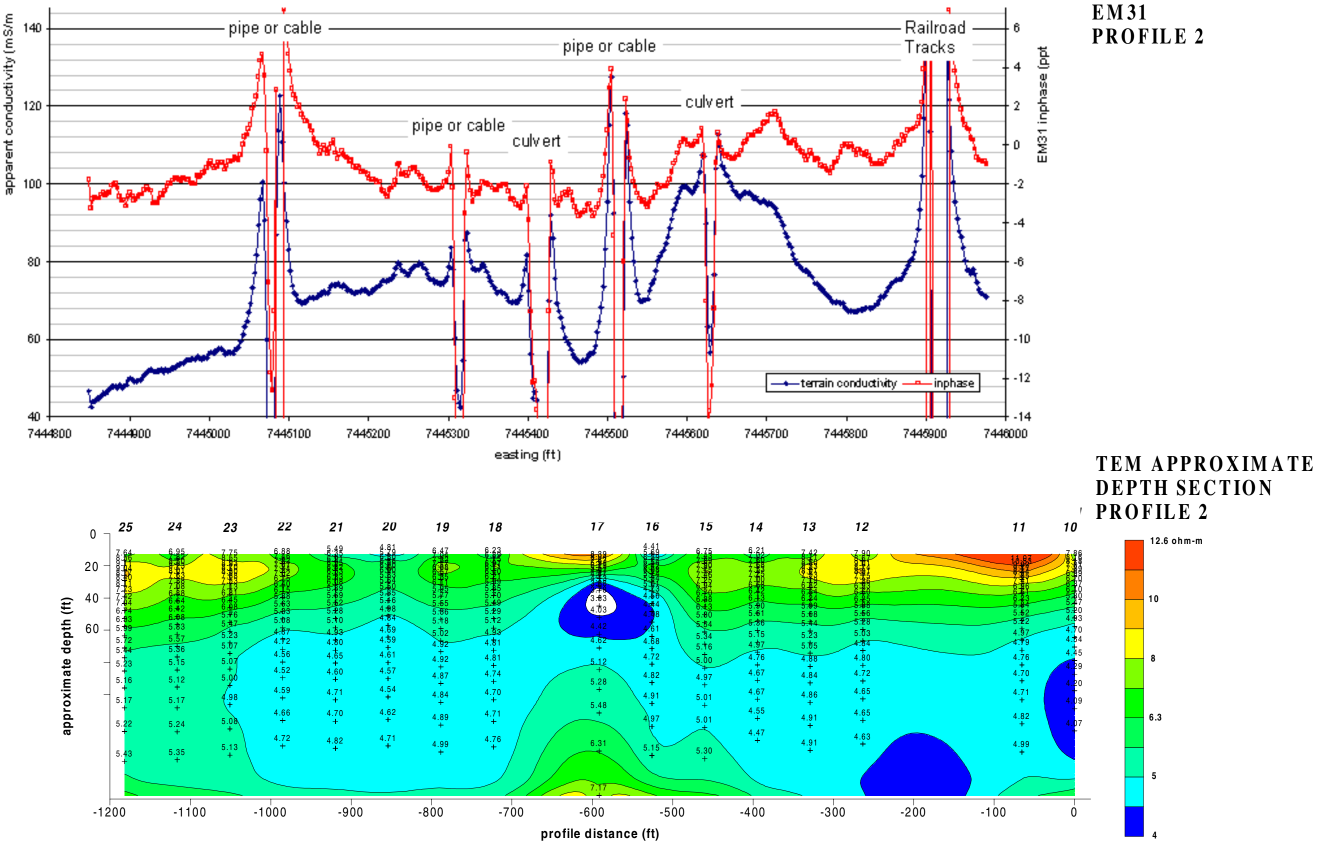


Figure 4. EM-31 data plot and TEM approximate depth versus resistivity section along PROFILE 2.

Resistivity Sounding Results

One resistivity sounding was obtained at the western end of the site, as shown in Figure 2, next to the loop corner of TEM1A. Since these data were collected using a digital voltmeter (a Fluke 79III multimeter) with an input impedance (R_i) of approximately 1MΩ, the observed voltages were scaled using the measured ground impedance R_g to obtain the corrected voltage, V_{corr}

$$V_{corr} = V_{observed}(R_g+R_i)/R_i$$

where $V_{observed}$ is the voltage recorded from the digital voltmeter. This scaling relation is necessary since the ground resistance is of the same magnitude as the input impedance of the voltmeter. Therefore, an effective voltage division occurs in which the observed voltage is only that voltage drop over the imput impedance of the voltmeter, not the voltage drop between the receiver electrodes, which is the required geophysical measurement.

Corrected voltages were converted to apparent resistivity and plotted versus electrode separations forming a standard Schlumberger sounding curve, shown in Figure 7. Model-derived data are also plotted on the same graph showing data fit.

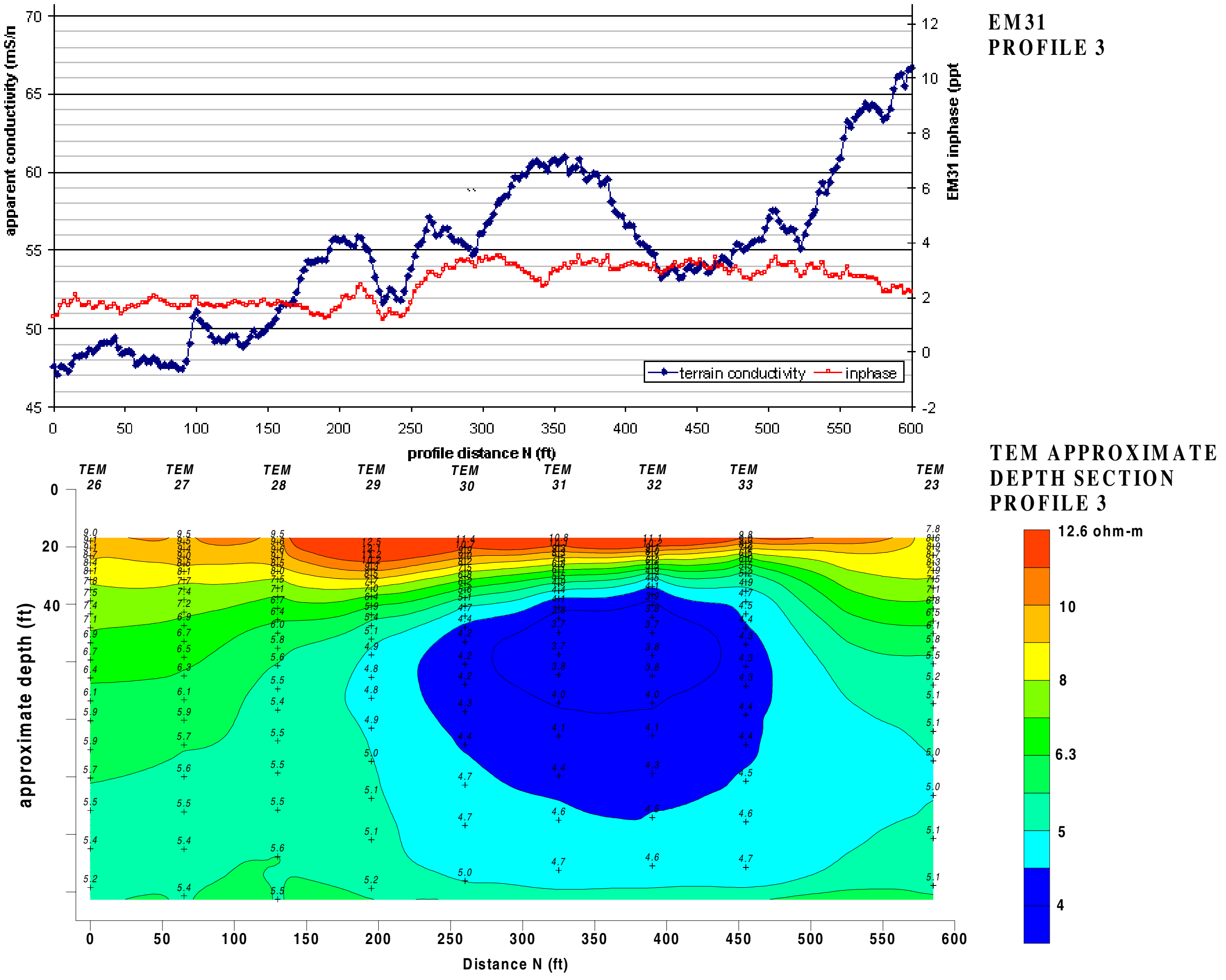


Figure 5. EM-31 data plot and TEM approximate depth versus resistivity section along PROFILE 3.

Discussion of Results

Two objectives of the geophysical survey included: 1) detection and delineation of coarse-grained channel-type deposits in the unconsolidated section above bedrock, and 2) to investigate any topography on the bedrock surface. The following discussion will address both of these objectives.

Delineation of Channel-Type Deposits

The TEM sounding method applied along profiles was chosen to provide lateral and vertical delineation of fluvial channel-type deposits as candidates for preferential pathways for migration of groundwater contamination beneath the site. However, the existance of extensive cultural interference sources (fences, pipelines, railroad tracks, metallic structures, etc.) prevented broad application of the method. Therefore, the small-source EM profiling method (EM-31) was chosen to extend the bulk lithological mapping to areas unable to be mapped by the TEM sounding method. In order to justify this, we needed to confirm the approach. Both TEM and EM-31 data are compared along PROFILE 1, PROFILE 2, and PROFILE 3 in Figures 3, 4, and 5. A discussion of these profiles follows.

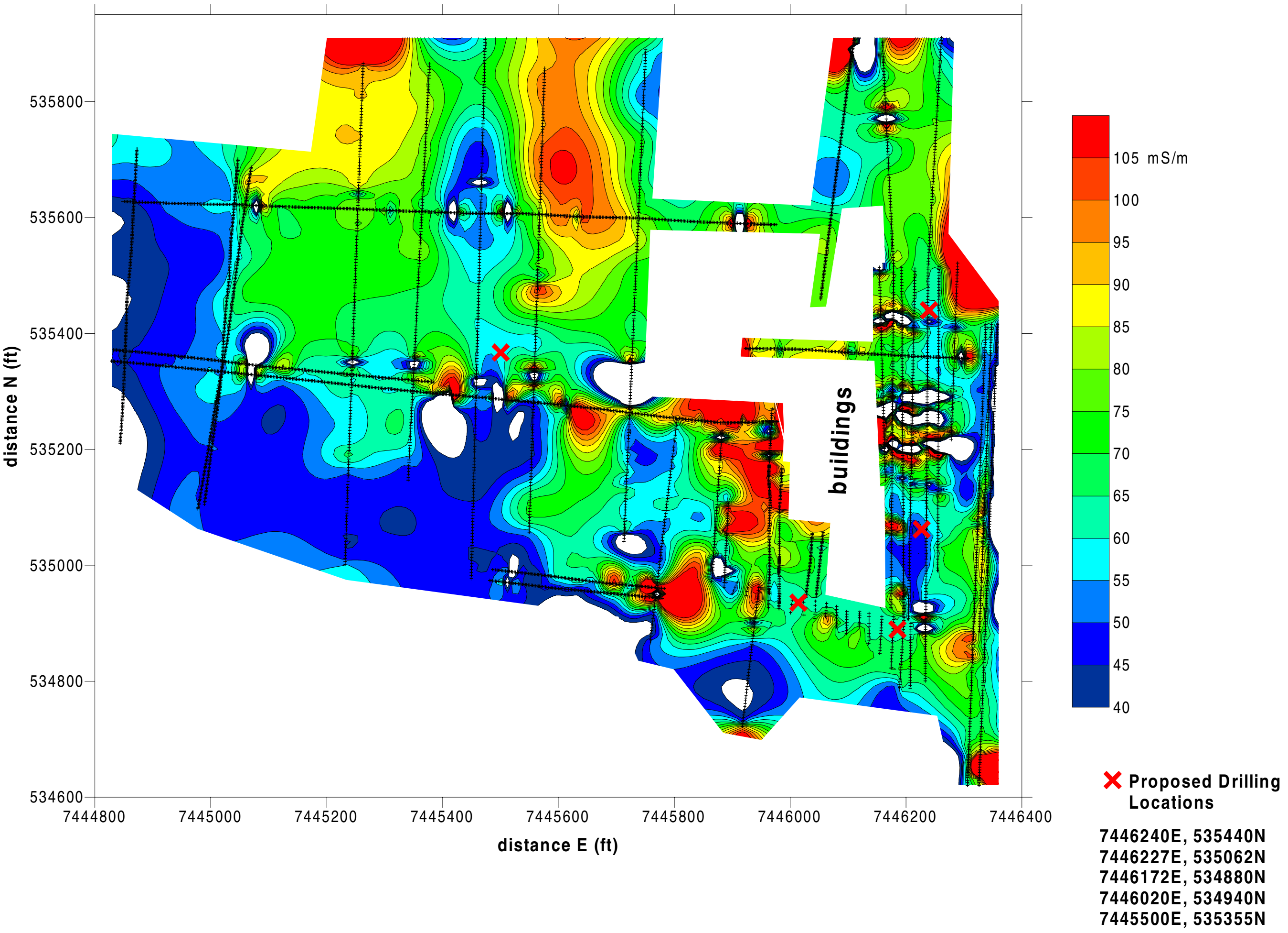


Figure 6. EM-31 terrain conductivity contour plot.

Figure 3 shows low resistivity (greater than 10 ohm-m) at the south end of the profile (around 0N through 100N) for shallow depths in the TEM approximate depth section. This is interpreted to be a region of coarse-grained channel-type deposits in the alluvial section. EM-31 terrain conductivity along this profile shows a low apparent conductivity along this interval. Another shallow high-resistivity interval occurs from 280N to 400N along PROFILE 1. Correspondingly, a terrain conductivity high occurs in the middle of this interval, but the overall region of the curve is depressed. This could be interpreted as a channel deposit where the groundwater is high in total dissolved solids (TDS). Therefore, this profile shows good correlation between TEM and EM-31 response.

Figure 4 again shows TEM and EM31 data along a similar traverse, PROFILE 2, but note that these data are slightly offset (by as much as 130 feet) as shown in Figure 2. Field notes indicated steel culverts at 7445410E and 7445625E, and railroad tracks at 7445915E, mapped in Figure 2 as the railroad spur. Pipe responses occur at three other positions along the EM-31 traverse as shown in Figure 4. TEM 17 was noted in the field notes as being contaminated by cultural noise, likely from the buried pipe indicated in the EM-31 data a short distance away (Figure 4). The extended spacing from TEM17 to TEM 18 occurred to avoid this metallic interference. Therefore, the anomalous response in the approximate depth section below TEM 17 should be ignored as due to metallic interference. Surficial high resistivity, indicative of channel deposits occurs at the west end of the profile (-1200 to –1000 on the plot), correlating with a region of low apparent conductivity in the EM-31 response. Another surficial high resistivity (channel deposit) occurs at the east end of the profile (from –200 to the east end at TEM 10). Again, this correlates with a broad apparent conductivity low in the EM-31 data (except for the railroad track response).

PROFILE 3, as shown in Figure 5, has no correlation between TEM and EM-31 response. This lack of correlation is due to cultural interference in the TEM response. During data collection, a buried pipeline was discovered running along the length of the traverse beneath the log piles. Therefore, the TEM data along this profile is responding to the pipe and not the lithology. EM-31 response along the traverse is more likely responding to the geological/hydrogeological system. Terrain conductivity lows at the south end of the traverse, and from 410 to 540 along the traverse likely correspond to channel deposits. These can be correlated to those from the parallel PROFILE 1, yielding an east-northeast trend of channels here.

Based on the correlation between TEM and EM-31 response in PROFILE 1 and PROFILE 2, there is confidence that mapping the remainder of the site with EM-31 should yield differential lithology resulting from the paleochannel system response. Figure 6 shows a contour map of terrain conductivity from all EM-31 data obtained at the Taylor Lumber site. Terrain conductivity lows are thought to result from coarse-grained paleochannel deposits. Also shown in Figure 6 are proposed drilling locations based on the analysis of these data. Proposed drill sites were also selected to sample paleochannels at their southern extent, downgradient from the drip-pad source areas, and also from the main treatment area.

Topography of the Bedrock Surface

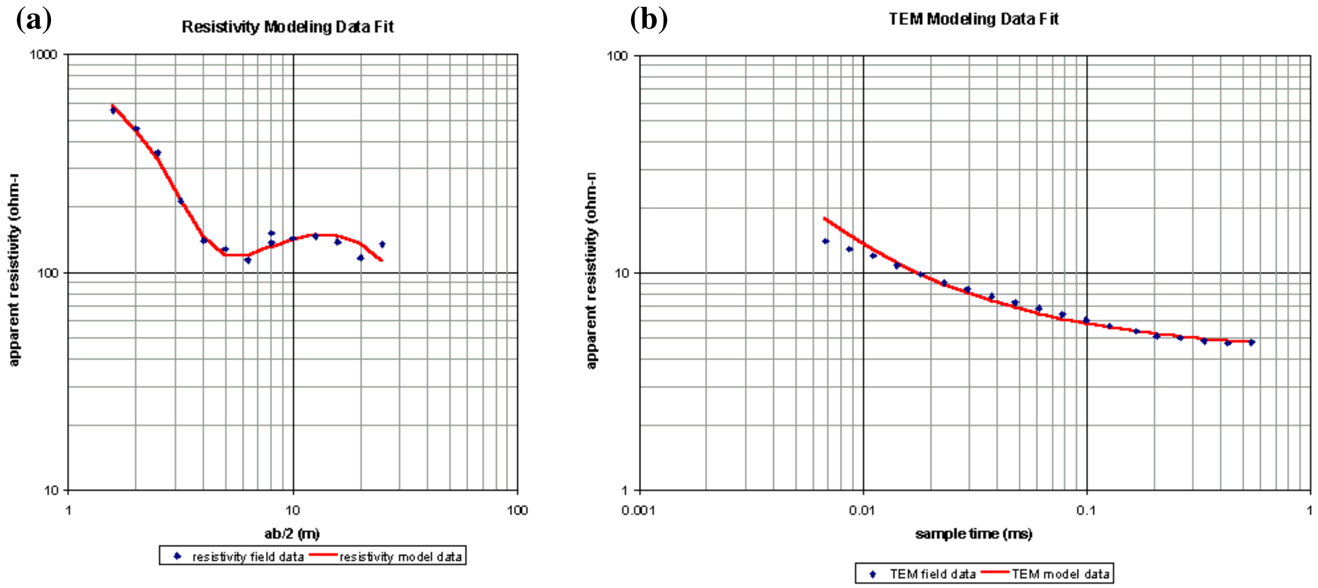
Bedrock was reported to dip east to north-east with approximately 4 feet of elevation change over 1000 horizontal feet, based on drilling information. Modeled bedrock depth, based on TEM modeling is about 2 feet depth change over 1200 feet, dipping toward the northeast, as derived from TEM 1A and TEM 11 modeling as shown in the next sections. This is consistent with the drilling information, noting that elevations were not available for the ground surface near these two soundings.

Simultaneous Inverse Modeling – Resistivity and TEM 1A

Simultaneous inverse modeling of the resistivity sounding and TEM 1A produced the results shown in Figure 7. An interpretation of the model is that the high-resistivity layers correspond to coarse-grained material, and the low-resistivity layers correspond to fine-grained material. The high resistivity unit shown as layer 3 of the model correlates to the gravelly unit above the bedrock surface noted in the drilling logs of several wells. The bottom layer (layer 4 of the model) correlates to the siltstone bedrock unit. Bedrock is modeled at (summing all layer thicknesses, 1.12 + 0.64 + 2.02 m = 3.9 m) 12.8 feet depth. Note the well-constrained confidence intervals for all parameters which indicates high resolution resulting from this simultaneous modeling.

Inverse Modeling – TEM 11

Figure 8 shows the results from the inversion of data from TEM 11. The siltstone bedrock is interpreted to be the low-resistivity bottom layer in the model (layer 3). Therefore bedrock depth is modeled at (3.48 + 1.01 = 4.49 m) 14.7 feet depth. However, resolution is not as high as for the simultaneous modeling of TEM 1A and the resistivity sounding. Parameter confidence intervals for the model, shown in Figure 8, show relatively tight control except for a very high confidence interval for the modeled layer 2 thickness. Therefore, the depth to bedrock is not well constrained here.



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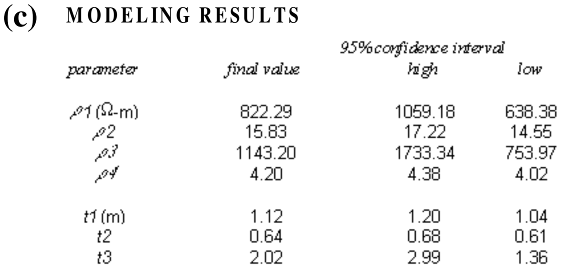


MODELING RESULTS

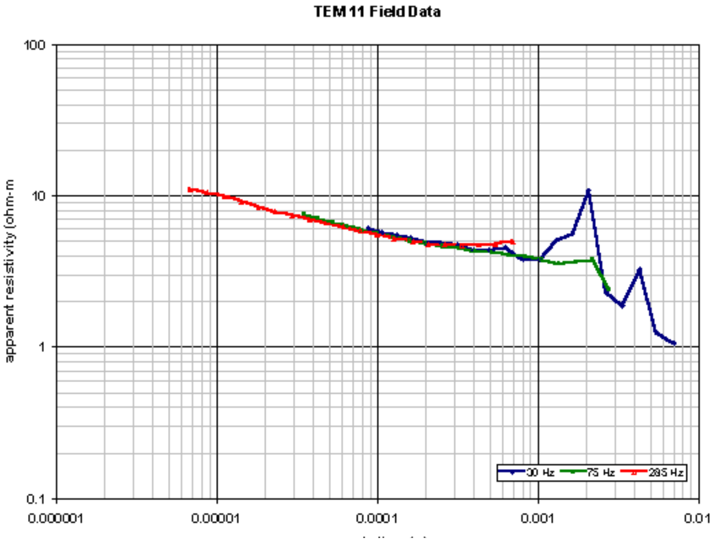
parameter	*final value*	*95% confidence interval* *high*	*low*
ρ_1 (Ω-m)	822.29	1059.18	638.38
ρ_2	15.83	17.22	14.55
ρ_3	1143.20	1733.34	753.97
ρ_4	4.20	4.38	4.02
t_1 (m)	1.12	1.20	1.04
t_2	0.64	0.68	0.61
t_3	2.02	2.99	1.36

Figure 7. Simultaneous inverse modeling results for the resistivity sounding and TEM1A. Data fits are shown (a) for the resistivity data, and (b) for the TEM data. TEM values are late-time asymptotic apparent resistivities. (c) Model layer parameters for the 4-layer model showing high and low bounds of a 95% confidence interval for each parameter indicating resolution.

Conclusions

TEM approximate depth sections clearly identified the paleochannel system in cross-section. Correlation with terrain conductivity response provided confidence in the terrain conductivity interpretation of the paleochannel system in areas where only that type of data were obtained. One resistivity sounding was collected near one of the TEM soundings in order to test the idea of improving the resolution of the electrical section interpretation. This proved valuable in delineating an electrical equivalent of the working model of the hydrogeological section based on drilling information.

A total of 5 locations were recommended for drilling which are based on the down-gradient location of interpreted channel-type deposits in the alluvial section. The positions of these drill sites and gps coordinates are indicated in Figure 6.



		95%confidence interval	
parameter	*final value*	*high*	*low*
$\rho 1$ (Ω-m)	64.85	74.41	56.51
$\rho 2$	10.69	22.00	5.20
$\rho 3$	3.93	3.99	3.88
$t1$ (m)	3.48	4.88	2.49
$t2$	1.01	3382.24	0.0003019

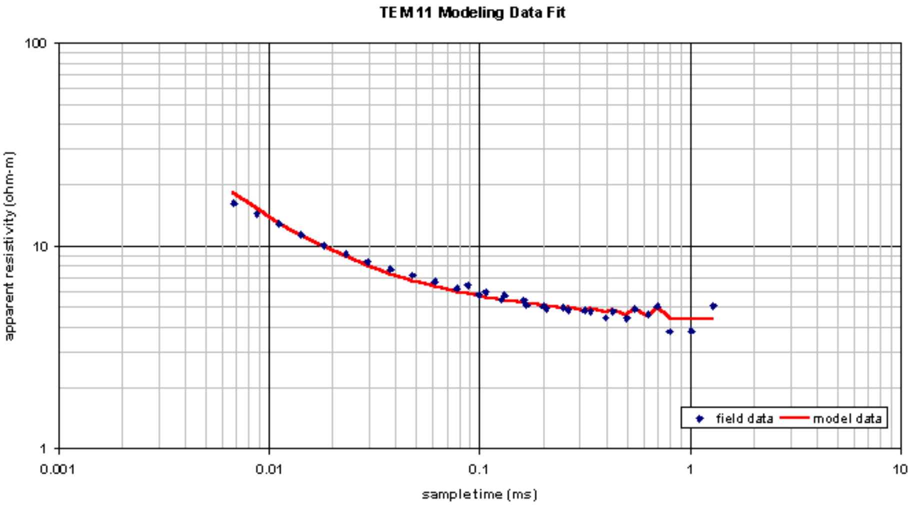


Figure 8. TEM 11 modeling results. (a) Field data values using "all time" apparent resistivity, (b) modeling results using late time asymptotic apparent resistivity, and (c) the resulting layered-earth parameters and 95% confidence intervals.

References

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