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4	3d-hrr-volume-buildup-resistive.avi	(multimedia digital-video)
5	3d-hrr-volume-down.avi	(multimedia digital-video)
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1.0 EXECUTIVE SUMMARY

HydroGEOPHYSICS contribution to the Vadose Zone Transport Field Study (VZTFS) was to perform surface high resolution resistivity (HRR) measurements and electrical measurements on the 32 existing steel casings. Emphasis was placed on the non-invasive capability of HRR (i.e. surface measurements) as opposed to borehole casing measurements. Measurements of both types were made before any injections were made as well as bracketing the fourth injection. Nearly 26,000 data points were acquired during the study. Summary presentations of the processed data are included in this report. As a result of this effort the following observations and conclusions have been made.

1. HRR technology works at the Sisson and Lu site and should work at any other hydrogeologically similar location within the general area.

2. The presence of the 32, 18-meter-long, steel-well casings interfered with the normal mode of data acquisition, but time-differencing the data removed nearly all casing effects and allowed diagnostic information to be determined.

3. HRR has the capability of shallow soil and sediment characterization in the Hanford formation.

4. The mode of application of HRR was too limited (focused too shallowly) to allow proper detection of the injected water column due to surface restrictions (cordoned radiological control areas).

5. HRR confirmed and mapped the presence of an electrically resistive “flushed” zone at the base of the injection well (at or above the top of the water column).

6. A new (or modified) algorithm (based on previous work) was developed for processing casing potential measurements in well clusters.

7. Processed casing measurements showed a surprisingly good correlation between potential differences and neutron-based soil moisture content.

8. Unlike cross-borehole methods, HRR and single-casing measurements can be cost effectively scaled up to cover large areas.

2.0 INTRODUCTION

As part of the Batelle Pacific Northwest National Laboratory's (PNNL) Vadose Zone Transport Field Study (VZTFS), hydroGEOPHYSICS performed surface high resolution and casing electrical resistivity geophysical surveys. The surveys were completed at various times before, during, and after two of the five completed injections. The exact timing is discussed later. Data acquisition was completed during two periods: May 24th through 31st and June 19th through 26th. The initial period was performed to establish a background data set prior to any injection. The second period spanned the fourth injection.

Nineteen surface data sets and two casing data sets were acquired during the two site visitations. Most of the data sets were acquired during the second visit, when the data acquisition system was programmed to make scans approximately every two hours.

All measurements were made at the Sisson and Lu injection test site (herein referred to as the Site). The Site was established nearly twenty years ago in the 200 Area within the Hanford Site. Survey efforts were centered on the 32-well study area previously defined. A single, two-dimensional grid was laid out for geophysical surveying and centered on the original injection well. Measurements were also made between the bottom of the new injection well and the tops of the 32 steel casings.

PNNL project manager was Mr. Glendon W. Gee, Senior Staff Scientist. On-site personnel for PNNL were Mr. Todd Caldwell and Mr. Jason Kidd. Mr. Gee also visited the site at various times to help coordinate field and logistical concerns.

hydroGEOPHYSICS personnel who completed the field data acquisition portion of the survey were Mr. Marc Levitt, Geological Engineer; Mr. Robert McGill, Project Engineer; and Dr. James B. Fink, President of hydroGEOPHYSICS. Subsequent processing was performed on-site and in the Tucson office by Mr. John Gurney and Mr. Marc Levitt; hydroGEOPHYSICS personnel.

2.1 Objective of Investigation

The objective of the survey was to characterize the dynamic subsurface hydrogeology of the Site by acquiring high resolution electrical resistivity (HRR) data on the ground surface and using the existing 32 steel well casings. Additionally, volumetric estimations of detected injection water were desired as well as any detectable preferred infiltration pathways.

2.2 Site Location

The U. S. Department of Energy's (DOE) Hanford Site is located approximately twenty miles northwest of the town of Richland, Washington. The Site location and background description are adequately discussed elsewhere. Access to the Site was by all-weather paved roads and a short dirt road. The surrounding area was relatively flat and fairly densely covered with sagebrush. Remote electrode locations were placed well away from the cordoned-off radiological hazard areas and accessed by walking through the sagebrush.

2.3 Survey Area & Logistics

From a geophysical standpoint, the Site is readily accessible and posed few logistical problems in acquiring data. Some logistical problems were encountered mostly during the initial visit. Due to time over-runs from other researchers, our measurement period was shifted into the Memorial Day weekend when there was little support available. The most serious problem encountered was the constancy of the electrical power source due to fuel shortages. It impeded progress but didn't stop it.

2.4 Grid Layout

Figure 1 (see page 5) is a plan map showing the location of the HRR 3-D grid, well casings, and associated features.

We numbered our grid so that the origin is in the southwest corner and all electrodes have positive numbers. We chose a combination letter-number system to label the electrodes in the field; e.g. A1 through J0. The letters refer to columns and the numbers to rows. We have avoided subsequent use of those labels to minimize confusion with the well nomenclature. In this report we refer to the electrode locations by their numeric grid location; e.g. (0,0) and (18,18), which represent A1 and J0, respectively. For example, the original injection well is at the center of the grid (9,9). The coordinates are metric.

Figure 1 shows the locations of the 32 steel casings, 8 or 9 additional steel casings within ten meters of the grid, ERT electrodes, all visible PVC casings, tensiometers, and soil borings. The location of a two dimensional HRR line performed across and beyond the grid is also indicated. The presence of such a large number of steel casings posed a problem in how to compensate for their effect on the electrical measurements. This is discussed in detail later.

No brushing was necessary for electrode layout and installation. Electrode spacing (2 meters) was measured using two steel metric measuring tapes. HydroGEOPHYSICS' fabricated stainless-steel electrodes were used for the surface measurements. Each electrode was approximately 0.46 meters (18 inches) long and driven into the ground

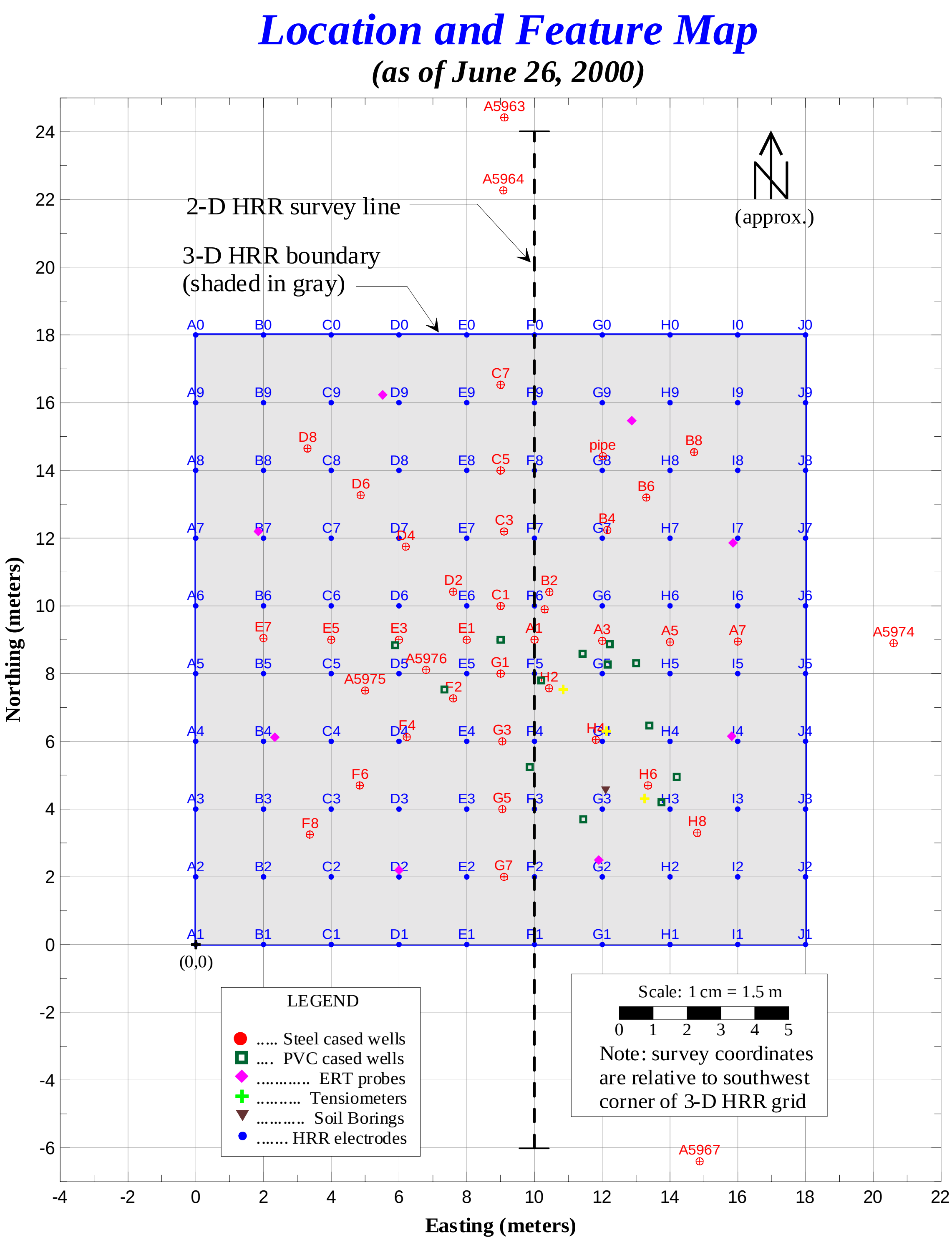

Figure 1 - Location and Feature Map

full length with a small scoop of soil removed around the tops of the electrodes. Each electrode had a pinflag attached to the top for station marking and visibility. Approximately ½ liter of drinking water was poured into the scooped area after electrode emplacement to ensure good electrode-to-ground contact. Because of obvious precipitation between the two periods of data acquisition, no water was added to the electrodes for the second period. This may have caused some problems in data processing that were not noticed immediately during second-period data acquisition.

All electrical measurements were made using either the pole-pole electrode array or some two-electrode variation of the pole-pole array. That is, some of the measurements used the 18 meter (60 feet) long steel casings as electrodes which violates the normal pole-pole array point-source theoretical assumptions. Within the survey grid area, electrode spacing varied from two meters minimum to eighteen meters maximum.

The largest spacing allowed a maximum depth-of-investigation of approximately fifty feet (15 meters), but the responses necessarily include volumetric contributions of material above and below that depth. Data acquired at that depth were very sparse compared to nearer-surface data and, as a result, have not been used in the volume modeling.

2.5 Equipment

The instrument used for the resistivity surveying was an OYO Corp. McOHM-21. The McOHM-21 is a DC-powered electrical resistivity instrument. The McOHM-21 is owned by PNNL and use of the instrument and peripherals was kindly authorized by Mr. Mark Sweeney. HydroGEOPHYSICS also owns an earlier version of the

McOHM-21 and provided additional peripherals for the study. The unit was used in conjunction with OYO scanners and cable sets.

The McOHM-21 has the capability of automatically switching between electrodes without having to physically move the wire connections after initial set-up. Automatic switching saves on physical labor and time, cuts down on human transcription and tracking errors, and better allows the operator to control array logistics. The McOHM-21 has an integral color-display CRT that allows real-time display of the transmitted and received waveforms. Stacking of the received waveforms ranged from 4 to 16. Maximum current output is 200 milliamps. An internal 3.5-inch floppy diskette drive allows for data storage and retrieval. Each data set acquired was labeled and archived for subsequent processing.

The greatest advantage the McOHM-21 unit has over other similar instruments, is the ability to pre-program a survey and repeat the program without operator intervention.

During the initial visit we used only the instruments and equipment available at the Site. This consisted of the McOHM-21, two electrode scanners, and two 16-electrode cables. Because the grid had 100 electrodes, a total of four cable moves (plus four additional minor moves) were required in order to acquire data for all 100 electrodes. For a static situation this was an inconvenience and time consuming, but did not affect the resultant data.

2.6 Data Acquisition

During the subsequent visit we used the above equipment and provided an additional electrode scanner and four more cables. This enabled us to measure 96 electrodes without time-consuming cable moves. We did not make measurements with the four corner electrodes during the second visit. Since we no longer had to move cables during the second visit, we could program the system to acquire consecutive data-sets when each measuring period was completed. In this manner, we acquired 18 data-sets during the second visit, the majority of which were time contiguous. Figure 2 shows the time-distribution of the individual three-dimensional (3-D) data sets during the second visit. The fourth injection is also indicated. The purpose for making repetitive measurements after the injection was to determine whether or not the dynamics of the downward infiltration would produce observable changes at the surface.

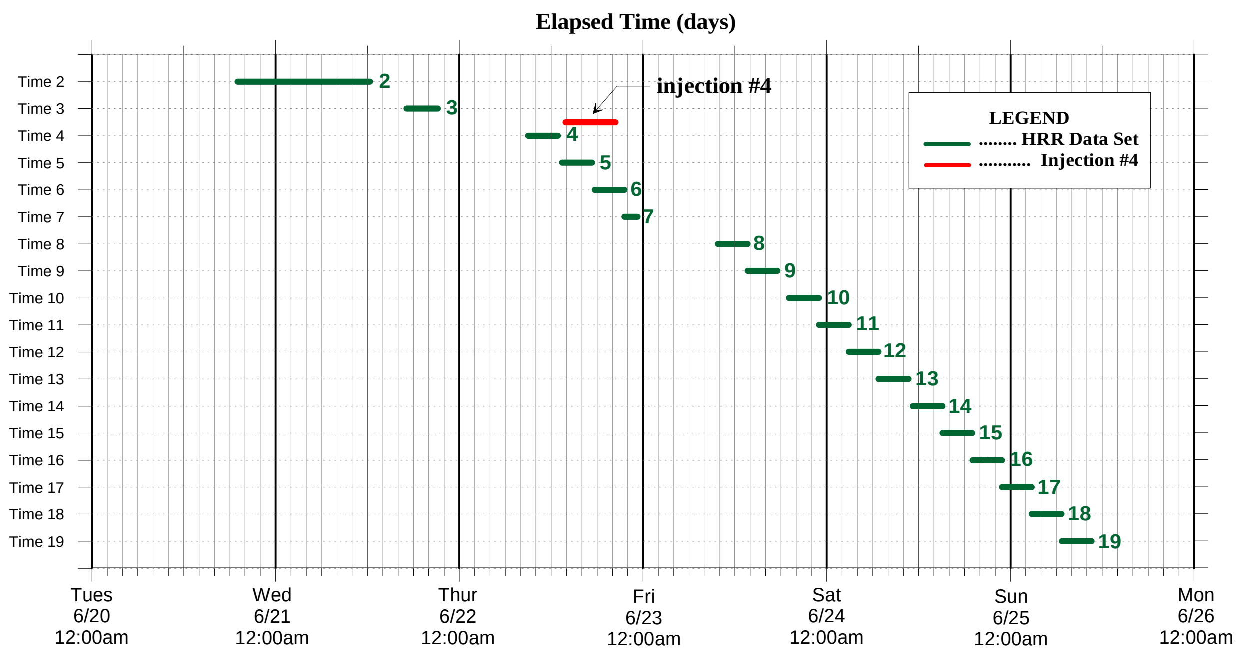

Figure 2 - Time Graph of HRR Data Acquisition Periods

Data for the steel well casings were acquired during separate data runs. We acquired data in two modes: casing-to-casing measurements and bottom-of-injection-well-to-casing measurements. The injection-well-to-casing measurements were made before any injections took place and after the fourth injection. The casing-to-casing measurements were only made during the pre-injection visit and were not repeated.

In addition to the grid and well-casing data, we also acquired data along a line going through the grid oriented north-south. We installed additional electrodes to the north and south of the grid and used selected electrodes within the grid to make up the line. This line was completed in order to obtain background resistivities away from the forest of steel casings.

2.7 Data Processing

All data were processed with hydroGEOPHYSICS' proprietary software package either on-site, in the Richland area, or in the Tucson office.

Twenty-three complete data sets, totaling over 25,793 data points, were acquired during the two site visits. The data are presented in a variety of formats. Data values presented are absolute apparent resistivities, resistivity differences, and simple voltages normalized to current.

For the difference plots, resistivity values for each repeated data point were used from the initial pre-injection survey. These "base line" values were then subtracted from each of the time-based data-sets and difference figures were created. This differencing process was essential for removing the effects of the 32 steel well-casings.

3.0 METHODOLOGY

3.1 Resistivity

The geophysical resistivity method is based on the capacity of earth materials to conduct an electrical current. The concept behind applying the resistivity method is to detect and map changes or distortions in an imposed electrical field due to heterogeneities in the subsurface. Changes in soil texture and moisture content will cause changes in an imposed electric field. Distortions of the electric field can be measured on the ground surface, in boreholes, or with a combination of the two. Resistivity measurements are made with a minimum of four electrodes in contact with the ground. Various electrode arrangements have been used over the decades, most of which involve collinear arrays such as Schlumberger, Wenner, dipole-dipole, three-array, pole-pole (also called "normal" in borehole logging), and many more. Each array shows merit in specific environments and all (ideally) produce useful information.

The data presented in this report have been processed with a proprietary software package that can incorporate topography into the reduction procedures and presents the data in a more physically valid basis. Each resistivity measurement involves an unknown volume of earth material but results in a single value of apparent resistivity. The manner in which the data are presented strongly influences the interpretation (although it shouldn't). It is difficult to represent a volumetric measurement with a point value. Consequently, the HRR method of data presentation accommodates the topography and the volume distribution within the earth based on electrode spacings and locations. We consider the HRR processing method to be a geometrically-constrained inversion.

For sectional plots, the vertical axis is labeled half-space depth, which means the depth at which that particular electrode spacing has a maximum response. The response also includes material above and below that depth.

In the case of 3-D surveys, such as at the Hanford Site, the data can be presented in plan, section, or volume. Depth-based plan maps show the lateral character of the data for a given depth (often referred to as depth slices). Several depth-based plan maps must be viewed to gain a sense of vertical character. On the other hand, volume presentations tend to show the overall character in a qualitative sense, but without the convenience or resolution of specific contours.

The casing-related measurements are the most difficult to present because of the tenuous understanding of the potential distribution along the casings. We have presented the casing data in both plan and volume format.

4.0 RESULTS & INTERPRETATION

4.1 Resistivity Results

Apparent resistivity values range from 150 to 600 ohm-meters. In general, higher resistivity values represent drier soil conditions and-or more coarse-grained media. High resistivity values (unless otherwise indicated) are expressed in warm (red hued) colors. Lower resistivity values (unless otherwise indicated) are shown in cool (blue hued) colors and generally represent an increase in moisture content. Typical values for undisturbed geologic media range from less than ten ohm-meters for clays to tens of ohm-meters for silts and sands, to several hundreds of ohm-meters for very dry alluvium and bedrock.

Because of the presence of the multitude of steel casings, the most meaningful way to evaluate the HRR method is to view the differences between data sets acquired before and after injection. In this way, the effects of the steel casings are minimized and the changes in apparent resistivity are emphasized. Injected ground water, especially saline water, should lower apparent resistivities *in the vicinity of the injection*.

A very interesting result of the injection was the unexpected change of apparent resistivities at the top of the injection. Contrary to the anticipated decrease in apparent resistivity of the soil due to the injection of river water, the observed differences actually increased. Such a change normally would signal problems in data processing or something other than physical changes in the geology. However, because other methods also saw similar changes in the shallowest portion of their data-sets, we are comfortable stating that some physical property change occurred within the sediments as a result of the injections.

During the informal meeting held on August 16th , this subject was raised by the Livermore group. They proposed a change in ionic concentration of the bound or interstitial water or air entrapment. We propose a more simplistic physical flushing of the fine-grained sediments that would retain the bound or interstitial water. We suggest this alternative because the relative changes between the pre-injection data and the post-saline-injection (#3) data show the same character as the pre-injection data and the post-injection (#4) data. We suspect that if the interstitial water were mostly responsible, then the increase in ionic content after injection #3 would produce the anticipated decrease in resistivity that was not observed after injection #4. In other words, both the post-saline injection and the post-river-water-injection produced an increase in apparent resistivity. By physically removing the material that would retain the bound water, i.e. the fines, then the expected changes would correlate better with the observed changes.

4.1.1 Two-dimensional HRR Data

Overall, there is a layered character to the data on all data sets that is best seen in the two-dimensional profile taken during the pre-injection period. Figure 3 (see page 14) shows the 2-D inverted geo-electric section.

The most salient feature of the section is the area of low resistivities evident at surface (the blue zone). These are due to the effects of the casings on the nearby electrode measurements. The closer the electrode spacing for a given measurement, the larger volume contribution a casing has within the immediate vicinity, regardless of casing orientation. Larger electrode spacings show less effect from the casings because of the smaller volume contribution and vertical orientation. The affected portion of the section shows as a down-warping of the contours. To the north and south of the casings the data return to more of a true background response.

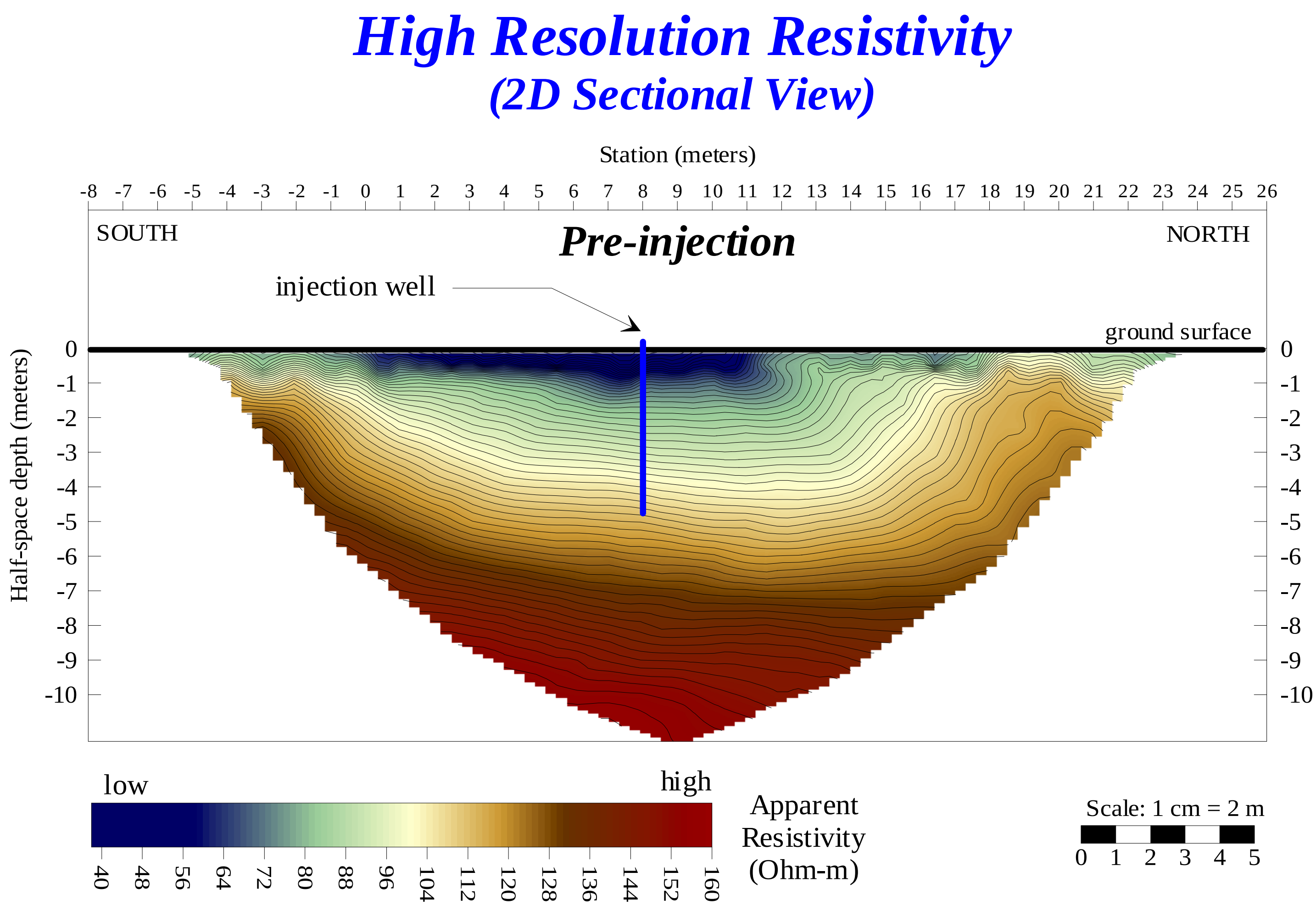

Figure 3 - HRR 2-D Section Plot

A thin layer of relatively low resistivity is indicated at surface in the sectional data. This likely represents the Hanford sands and a minor amount of retained moisture. On average - across the surveyed area - the thickness of this surface layer is less than one meter.

Beneath the surface layer, there is a northerly dip to the contours which most likely represents a gentle northerly dip of the underlying sediments (upper Hanford gravels). The injection depth is within the Hanford gravels. Although an east-west HRR line was not performed, the plan views of the 3-D data suggest a northeasterly dip to the sediments. There are some subtle, but not fully diagnostic, indications of conductive layers occurring below 8 meters. The data suggest the maximum depth-of-investigation is still within the Hanford gravels.

4.1.2 3-D HRR Results – Pre-Injection Data

Figure 4 (see page 16) shows the plan views at various depths of the 3-D data. The pre-injection resistivity data are dominated by the 32 steel casings. Nevertheless, as with the two-dimensional data, the three-dimensional results show a monotonic increase in resistivity with depth. An immediately obvious advantage of the gridded data is that the northerly dip character of the interpreted Hanford gravels (based on the 2-D HRR section) can be seen to be a northeasterly dip that actually changes with depth to become more easterly. Such a change in character of the electrical data suggests hydrologic anisotropy in the sediments, which has also been observed in neutron logging and other geophysical methods.

3-D HRR Depth Levels (plan view)

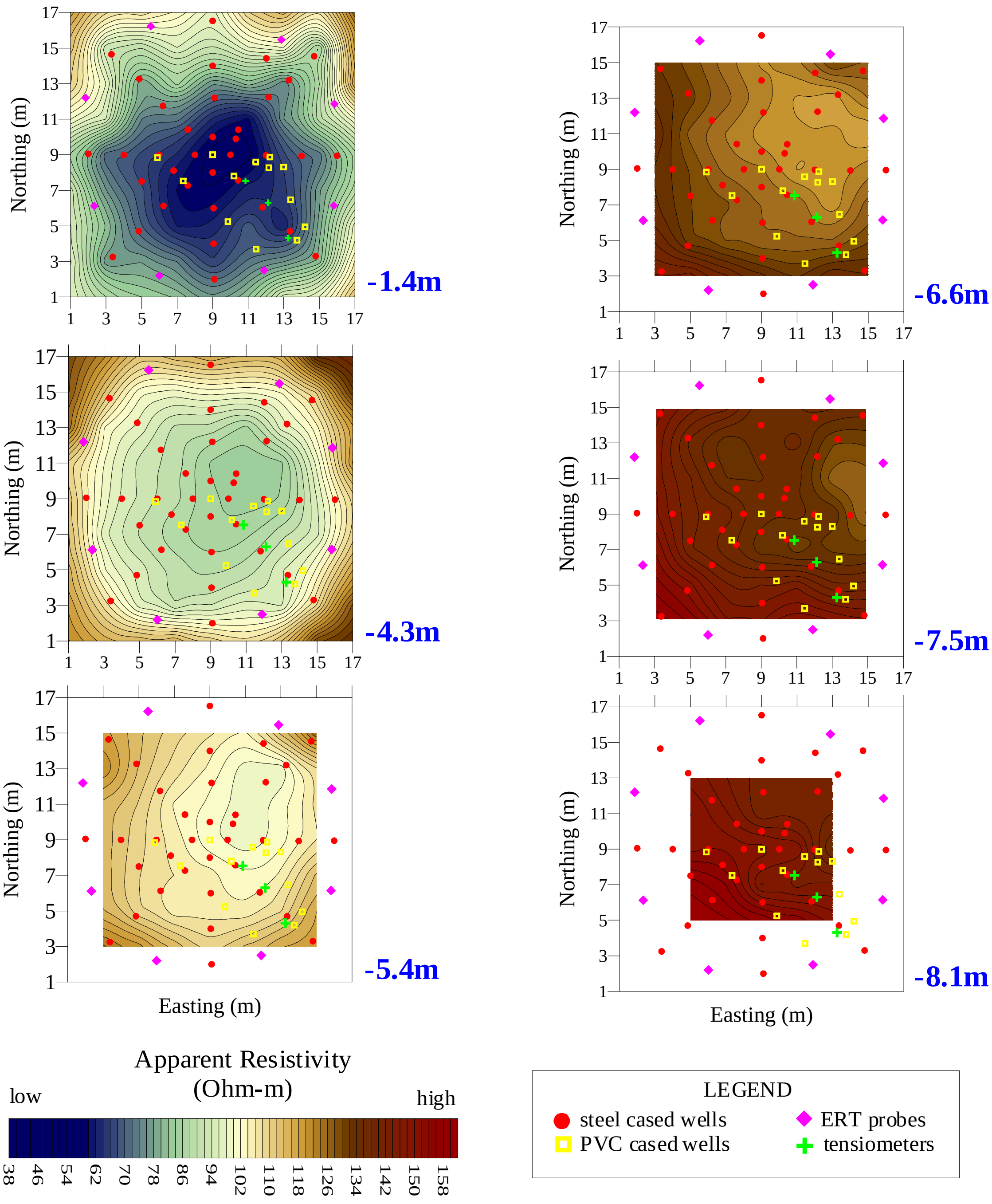

Figure 4 - Plan views of 3-D HRR Depth Levels

4.1.3 3-D HRR Results – Post-Injection Data

To obtain the most useful information from the pre- and post-injection resistivity measurements we selected a specific post-injection data-set and, from it, subtracted the pre-injection data-set. Relative to the pre-injection data-set, a decrease in resistivity would show as a negative value. No change would show as zero, and an increase in resistivity would show as a positive value. The differencing process produced an unusual result in that the changes observed in the data specifically associated with the injection were positive, indicating an increase in resistivity. Confirmation by other methods suggests the observed changes are valid.

Data from other methods indicate that anticipated decreases in resistivity do indeed occur below this resistive "cap", suggesting that the capture and-or retention of injected water is occurring well below the point of injection. These responses are as we would anticipate and agree with intuition. However, the increase in resistivity at the point of injection strongly suggests that injected water was *not* retained in the immediate vicinity of the injection well.

A proposed causal effect for this change was discussed earlier. We infer that tanks similarly leaking into the Hanford gravels may also produce similar changes close to the source. It should be kept in mind that such changes will further complicate the interpretation of any electrical or electromagnetic data.

The most visually appealing presentation of the differenced three-dimensional data is in volume form. Figure 5 (see page 18) shows the inverted surface HRR data. Deviations in the resistivity differences are color-coded. Yellow colors represent negative deviations (lower than background), and purple colors represent positive deviations (higher than background).

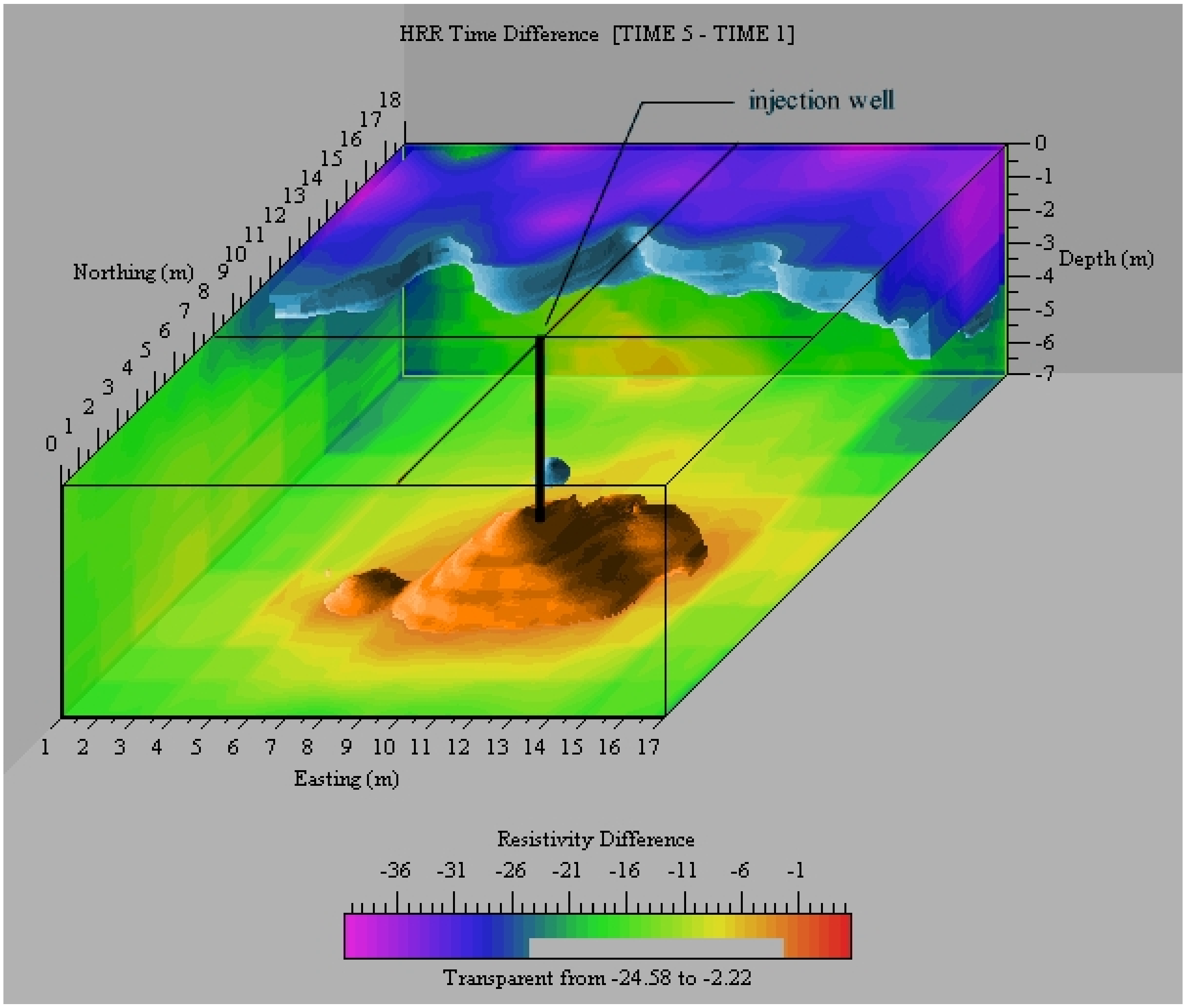

Figure 5 - Volume Plot of Resistivity Measurement Differences

There are two specific features shown in Fig. 5: the volume of resistive material around the injection point (i.e. above the very top of the injected water column) and the relatively conductive, northeasterly dipping, near-surface material. The presence of the near-surface layer is not of any great importance for the purposes of the survey, but, by indicating its presence, it can be included in site characterization information.

It also demonstrates that the HRR inversion process will work through variations in surface characteristics.

Various animated versions of Fig. 5 accompany (electronically) this report. Those versions show movement of vertical and horizontal slices through the volume and reveal additional detail not easily seen in a single snapshot such as Fig. 5.

There is a distinct northeasterly trend to the shape of the resistive feature. Also, because the detected resistive feature does not represent the actual injected water, volume estimates cannot be made. What is clear is that the location and impact of the injection was *detected by a non-invasive method*. Larger electrode spacings would have produced more information at greater depth, and may have coarsely defined the conductive column of water, but grid size was constrained by the presence of the cordoned off radiological hazard to the east.

4.1.4 Casing Measurement Data

Casing measurements consist of simple voltage measurements made at the top of each casing due to an “injected” electrical current at the bottom of the injection well. Plans to make additional measurements with electrodes placed at the bottom of the 32 casings were changed when the schedule was rearranged and we were tasked with drilling holes in all the casings, as well as carrying on with the other measurements.

We simply ran out of time to complete all the planned measurements. This is discussed more under Future Considerations.

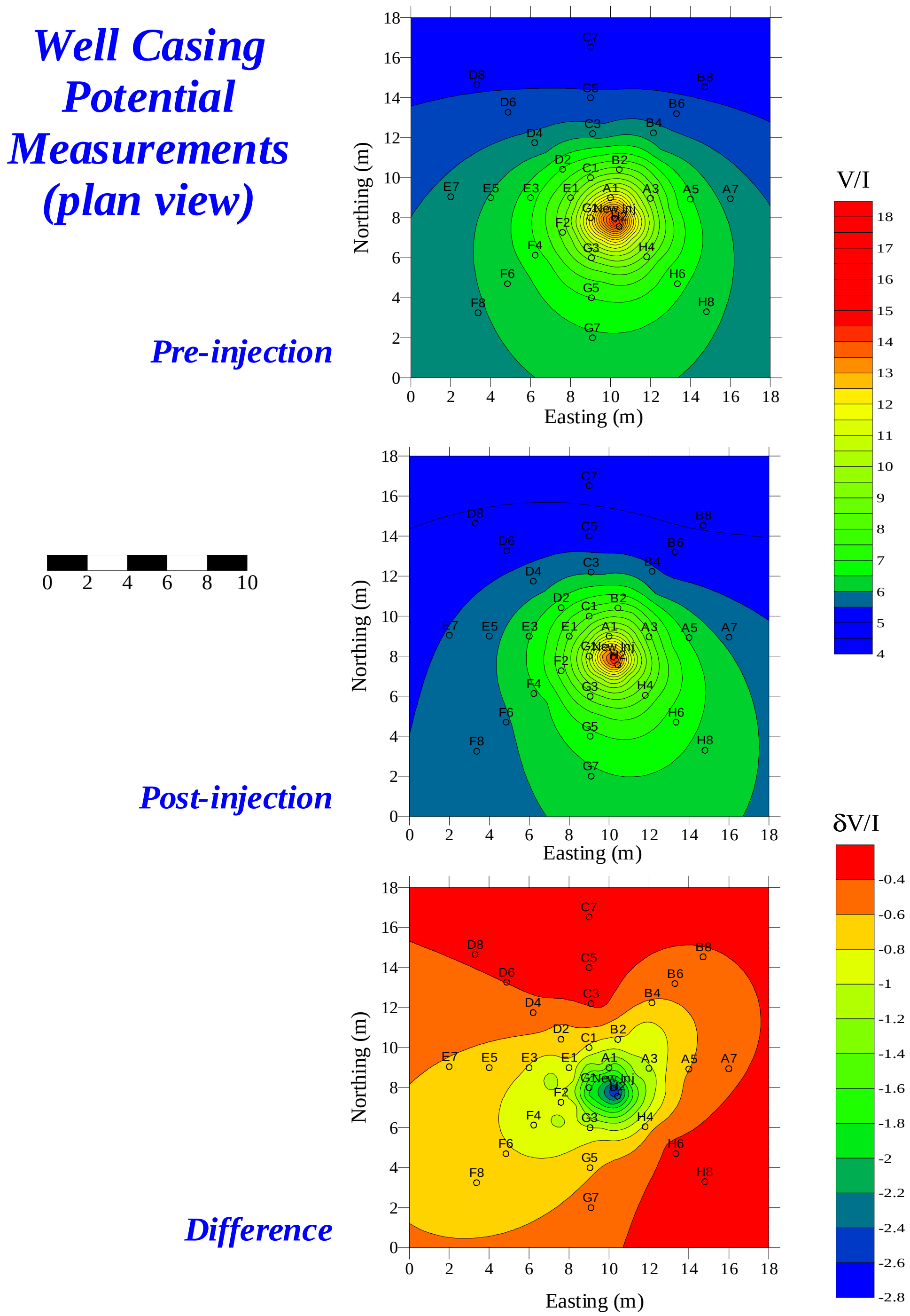

Figure 6 - Plan Views of Pre-, Post- and Difference Well Casing Measurements

Fig. 6 shows the two-dimensional distribution of potentials at each casing for the pre-injection, post-injection, and difference. All three plots on Fig. 6 show a predictable logarithmic decrease in potential as a function of distance from the injection well. As might be expected, the largest changes occur in the immediate vicinity of the injection well. The northeasterly trend seen in the two-dimensional HRR data is repeated in the well-casing differenced data plot.

To obtain three-dimensional information from the casing measurements, we assumed a biased, Poisson distribution of potential along the length of each casing. These distributions were then integrated, normalized, and differenced at one-meter intervals along the length of the casing (actually from 4 meters to the bottom, because of the depth of injection at 4.6 meters). The resultant data are presented in volume form in Figure 7 (see page 22).

Fig. 7 shows that the lateral distribution of potential is not a smooth function of distance from the injection well. The “lobed” character of the volume is determined by the location of the casings and the selected value of potential difference. The size of the volume presented is arbitrary and is controlled only by the selected value of potential difference. Attached (electronic) animations show the changes in volume as a function of the amplitude of the potential difference. The animations show an expanding volume that is controlled by successively decreasing the potential difference at which the volume is determined, and the view angle rotating around the volume.

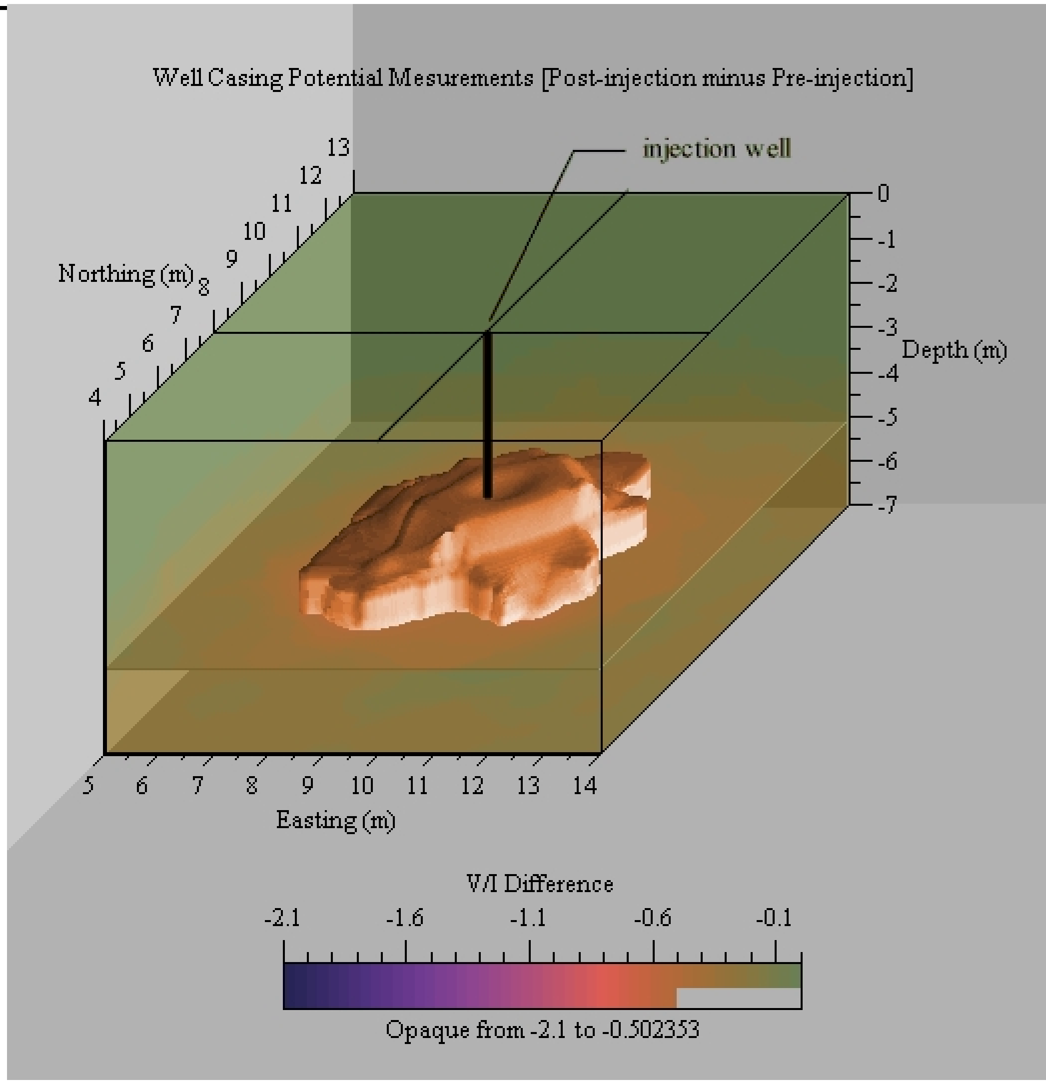

Figure 7 Volume determined from well-casing electrical measurements

Following the well-casing figure is the neutron data acquired during June 9th. Figure 8 is confined to the upper-most portion of the borehole range in order to match the well-casing electrical data (Fig. 7). The similarity between the two volumes is striking.

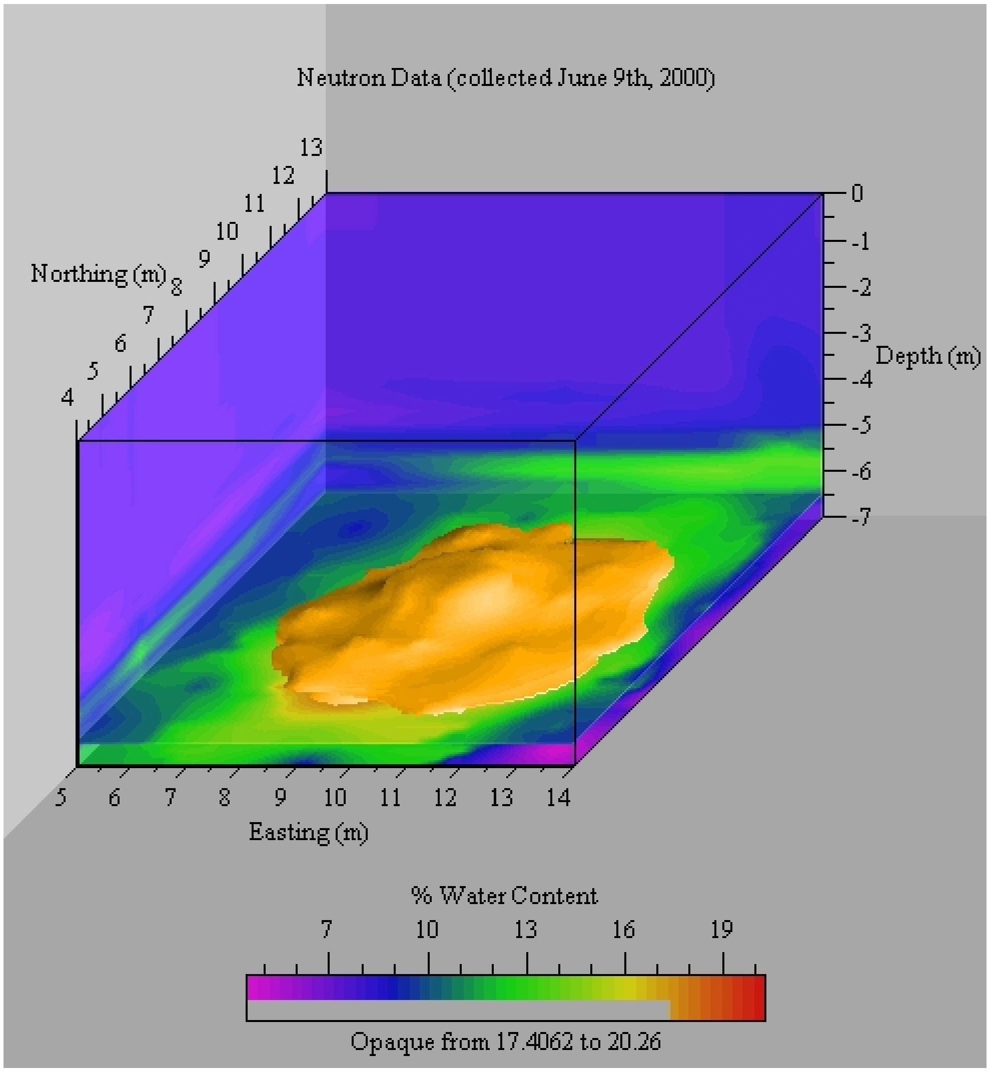

Figure 8 - Neutron data rendered at the 17.4% moisture level

Not only is the general shape similar, but many of the small lobes are comparable to the well-casing data in size, shape, and location. We used the volume determined in the well casing data of 27.4 cubic meters. The equivalent moisture cutoff in the neutron data is 17.4 percent. This results in roughly 4,800 liters of water contained in the volume defined by well-casing measurements. There is a disparity in this comparison because the neutron data (available for this plot) were acquired after 8,000 liters had been injected and the casing potential measurements were taken after 12,000 liters had been injected. We could justify the 4,800 liter calculation by claiming that the previous 7,200 liters had already migrated past that volume of ground.

One significant difference is in the vertical location of the well-casing response. It is vertically displaced upwards approximately one and one-half meters from the neutron data. Frankly, we are surprised that it is that close. We have little control on the vertical location of the electrical response of the well-casings (because the potential is distributed along the length), so, the fact that the well-casing response is as close as it is should be considered more fortuitous rather than a predictable outcome. Additionally, in a blind situation the appropriate data cutoff used to produce a volume figure might not be so close.

Nevertheless, we are pleased with the outcome of the well-casing data.

5.0 SUMMARY & RECOMMENDATIONS

HRR surveying has shown good capability in identifying the injection and mapping the uppermost portion. It is rather disappointing that more of the actual water column was not detected, but, that is partially a result of the tactical decision about the size of the array that was installed as well as the physical constraints.

The detection of a resistive top to the injection was a surprise, but it highlights the need to better understand the physical and chemical characteristics of the Hanford formation. We propose that the injection flushed the immediate area around the injection well of fines and that any chemically altered water, that might still be in the affected volume, would have less influence on the externally observed electrical properties than the absence of the water normally retained by the removed fines. This would produce the observed increase in resistivity values.

It is difficult to compare the HRR results with the neutron gamma results because of the lack of useful electrical data at the depths at which the injected water was retained. However, comparing the well-casing data with the neutron data proved very successful in identifying equivalent volumes of high moisture content.

Differencing data over time has shown to be a powerful approach to site characterization with volume calculations feasible.

HRR surveying met some of the objectives of defining interpreted dynamic hydrogeologic characteristics. In particular, the vertical hydraulic conductivity is unusually high in the Sisson and Lu Site, *at the level of injection*. This conclusion can be determined in several ways: from observation of the rate of injection, from the distribution of water below the point of injection as determined by borehole methods, and by the characteristics of HRR surface measurements. Other methods confirm well-defined strata of differing hydraulic conductivities indicating vertical anisotropy and heterogeneities within the Hanford gravels. This knowledge helps put limits on hydrologic modeling parameters which, in turn, helps reduce uncertainty in the modeling.

6.0 FUTURE CONSIDERATIONS

HRR applications in this environment have the potential for 1.) non-invasive mapping of changes in character of the Hanford sediments, 2.) non-invasive mapping of “footprints” of past leaks, and 3.) non-invasive monitoring of active leakage. The low cost of HRR compared to invasive methods (particularly in the Hanford environment) should be a favorable consideration. Subsequent efforts at non-invasive HRR data acquisition should use larger arrays and more aggressive electrode-grounding.

Surface measurements will always suffer dilution in resolution with increasing depth-of-investigation. However, it is a good screening method for determining appropriate borehole locations for higher resolution borehole geophysical measurements in both areas where there are existing wells and areas where the are no wells. This approach would minimize the cost of drilling and optimize the borehole locations.

One approach that was not attempted, due to time constraints, is surface potential mapping using casings as electrodes. hydroGEOPHYSICS has successfully performed such measurements around individual wells. Considering the success of the well-casing measurements, further tests using well-casings should be considered. In the case of the tank farms, the existing wells (assuming they are accessible) may serve as better line-source electrodes than a 32-well cluster. Also, the data obtained from surface measurements around existing wells will help optimize the location of well clusters for cross-borehole techniques.

This report is based on our best understanding of the electrical properties of earth materials and is limited to the areas where the surveys were performed. We would appreciate any feedback regarding the interpretation based on additional surveying or intrusive characterization. We acknowledge and appreciate the support provided by PNNL personnel.

Respectfully submitted,

James B. Fink, Ph.D., P.E. (geophysical), R.L.S.
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Robert L. McGill,
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