PNNL-29430
WA1ERT-RPT-0001 Rev 0.0

Electrical Resistivity Tomography of the 216-U-5 and 216-U-6 WA-1 Waste Sites

November 2019

TC Johnson
J Thomle
J Robinson
I Demirkanli

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical
Information,
P.O. Box 62, Oak Ridge, TN 37831-0062
www.osti.gov
ph: (865) 576-8401
fox: (865) 576-5728
email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
or (703) 605-6000
email: info@ntis.gov
Online ordering: http://www.ntis.gov

PNNL-29430
WA1ERT-RPT-0001 Rev 0.0

Electrical Resistivity Tomography of the 216-U-5 and 216-U-6 WA-1 Waste Sites

November 2019

TC Johnson
J Thomle
J Robinson
I Demirkanli

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

The subsurface below the 216-U-5 and 216-U-6 sites needs to be characterized as part of the remedial investigation of the 200-WA-1 operable unit at the Hanford Site. Electrical resistivity tomography (ERT) was selected as a first step in this characterization effort to provide information about the three-dimensional distribution of historically disposed waste fluids in the subsurface beneath these sites. ERT does not directly image specific contaminants. However, ERT provides a three-dimensional image of subsurface zones where the bulk electrical conductivity is higher than surrounding background values. Disposed waste fluids can increase the bulk electrical conductivity in the subsurface where they are present by increasing the moisture content and because the high concentration of waste-fluid constituents such as nitrate cause the fluid to have a higher specific conductance than background pore water. Thus, zones of increased bulk electrical conductivity in the subsurface can be interpreted as zones where waste fluids are present.

An ERT survey of the subsurface beneath the 216-U-5 and 216-U-6 sites was conducted to collect ERT data suitable for interpreting the bulk electrical conductivity distribution in the subsurface. Data interpretation was applied using the NQA-1 qualified E4D ERT parallel modelling and inversion code (Johnson 2014). A summary cross-section and interpretation of the 216-U-5 and 216-U-6 ERT is provided in Figure S.1. The ERT image reveals two distinct zones of anomalous bulk conductivity emanating from 216-U-5 and 216-U-6 that merge at a depth of approximately 14 m below the surface and continue to a depth of no more than 26 m below the surface, which is approximately 60 m above the current water table elevation. The image also suggests that lateral transport of waste streams disposed into 216-U-5 and 216-U-6 was limited. These results are consistent with historical groundwater monitoring, which indicated that the disposed waste had not migrated to the water table, possibly due to the relatively low volumes of waste discharge into 216-U-5 and 216-U-6. The ERT information provides a line of evidence supporting this conclusion and can be used to guide the selection of characterization borehole(s) location and depth as needed for additional characterization of the contaminant distribution and properties at these sites. Locations of bulk conductivity anomalies associated with 216-U-5 and 216-U-6 releases are offset approximately 10 m to the west of the locations of 216-U-5 and 216-U-6 as recorded in the Waste Information Data System database.

There are two predominant regions of elevated bulk conductivity in addition to those associated with 216-U-5 and 216-U-6. The first is located beneath Beloit Ave. from approximately 190 to 195 m in elevation. The small region of high conductivity directly beneath Beloit Ave. is likely an artifact resulting from the failure to account for the Beloit Ave. topographic rise in the ERT modeling, as that information was unavailable. Information concerning the precise positioning of the railroad tracks shown was also unavailable, particularly in the vertical dimension. The high conductivity anomaly beneath the assumed railroad track location is likely caused by misplacement of the tracks in the ERT model.

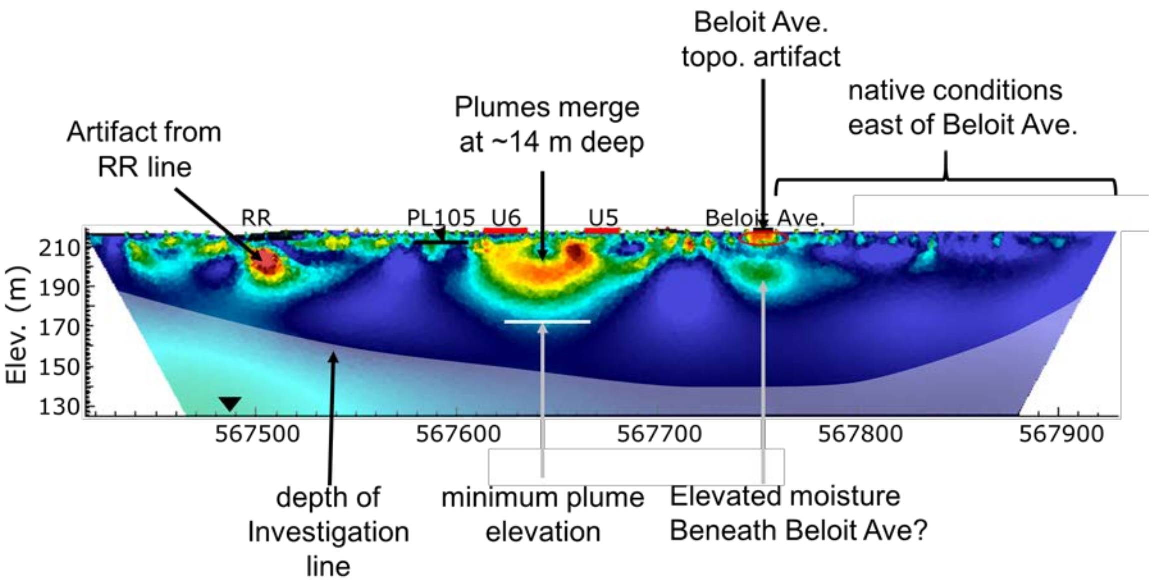

Figure S.1. Summary results of 216-U-5 and 216-U-6 electrical resistivity tomography imaging.

Contents

Figures

1.0 Introduction

The subsurface below the 216-U-5 and 216-U-6 sites needs to be characterized as part of the remedial investigation of the 200-WA-1 operable unit (OU) at the Hanford Site (DOE 2016). The nature and extent of subsurface contamination needs to be characterized to support risk assessment and to evaluate the potential groundwater impact. For the 200-WA-1 OU, the characterization approach includes installation of boreholes to collect vertical profile data of contaminant distribution and relevant subsurface properties and conditions. An estimate of the three-dimensional distribution of subsurface contamination is also needed to support the conceptual site model and interpretation of characterization data for the risk assessment and, as necessary, for the feasibility study as part of Hanford cleanup under the *Comprehensive Environmental Response, Compensation, and Liability Act*.

Electrical resistivity tomography (ERT) was selected as a first step in the characterization effort to provide information about the three-dimensional distribution of historically disposed waste fluids in the subsurface beneath 200-WA-1 OU waste sites. ERT does not directly image specific contaminants. However, ERT provides an imperfectly resolved three-dimensional image of subsurface zones where the bulk electrical conductivity is higher than surrounding background values. Disposed waste fluids increase the bulk electrical conductivity in the subsurface where they are present by increasing the moisture content and because the high concentration of waste-fluid constituents such as nitrate cause the fluid to have a higher specific conductance than background pore water. Thus, zones of increased bulk electrical conductivity in the subsurface can be interpreted as zones where waste fluids are present.

An ERT survey of the subsurface beneath the 216-U-5 and 216-U-6 sites was conducted to collect imaging data suitable for interpreting the three-dimensional bulk electrical conductivity distribution in the subsurface. The resulting ERT image can be used to guide the selection of characterization borehole(s) location and depth if needed for additional characterization of the contaminant distribution and properties at these sites.

2.0 Site Setting

The 216-U-5 and 216-U-6 sites are part of the 200-WA-1 OU, located on the U.S. Department of Energy Hanford Site in southeastern Washington State. The 200-WA-1 OU consists of liquid waste disposal sites in the 200 West Area within the Central Plateau (Figure 1). Characterization in the 200-WA-1 OU is being conducted according to the Remedial Investigation/Feasibility Study Work Plan 200-WA-1 and 200-BC-1 Operable Units (DOE 2016). The 216-U-5 and 216-U-6 sites are located north of the U-Plant (221-U) facility (Figure 2). The current subsurface hydrogeology conceptual model is depicted in Figure 3. The current depth to groundwater is about 86 m below ground surface. The conceptual site model for the 216-U-5 and 216-U-6 sites suggests that the discharged waste fluids are still present within the upper portion of the vadose zone and have not impacted groundwater (DOE 2016).

Figure 1. Location of 200-WA-1 and 200-BC-1 operable unit on the Central Plateau at the Hanford Site (adapted from DOE 2016).

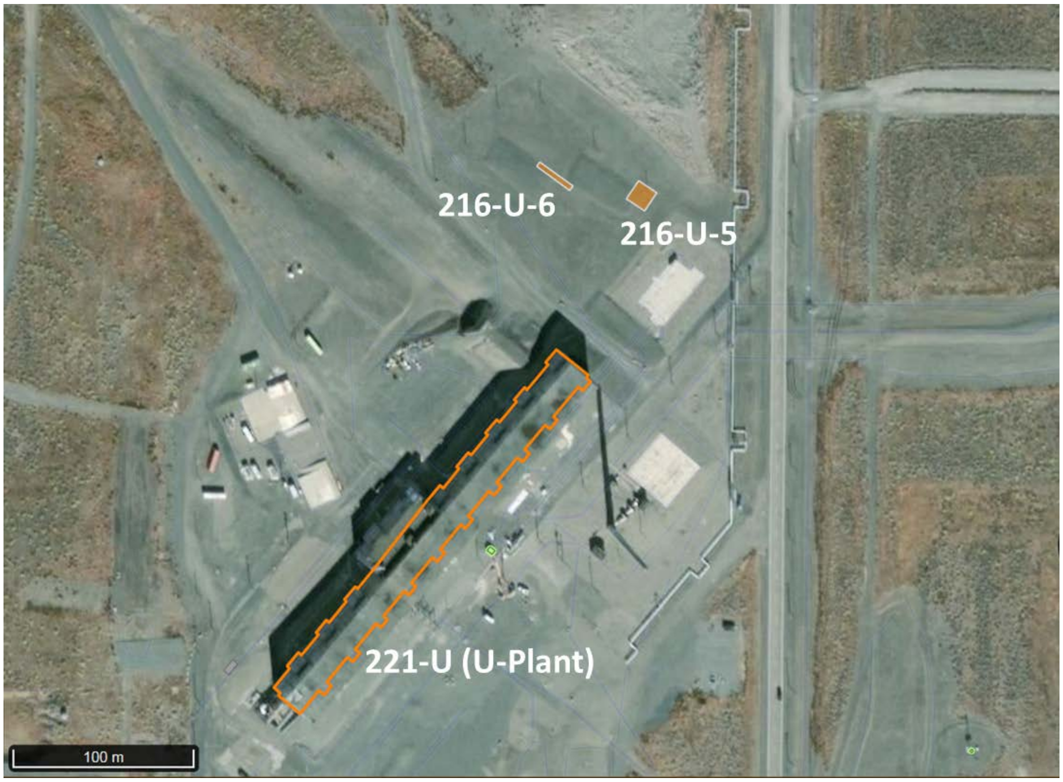

Figure 2. Location of the 216-U-5 and 216-U-6 sites (adapted from an image captured from www.phoenix.pnnl.gov).

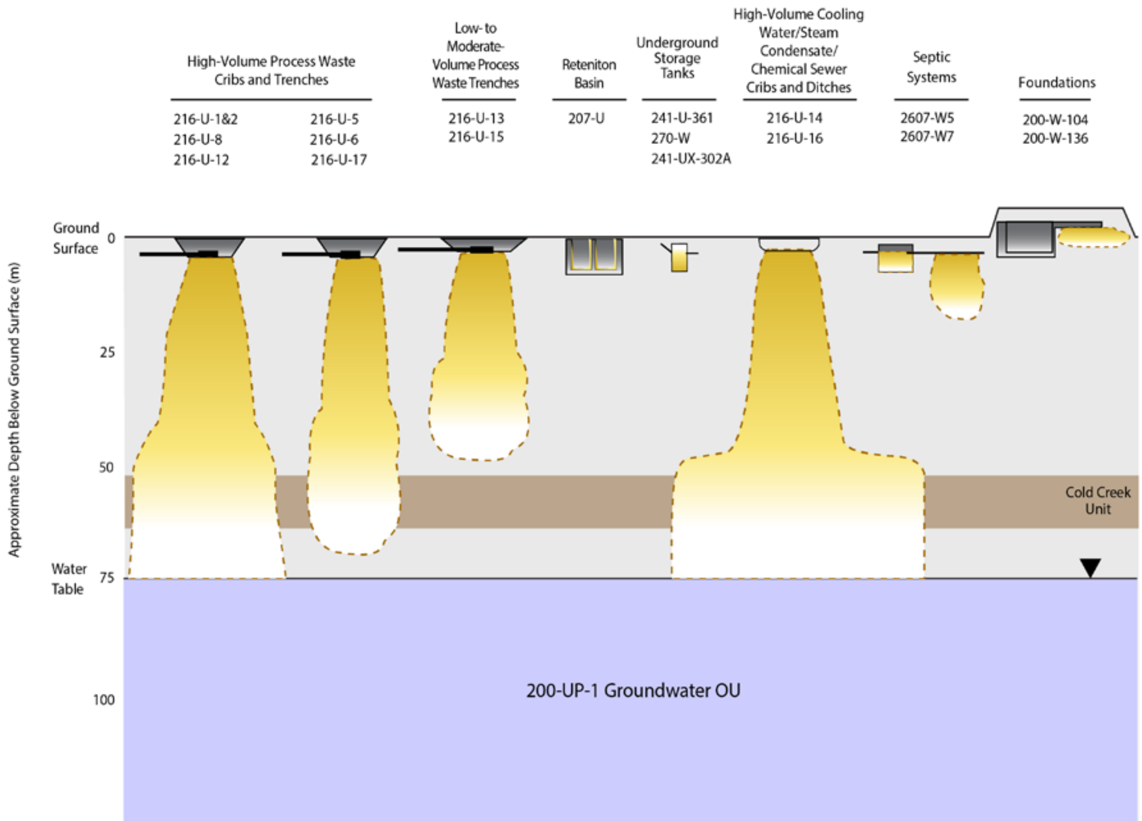

Figure 3. Hydrogeologic conceptual model in the vicinity of the 216-U-5, 216-U-6 waste sites (adapted from DOE 2016).

3.0 Electrical Resistivity Tomography Array Design and Data Collection

The ERT surface electrode array configuration and measurement sequence was designed using the E4D code as described below. Data collection activities are also summarized.

3.1 Electrical Resistivity Tomography Array Design

The ERT surface electrode array was designed to identify the vertical and lateral extent of contamination in the subsurface below the 216-U-5 and 216-U-6 sites, subject to the resolution limitations of surface ERT imaging. Locations of the ERT trailer, the ERT cable routing, and the four ERT electrode line locations are shown in Figure 4.

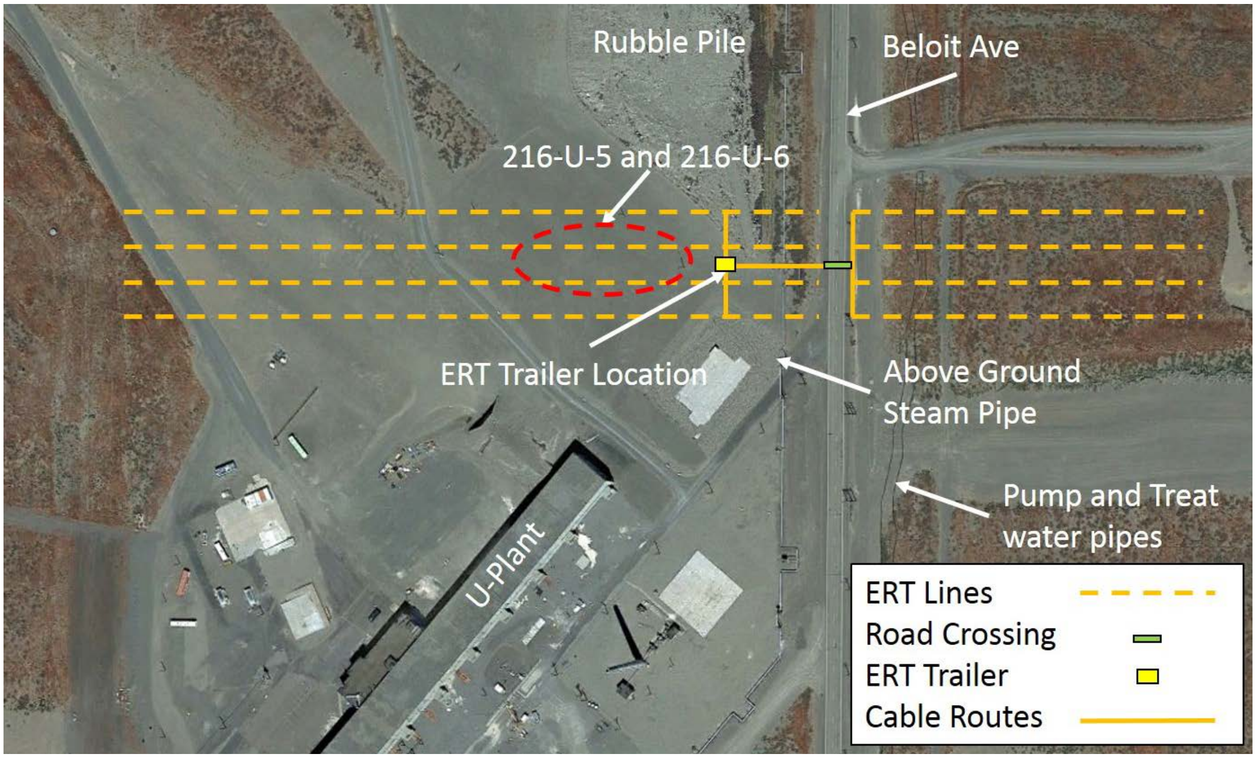

Figure 4. Location of ERT trailer, electrode lines, and cable routing at the survey site.

A total of 226 electrodes were installed in the ground surface along the lines shown in Figure 4. The electrodes are 10-inch-long galvanized carbon steel spikes with a 3/8-inch-diameter shaft and a 5/8-inch-diameter head. The electrodes were installed manually using hand tools (hammer) through two 1/2-inch-diameter holes in an electrical isolation box (Figure 5). The electrodes acted as stakes to hold down these boxes. Polycase (model WQ-50-02) boxes made of fiberglass-reinforced polycarbonate with a polycarbonate lid were used to isolate the electrodes from exposure during operation.

The electrodes were spaced 10 m apart along the outer northern and southern lines. The interior lines (closest to the ERT trailer) had a 10-m spacing at the east and west ends of each line and 5-m spacing in the middle of the line in the vicinity of the waste discharge sites (Figure 6). Electrode spacing was refined over the waste sites to enhance resolution in the target zone, particularly in the shallow vadose. Coarser electrode spacing in the line extensions beyond the waste sites was implemented to enable data sensitivity to the deep vadose zone. Fourteen ERT cables were used to connect the electrodes to the ERT survey instrument. A Multiphase Technologies (MPT-DAS1) ERT system was used in conjunction with three multiplexers (MUX-1). Connection cables were composed of 16 conductor 24 AWG stranded tin copper (jacketed with polyurethane insulation rated up to 1100 VDC) to safely transmit up to 3.6 amp with a resistance of 36 ohm per 1000 ft.

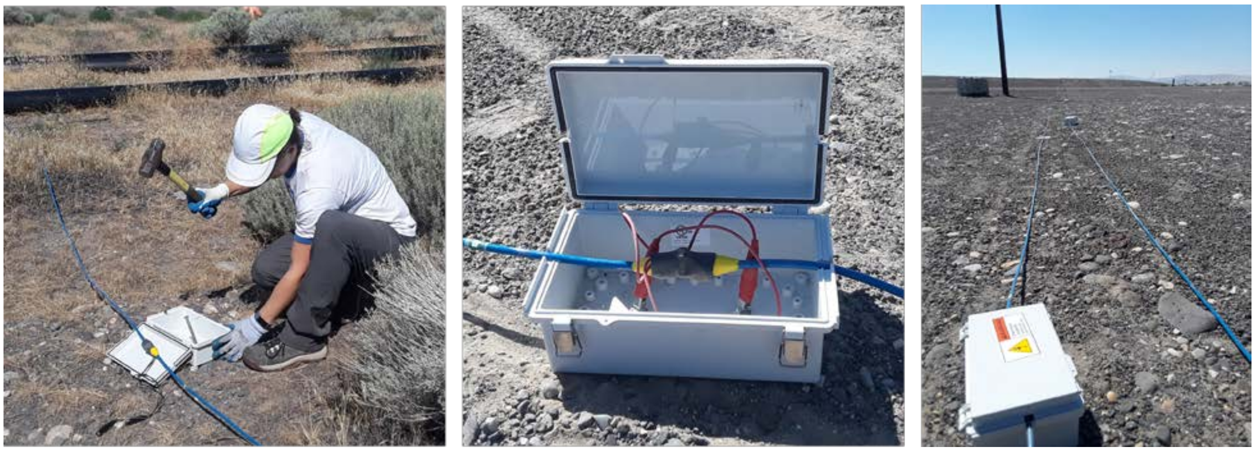

Figure 5. Electrode installation detail: (left) installation of two 10-inch- long steel spikes through the bottom of the electrical isolation box; (middle) multi-conductor electrode cable attached to electrodes in isolation box; (right) final configuration showing electrode isolation boxes and ERT cables.

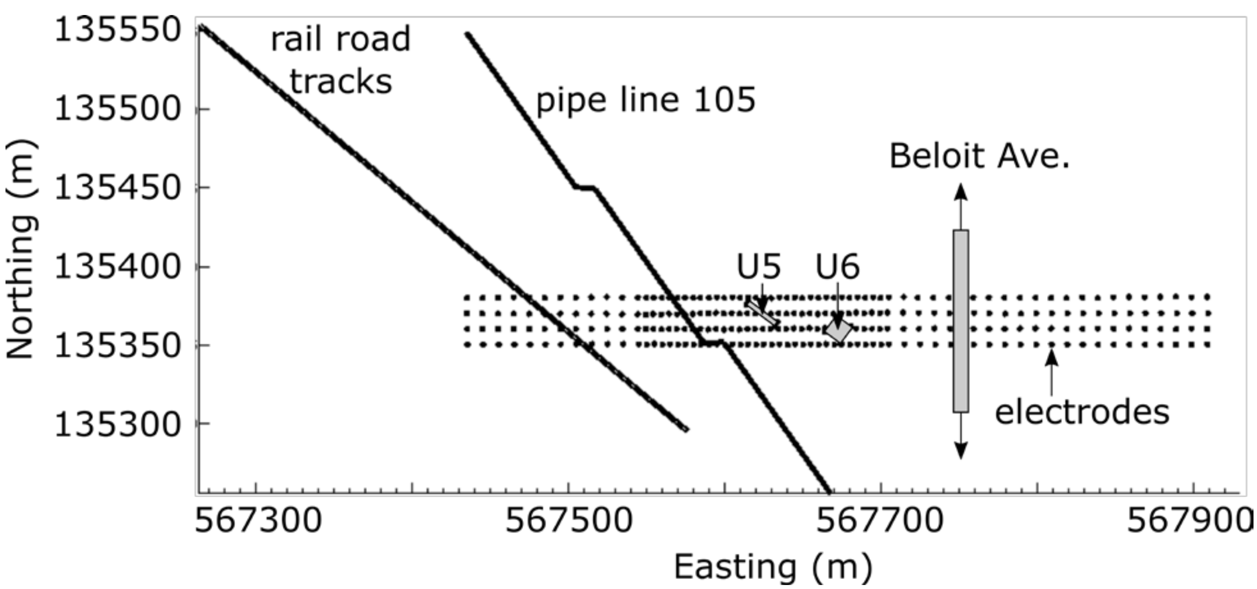

Figure 6. Plan view of electrode layout with respect to 216-U-5 and 216-U-6 cribs and buried metallic infrastructure (i.e., railroad tracks and waste transfer pipeline 200-W-105-PL).

The MPT-DAS1 system and the internal high-voltage transmitter were powered using two 12V batteries – one battery for the transmitter and one battery for the MPT-DAS1 control module, multiplexers, and a power inverter for the controlling PC.

3.2 Ground Surface Voltages

Ground surface voltages were simulated to evaluate the risk of exposure to hazardous electrical energy. The simulation considered a case in which current injection electrodes were 32.81 ft (10 m) apart. The ground conductivity was assumed to be 0.002 S/m, which nominally represents dry surface materials in the 200 West Area, as determined from Phase A ERT inversion results (Johnson and Thomle 2016; Figure 7). Lower conductivity materials generate larger surface voltages for a given unit of current injected, and therefore represent the highest risk in terms of electrical safety. The simulation assumed 0.5 A of current was applied between the electrodes. Typical currents injected in the 200 West Area are 0.1 to 0.2 A, and have not been observed to exceed 0.4 A, particularly in low-conductivity soils (i.e., 0.002 S/m assumed in this simulation). These conditions represent a conservative estimate of actual field conditions in terms of electrical safety. Simulated voltage error distributions have a standard deviation of approximately 1.5% (Johnson and Wellman 2015). Maximum voltages of approximately 53.4 volts are generated at the surface directly above the current source located under the junction boxes, where it cannot be contacted. No electrical safety issues were identified for this ERT survey under the imposed work controls.

3.3 Data Collection

Data collection was conducted using an approved operating procedure. A single ERT measurement involves injecting current between one electrode pair and measuring the resultant electrical potential (i.e., the voltage) across a second (or more) electrode pair(s). Raw ERT data are provided to the inversion algorithm as the observed voltages normalized by the injected currents and have units of resistance (ohms). Many such measurements are strategically chosen optimize imaging resolution. ERT measurements collected for the 216-U-5 and 216-U-6 survey included a comprehensive series dipole-dipole and Wenner-Alpha type four-electrode configurations. Small-offset dipoles (electrodes pairs in close proximity to each other) provide high resolution in the vicinity of the electrodes and constrain near surface structure in the ERT inversion. Large offset dipoles probe deeper into the subsurface. The comprehensive combination of small, intermediate, and large offset dipoles used in the survey was implemented to provide optimal resolution for both shallow and deep structures to the extent possible. The survey was also optimized to leverage the eight channels available in the MPT-DAS 1 system; eight different potential electrode pairs were recorded for each current electrode pair. In total, 11,944 measurements were collected. Average errors on repeat measurements were less than 1%.

3.4 Forward Modelling

Initial inverse modeling was conducted without explicitly modeling the effects of buried metallic infrastructure located in the vicinity of the ERT array. The corresponding ERT image exhibited high-conductivity artifacts beneath the location of pipeline 200-W-105-PL and the now-buried railroad tracks shown in Figure 6. Pipeline 200-W-105-PL consists of a series of parallel metallic pipes historically used to transfer liquid waste from the 221-U separations plant (Figure 4) to underground storage tanks. The railroad tracks provided railway access to the 221-U separations plant. Buried metallic infrastructure such as pipelines and railroad tracks redistributes subsurface current flow during ERT measurements and can significantly affect ERT images. Without correction, the processing algorithm compensates by placing anomalously high conductivity features in the vicinity of the infrastructure in order to match the ERT measurements. These deleterious artifacts mask subsurface bulk conductivity and reduce the utility of ERT. Johnson and Wellman (2015) demonstrated a method of removing the effects of buried infrastructure by explicitly modeling the infrastructure in the forward modeling phase of the ERT imaging algorithm. That method was used herein by modeling 200-W-105-PL and the 221-U Plant railroad explicitly as shown in Figure 6. The efficacy of the infrastructure removal procedure depends critically on the accurate modelling of buried metallic components, including dimensions and locations. Pipeline 200-W-105-PL was incorporated into the forward model using the detailed historical drawings. No such drawings were available for the railroad tracks, so the railroad track positions and depth of burial were estimated from aerial photographs. The effects of pipeline 200-W-105-PL were effectively removed, but the effects of the railroad tracks were not, suggesting they were not modeled with adequately accurate position and dimension in the forward modelling phase. A solution for accurately locating the railroad tracks was not identified for this report.

3.5 ERT Imaging Resolution

ERT images are limited in resolution. Consequently, small-scale features may not be resolved and larger resolvable features will be manifest as smoothed or blurred versions of the actual subsurface bulk conductivity. Imaging resolution is governed by many factors, including electrode spacing, proximity to electrodes, background electrical noise, measurement sequence, and bulk conductivity distribution. Resolution cannot be quantified prior to collecting field data. ERT survey design, which is the process of choosing electrode locations and which ERT measurements should be collected to optimally resolve targeted subsurface locations, was based on assumed conditions and trial-and-error synthetic imaging experiments. One such experiment is shown in Figure 7, where a target plume placed beneath in the vicinity of 216-U-5 and 216-U-6 is imaged using a comprehensive set of simulated ERT measurements. The targets and ERT images demonstrate the effects of limited resolution. Namely, the near-surface target is better resolved than the deeper target because it is closer to the electrodes. Both targets are clearly detected and imaged, but the images are blurred and have a larger footprint than the actual targets. Limited resolution effects such as these are important to consider when interpreting ERT images. In particular, the footprints of bulk conductivity plumes are likely to be larger in the ERT images than they are in reality, and the outer extents of plumes will typically bound the true extents, assuming the plume is within the zone of investigation.

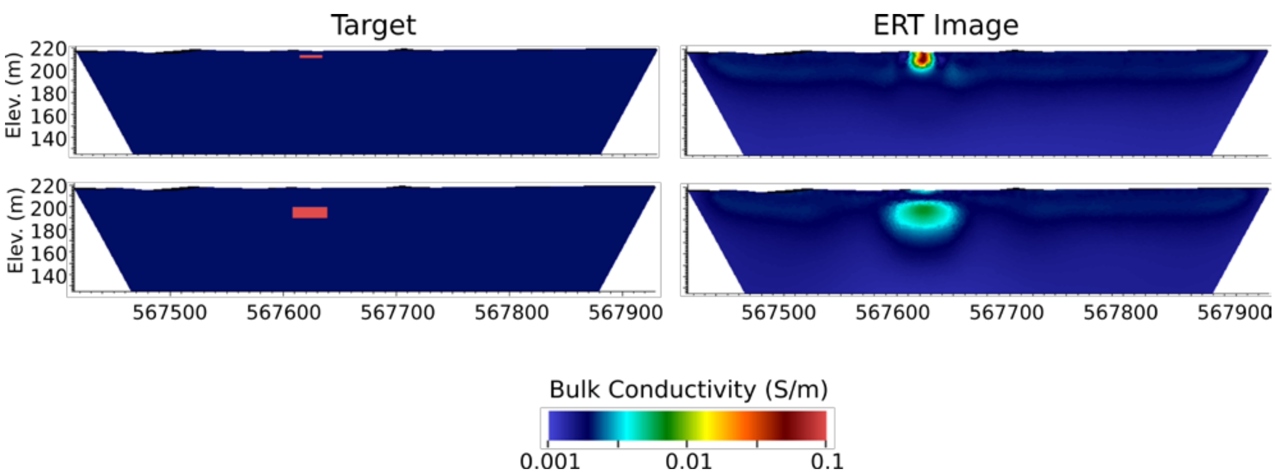

Figure 7. Synthetic imaging example demonstrating the effects of limited resolution.

4.0 216-U5/U6 Electrical Resistivity Tomography Survey Results

The ERT data were processed in parallel using 258 processing cores on the Constance supercomputer located at Pacific Northwest National Laboratory. The imaging mesh consisted of approximately 1.35M tetrahedral elements where subsurface bulk conductivity was estimated, and required approximately 6 hours to converge. The raw ERT data were matched with high fidelity (Figure 8), which requires high quality data, accurate electrode locations, and accurate forward modeling simulations in the imaging algorithm.

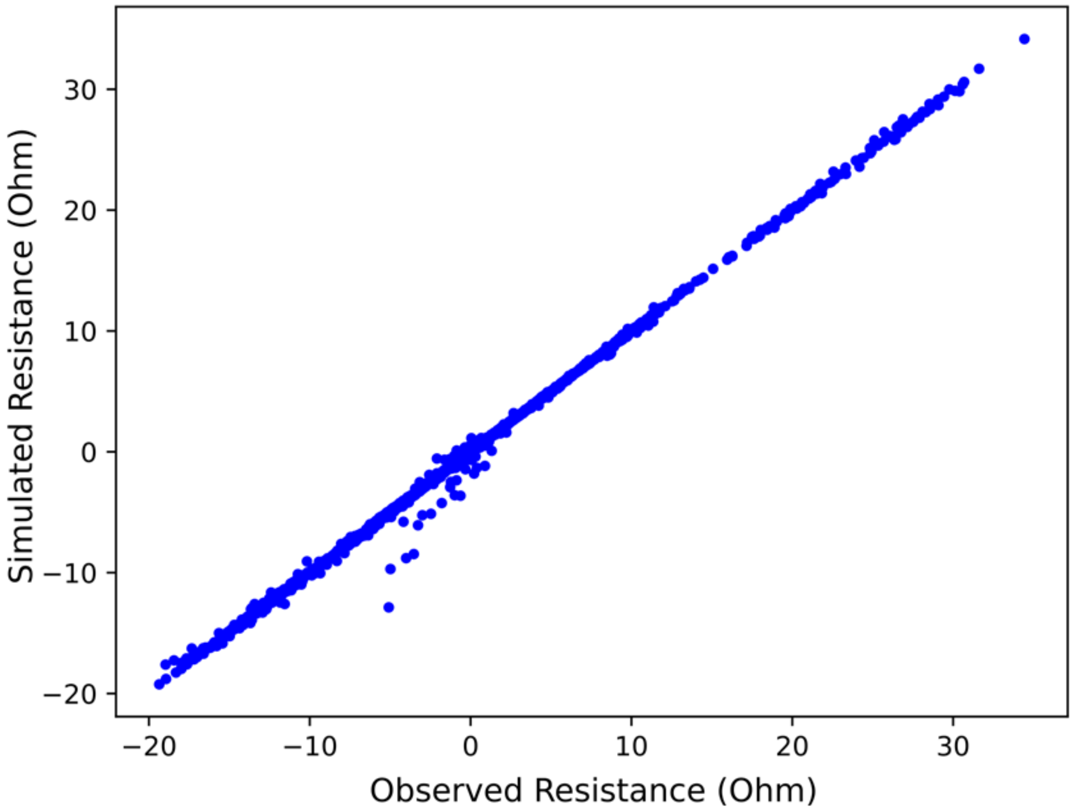

Figure 8. Simulated ERT vs. observed ERT data for each of the 11,944 measurements.

Figure 9 through Figure 13 show the results of the 216-U-5 and 216-U-6 ERT image in three different formats. Figure 9 and Figure 10 show east-west cross sections at 5-m intervals from the southern to the northern extents of the electrode array. The shaded regions at depth represent poorly resolved zones as determined through a depth of investigation analysis following the method of Oldenburg and Li (1999). Figure 11 shows horizontal cross-sections of the ERT image at 2-m intervals starting at an elevation of 216 m and ending at an elevation of 184 m above sea level. Figure 12 shows regions with anomalously high bulk conductivity as three-dimensional iso-surfaces, including one easting-normal view and one oblique view for perspective.

For comparison, the subsurface bulk conductivity east of Beloit Ave. appears to represent relatively native conditions in comparison to the areas west of Beloit Ave. in the vicinity of the ERT array. From the western end of the array to Beloit Ave., there are three predominant elevated bulk-conductivity anomalies. From west to east, the first anomaly is likely associated with the railroad tracks. The second anomaly is associated with the 216-U-5 and 216-U-6 cribs and the third anomaly is associated with Beloit Avenue.

The high-conductivity anomalies near the railroad tracks suggest the tracks may not have been correctly represented in the ERT forward modeling. Inspection of aerial images (Figure 4) suggests there may be a second set of buried railroad tracks crossing beneath the southwest corner of the ERT array that was not included in the ERT model. For reference, there is no high-conductivity anomaly beneath 200-W-105-PL, suggesting the pipeline is correctly represented within the ERT forward model. Similar results would be expected for correctly represented railroad tracks.

The high-conductivity anomalies beneath the 216-U-5 and 216-U-6 cribs are presumably caused by the presence of liquid waste discharged into the cribs. Two distinct plumes, one beneath each crib, merge into a single combined plume at an elevation of approximately 202 m, or a depth of approximately 14 m below ground surface. Considering the resolution limitations of surface ERT imaging and the corresponding image smearing that occurs at depth (Figure 7), the combined plume appears to terminate no deeper than 26 m below ground surface, at an elevation of approximately 180 m, which is approximately 60 m above the current groundwater elevation. There is no indication of significant lateral spreading of contaminants beneath the cribs. Most of the plume appears to be confined within the footprint of the ERT electrode array (Figure 11), except for the southern margin, which appears to extend southward slightly beyond the 135350 m northing boundary (Figure 9 and Figure 11).

A third high-conductivity anomaly occurs beneath Beloit Ave. Close inspection of Figure 9 through Figure 11 shows this anomaly is separated into an upper high-conductivity zone extending from the surface to approximately 210 m in elevation and a lower, more spatially extensive zone of elevated conductivity existing nominally from 190 to 195 m in elevation. Because surface elevations were only measured at the locations of the ERT electrodes, the topography of Beloit Ave. was not included in the ERT model. The resulting model error is likely manifest as the high conductivity shallow artifact directly beneath Beloit Ave. to 210 m in elevation. The origin of the lower anomaly beneath Beloit Avenue is unknown, but may be the result of runoff from Beloit Avenue during high precipitation events and subsequent water infiltration into the subsurface.

A summary of the ERT inversion results and interpretation is shown in Figure 13.

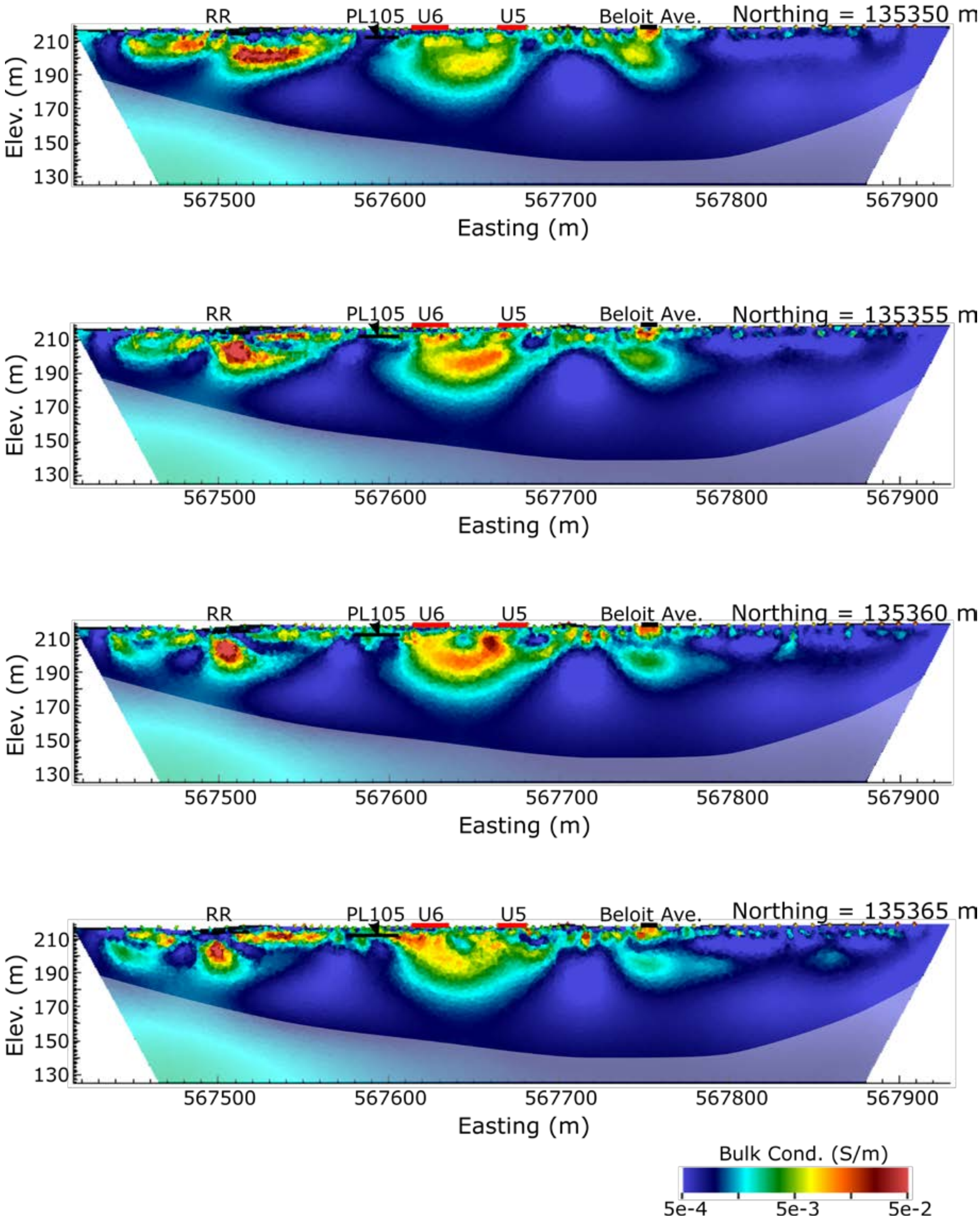

Figure 9. Northing-normal ERT image cross-sections from northing 135350 m to 135365 m.

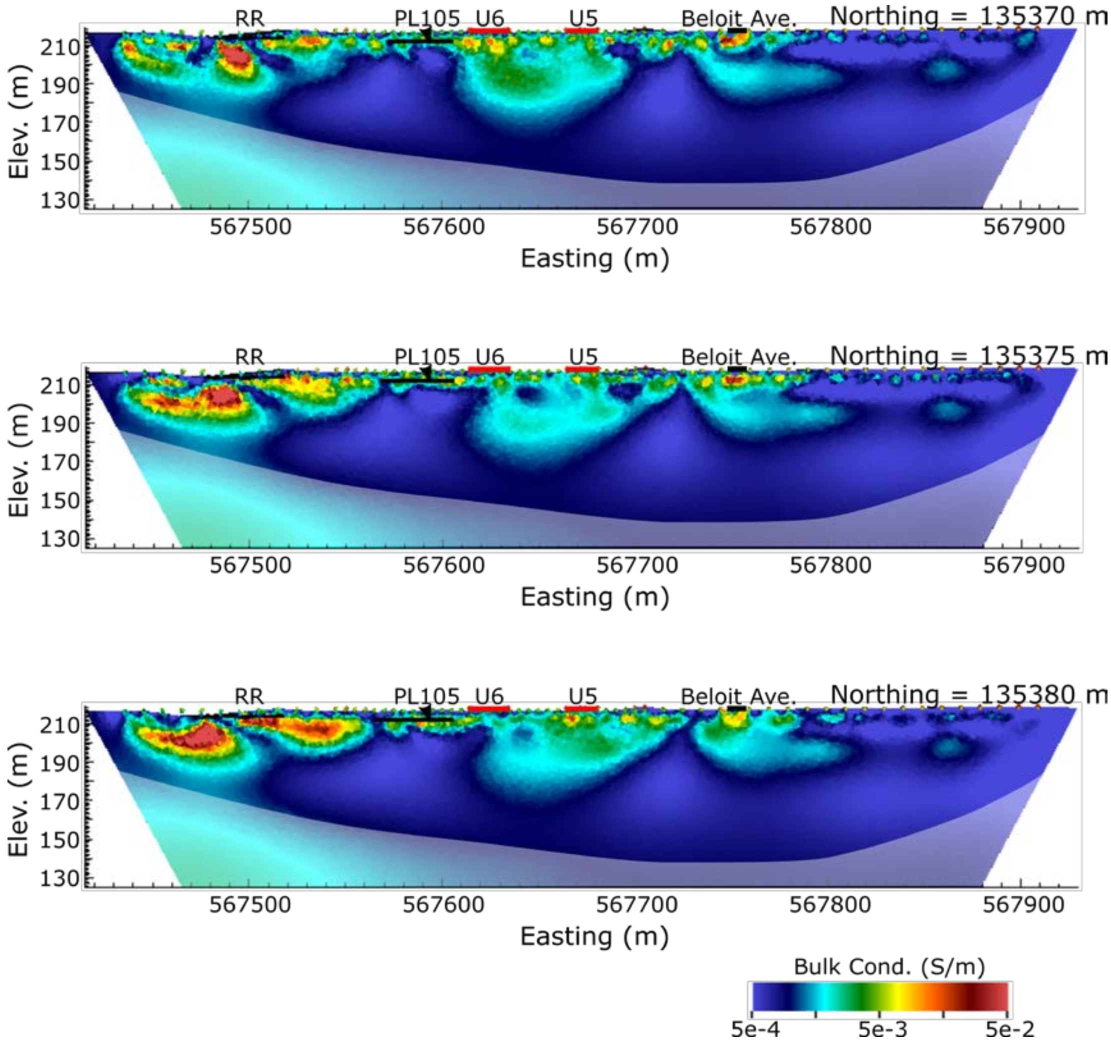

Figure 10. Northing-normal ERT image cross-sections from northing 135370 m to 135380 m.

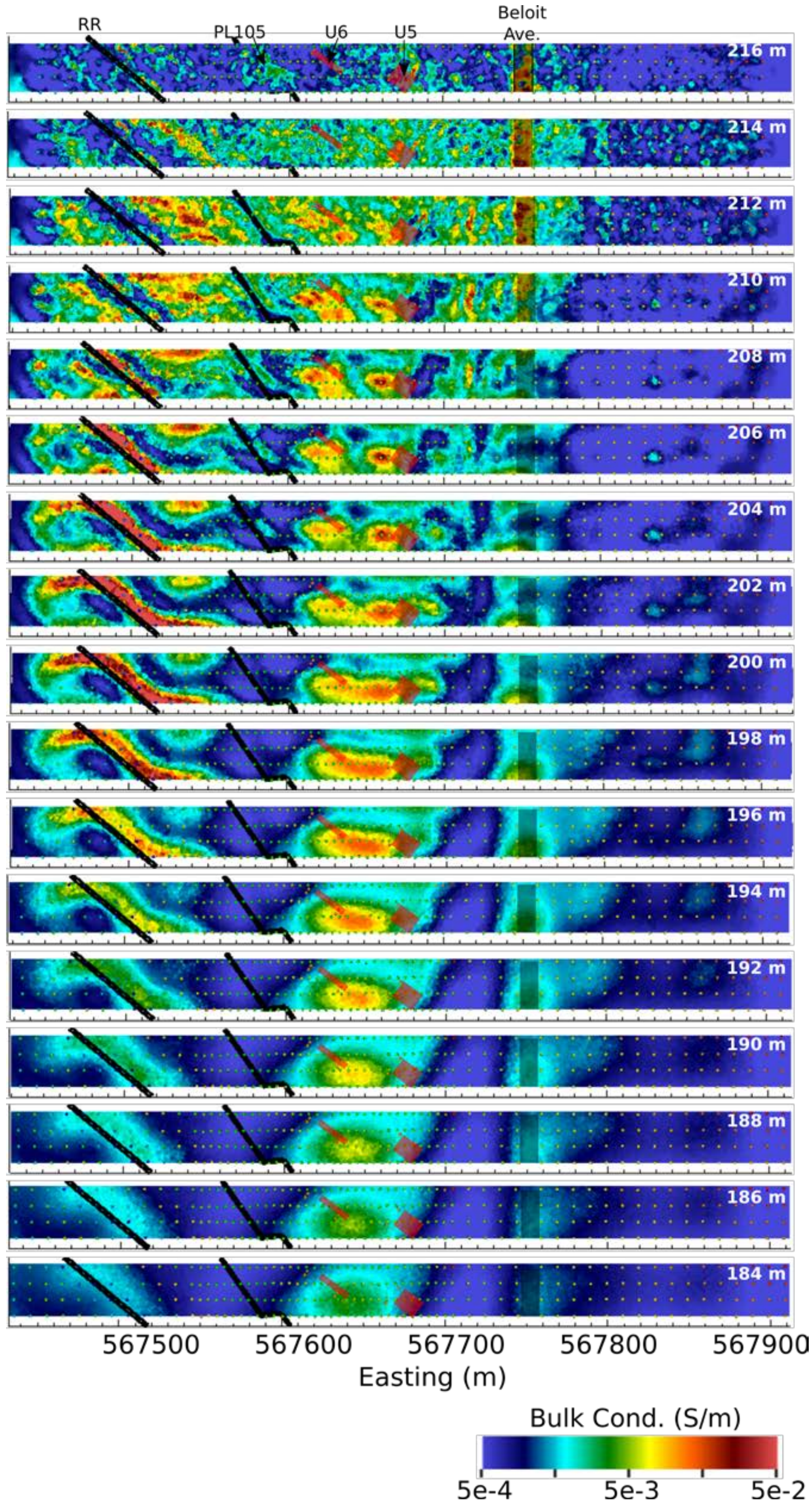

Figure 11. ERT depth cross-sections from ground surface (~216 m) to 184 m elevation.

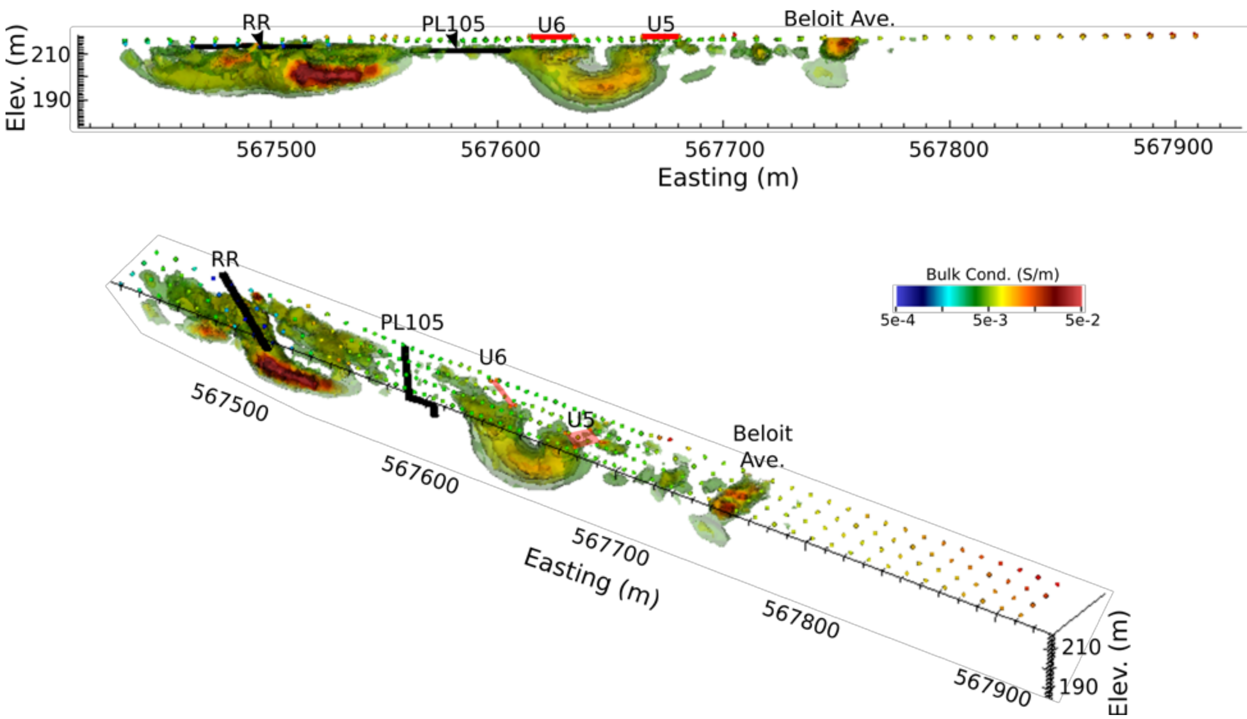

Figure 12. Iso-surface representations of bulk conductivity anomalies show the estimated three-dimensional extent of U5 and U6 vadose zone plumes. Anomalies associated with Beloit Avenue and the buried 221-U railroad tracks are also evident.

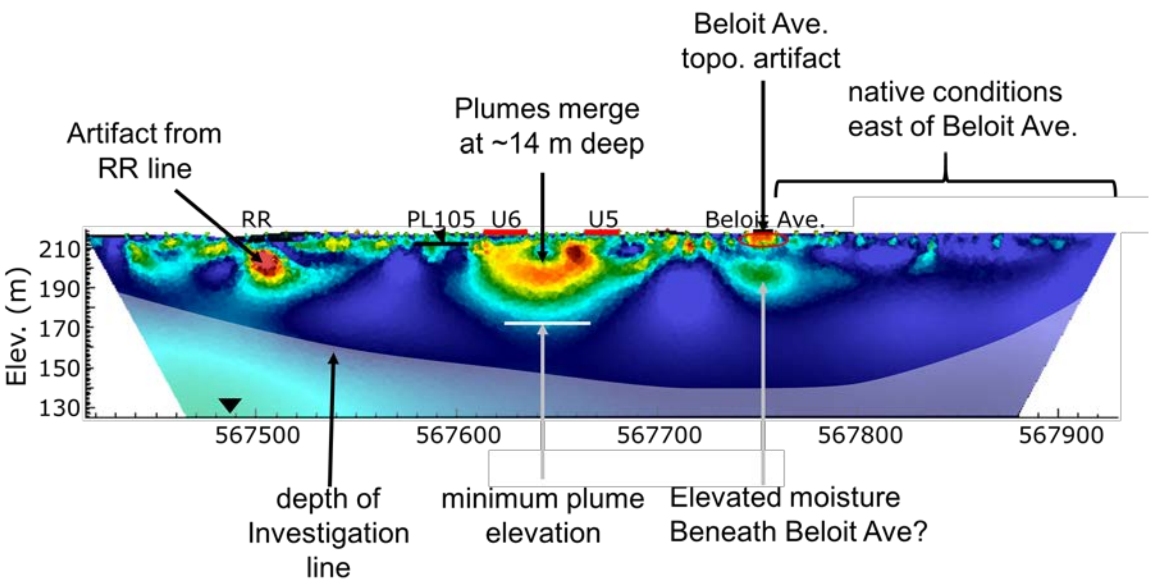

Figure 13. Summary results of 216-U-5 and 216-U-6 electrical resistivity tomography imaging.

5.0 Conclusions

ERT provides a limited resolution, three-dimensional image of subsurface bulk electrical conductivity. Disposed waste fluids typically increase the bulk electrical conductivity in the subsurface where they are present by increasing the moisture content and because the high concentration of waste-fluid constituents such as nitrate cause the fluid to have a higher specific conductance than background pore water. Thus, zones of increased bulk electrical conductivity in the subsurface can be interpreted as zones where waste fluids are present. Analysis of bulk conductivity contrasts in the subsurface suggest a contiguous zone of increased bulk electrical conductivity emanating from the 216-U-5 and 216-U-6 sites into the subsurface to a depth of no more than 26 m. The deepest portion of this zone is 60 m above the current water table elevation.

These results are consistent with expectations that the disposed waste would not have migrated to the water table because of the relatively low waste volumes discharged at these sites. The ERT information provides a line of evidence supporting this conclusion and can be used to guide the selection of characterization borehole(s) location and depth as needed for characterization of the contaminant distribution and properties.

6.0 Quality Assurance

This work was performed in accordance with the Pacific Northwest National Laboratory (PNNL) Nuclear Quality Assurance Program (NQAP). The NQAP complies with U.S. Department of Energy Order 414.1D, *Quality Assurance*, and 10 CFR 830 Subpart A, *Quality Assurance Requirements*. The NQAP uses NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Application*, as its consensus standard and NQA-1-2012 Subpart 4.2.1 as the basis for its graded approach to quality.

7.0 References

10 CFR 830, Subpart A, *Quality Assurance Requirements*. U.S. Code of Federal Regulations.

DOE. 2016. *Remedial Investigation/Feasibility Study Work Plan for the 200-WA-1 and 200-BC-1 Operable Unit*. DOE/RL-2010-49, U.S. Department of Energy, Richland Operations Office, Richland, WA.

DOE Order 414.1D, *Quality Assurance*. U.S. Department of Energy, Washington, D.C.

Johnson TC. 2014. *E4D: A Distributed Memory Parallel Electrical Geophysical Modeling and Inversion Code*. PNNL-SA-23783, Pacific Northwest National Laboratory, Richland WA. https://e4d.pnnl.gov/Documents/E4D_User_Guide.pdf.

Johnson TC and D Wellman. 2015. "Accurate modelling and inversion of electrical resistivity data in the presence of metallic infrastructure with known location and dimension." *Geophysical Journal International* 202(2):1096-1108. https://academic.oup.com/gji/article/202/2/1096/593888.

Johnson TC and JN Thomle. 2016. *Stage A Uranium Sequestration Amendment Delivery Monitoring Using Time-Lapse Electrical Resistivity Tomography*. PNNL-25232. Pacific Northwest National Laboratory, Richland, WA.

NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Application*. American Society of Mechanical Engineers, New York, NY.

Oldenburg DW and Y Li. 1999. "Estimating the depth of investigation in dc resistivity and IP surveys." *Geophysics* 64(2). https://doi.org/10.1190/1.1444545.

PNNL-29430
WA1ERT-RPT-0001 Rev 0.0

**Pacific Northwest
National Laboratory**

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov