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Surface 3D Electrical Resistivity Tomography Inversion of 2005 BC Cribs and Trenches Datasets

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Timothy Johnson
Judy Robinson
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U.S. DEPARTMENT OF ENERGY

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Summary

Hydrogeophysics, Inc. (HGI) conducted an electrical resistivity tomography (ERT) dataset at the BC Cribs and Trenches site, located in the Central Plateau of the Hanford Site. The 20 trenches and 6 cribs received large volumes of liquid inorganic waste in the 1950s, resulting in a large inventory of contaminants in the vadose zone. The objective of the ERT survey was to map plume extents resulting from the legacy discharges.

The HGI interpretation of the resistivity data was performed using geometric inversion to interpolate 2D lines into a 3D image. To demonstrate a newly developed geophysical code capability (E4D), the resistivity data were re-processed to fit a full 3D model of the bulk electrical conductivity. This proof-of-concept model inversion was executed in calendar year 2011, as the large dataset was well-suited for the use of high-performance computing.

The 3D re-processing of the BC Cribs and Trenches ERT data conducted in 2011 resolved the true bulk electrical conductivity. This means that all of the resistivity data were fit to a single model of the bulk electrical conductivity, with true horizontal and vertical dimensions. This differed from the HGI data interpretation approach that used geometric inversion to process 2D lines independently, which were then interpolated into a 3D image.

Both the full 3D re-processing and the 2D interpolation to a 3D image demonstrated a higher electrical conductivity observed immediately beneath the trenches and cribs. The electrical conductivity is strongly correlated with nitrate concentrations, indicating the presence of nitrate and other co-located contaminants.

Acknowledgments

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Acronyms and Abbreviations

BEC	bulk electrical conductivity
E4D	geophysical modeling and inversion code used for ERT data inversion
ERT	electrical resistivity tomography
FIO	For Information Only
HARN	High Accuracy Reference Network
HGI	hydroGEOPHYSICS, Inc.
HRR	high-resolution resistivity
PNNL	Pacific Northwest National Laboratory

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1.0 Introduction

The Hanford Site is a former plutonium production site located in southeastern Washington State, adjacent to the Columbia River (Figure 1). More than 91,000 tonnes of nuclear fuel were reprocessed between 1944 and 1990, requiring between 2100 and 16,500 L (550 and 4360 gal) of water per tonne of fuel. Hundreds of thousands of tonnes of chemicals, including acids, solvents, nitrates, ammonia, and carbon tetrachloride, were also used to reprocess fuel (Gee et al. 2007). As a result, large quantities of radioactive and chemical wastes remain in the vadose zone at Hanford and are a potential threat to groundwater.

The BC Cribs and Trenches site, a 30-hectare waste disposal site located in the Central Plateau of the Hanford Site (Figure 1), received approximately 30 million gallons of scavenged waste from the uranium and ferrocyanide recovery processes from 1956 to 1958 in 20 unlined disposal trenches and 6 concrete-lined disposal cribs. Waste discharges to the BC Cribs and Trenches site comprise one of the largest liquid waste volumes released to the ground in the Hanford Central Plateau, including the largest inventory (~410 Ci) of technetium-99 (Tc-99) and large masses of nitrate and uranium-238 (U-238) (DOE-RL 2008).

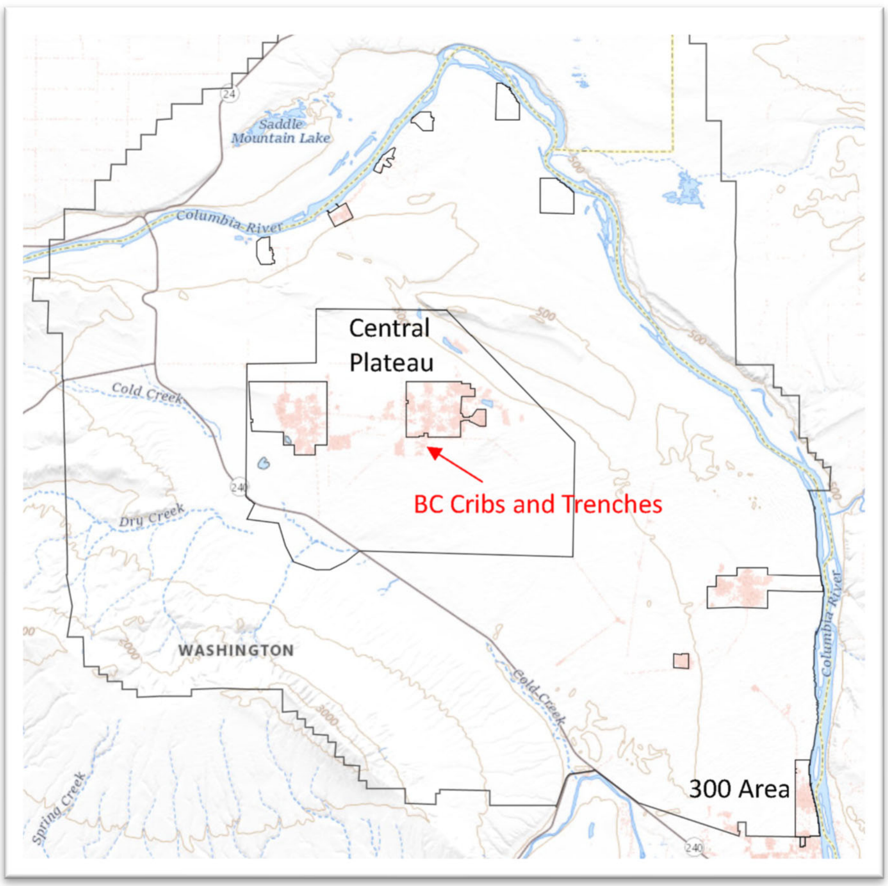

Figure 1. Location of BC Cribs and Trenches site within the Hanford Site.

The vadose zone at the BC Cribs and Trenches site is approximately 107 m thick and is largely composed of sediments that belong to the Hanford formation, a major stratigraphic unit at Hanford. However, the subsurface may contain relatively thin (0.5 m or less), fine-textured sediments that can extend laterally for tens of meters (Serne et al. 2009), although the distribution of the fine-grained layers is largely unknown. Since contaminant migration is dependent on subsurface structure and connectivity, the influence of the less-permeable lenses will impact the distribution and extent of contaminants at the BC Cribs and Trenches site. Lateral migration of contaminants due to fine-grained lenses is suggested to be the cause of limited vertical migration at the site (Serne et al. 2009).

1.1 Site Characterization

Similar to other waste sites at Hanford, the BC Cribs and Trenches site was evaluated for the soil capacity to act as a retention zone for liquid disposal. It was postulated that contaminants discharged to the subsurface could be selectively retained through ion exchange, with any radioactivity decaying away over time. This concept was referred to as specific retention (Gee et al. 2007).

Several borehole geophysical studies (spectral gamma logs) have been completed at the site to assess the effectiveness of the BC Cribs and Trenches subsurface sediments at adhering to the provisions of specific retention (e.g., Horton and Randall 2000). These studies demonstrated that no significant vertical migration had occurred during the period of 1977 to 1999. Geologic, geochemical, and hydraulic measurements from four boreholes from the BC Cribs and Trenches area (Serne et al. 2009) also confirmed limited vertical contaminant migration, approximately 70 m below ground surface.

Electrical resistivity surveys were conducted at the BC Cribs and Trenches area (Benecke et al. 2006, Rucker and Fink 2007) to identify regions associated with past liquid waste discharges. The introduction of liquid waste, composed primarily of high sodium and nitrate concentrations, locally altered the electrical properties within the subsurface to a degree measurable (and interpretable) using surface-based soil-resistivity surveys. These electrical measurements were later compared to geochemical measurements on cores reported in Serne et al. (2009) to confirm the high correlation between nitrate concentrations and electrical conductivity of pore water associated with nitrate.

1.2 Quality Assurance

This report documents a proof-of-principle inversion of electrical resistivity tomography (ERT) data that hydroGEOPHYSICS, Inc. (HGI) collected from 2005 to 2006. These data were transmitted to Pacific Northwest National Laboratory (PNNL) in a spreadsheet (filename: *BC_Cribs_Resistivity_Dataset_2004-2006_(Full).xlsx*). PNNL did not specify or verify the controls that HGI applied for the collection of the ERT data. These data served as inputs to the E4D software, which in 2011 when the ERT inversion was performed, did not have a formal version control system in place, nor had the code been qualified to NQA-1 standards. The information associated with this report should not be used as design input or operating parameters without additional qualification.

The inversion was performed as an independent effort, without a formal scope of work, project, or client. The information in this report is For Information Only (FIO), as no formal quality standards were applied to this analysis. Expert judgment was used to assess the measured data and inversion results.

1.3 Objectives

The primary objective of this report is to document the re-processing of the electrical resistivity survey data conducted at the BC Cribs and Trenches site that was documented in Benecke et al. (2006) and Rucker and Fink (2007). The field campaign included 55 pole-pole resistivity transects collected independently along parallel and orthogonal lines. As noted in Serne et al. (2009), the initial interpretation of the surface-based geophysical survey data suffered from myopia, where depth-discrete pore-water salt concentrations were difficult to resolve. For this reason, the survey data were re-interpreted in 2011 using open-source, parallel software called E4D, permitting a full-scale 3D inversion of the large, high-frequency dataset (Johnson et al. 2010).

This report is organized as follows. In Section 2.0, a brief description of ERT is provided along with the HGI data interpretation reported in Benecke et al. (2006) and Rucker and Fink (2007). This section also describes the approach documented in this report. The results of the full 3D inversion are presented in Section 3.0, followed by a brief summary in Section 4.0. Although not directly related to the BC Cribs and Trenches area, formation factor and surface conductivity measurements performed on cores located adjacent to the Columbia River in the 300 Area (see Figure 1) are provided in Appendix A for their potential application to the BC Cribs and Trenches and other areas of the Hanford Site

2.0 Electrical Resistivity Tomography

Electrical resistivity (the inverse of electrical conductivity) quantifies how strongly a material opposes the flow of an electrical current. This is controlled by porosity, moisture content, temperature, pore water fluid conductivity, and soil texture. ERT is an active source geophysical method that uses an array of electrodes to collect data. Electrodes placed along linear transects are commonly used to acquire 2D datasets. Parallel or intersecting linear transects can be independently collected and combined for 3D analysis.

Electrode configurations with four electrodes (Ward 1988) are typically used to collect resistivity data where two current electrodes are used to inject a direct current into the subsurface, and two potential electrodes are used to measure the voltage drop (ΔV). The basic unit of ERT data is transfer resistance (Ohm), which is the measured voltage drop across potential electrodes divided by the injected current (I). Hundreds of thousands of ERT measurements can be collected in a single ERT survey.

2.1 BC Cribs and Trenches ERT Survey

For the BC Cribs and Trenches site, a pole-pole array was used (Figure 2) (Rucker and Fink 2007). In this configuration, current and potential electrodes (C2, P2) are ideally placed more than 20 times the maximum separation distance between other current and potential electrodes (C1, P1). C1 and P1 are referred to as infinity electrodes and C2 and P2 are modeled as single poles. The pole-pole array has a wider horizontal coverage, a deeper depth of investigation, and poorer spatial resolution when compared to more commonly used electrode configurations (Loke 1999). For the BC Cribs and Trenches site, HGI selected the pole-pole array to provide rapid data acquisition (Rucker and Fink 2007).

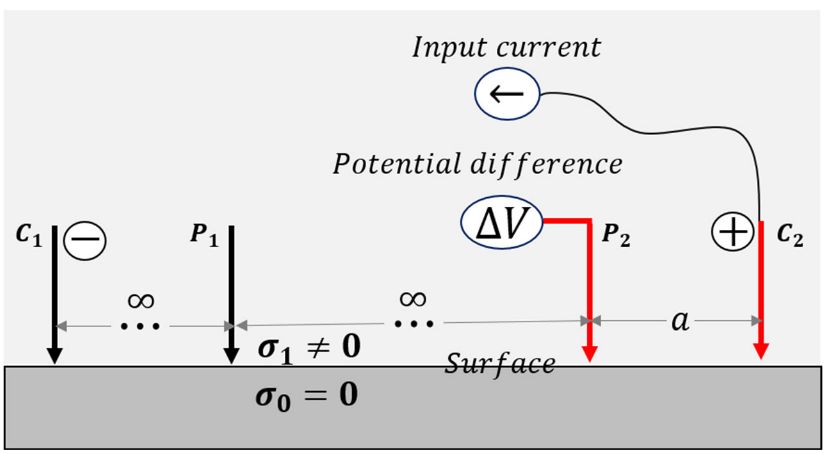

Figure 2. Schematic of a pole-pole electrode surface configuration used for the BC Cribs and Trenches ERT data collection (from https://wiki.seg.org/wiki/Electric_resistivity_surveys#Pole-Pole_array)

The location of the ERT survey is shown in Figure 3. This method was designated as high-resolution resistivity (HRR) as reported in Benecke et al (2006). ERT data were independently collected along 51 closely spaced 2D transects spaced approximately 15 m apart. The lines were organized as a grid to fill in areas that were not directly overlapping the cribs and trenches (Figure 4). Additionally, HGI extended the lines past the known disposal facilities into adjacent properties to distinguish the edges of the plume (Benecke et al. 2006; Rucker and Fink 2007).

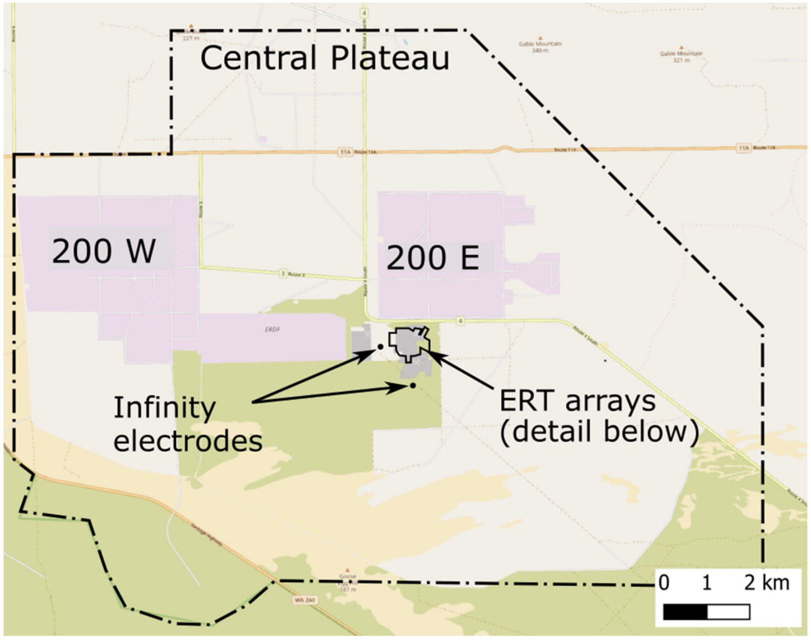

Figure 3. Location of ERT electrode arrays at the BC Cribs and Trenches site.

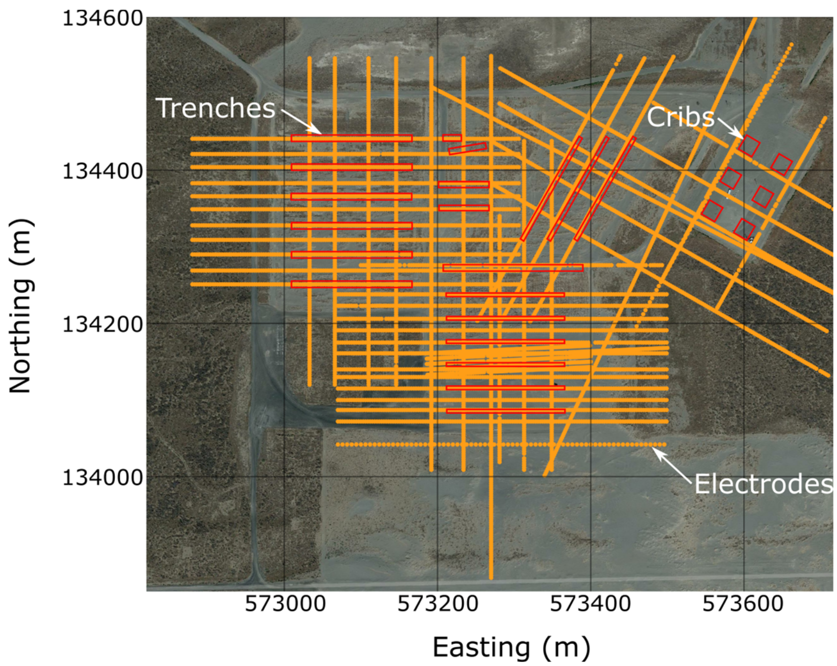

Figure 4. Location of 2D ERT electrode arrays with locations of BC cribs (red squares) and trenches (red rectangles) in Washington State Plane (NAD83 HARN) coordinates.

2.2 HGI Data Interpretation

As reported in Benecke et al. (2006) and Rucker and Fink (2007), the measured transfer resistances for a homogeneous, isotropic half-space, can be converted to an apparent resistivity ρ_a (or its inverse apparent conductivity σ_a) using equations based on Ohm's law:

$$\rho_a = 2\Pi Ra \tag{1}$$

$$\sigma_a = 1/2\Pi Ra \tag{2}$$

where R is the measured transfer resistance and a is the distance between C2 and P2 (refer to Figure 2). ρ_a and σ_a for an ERT survey can be assimilated to provide a pseudo section that is a visual representation of the data. Values of ρ_a and $\sigma_a$are plotted at x-coordinates equal to the midpoint of C2 and P2. Z-coordinates (e.g., depth) are estimated based on a. Note that ρ_a and σ_a are not the true resistivity and conductivity of the subsurface given the mathematical assumptions. Depths can only be approximated as a pseudo depth.

The first published analyses of the HRR survey used a geometric inversion and pseudo depth approach to interpret the resistivity data. This is a proprietary algorithm that allowed additional parameters (e.g., in addition to the electrode spacing) to determine the depth of investigation and also included a correction for topography (Benecke et al. 2006; Rucker and Fink 2007). The ERT geometric inversions were interpolated with Rockworks[1] software, using an anisotropic inverse-distance weighting algorithm to interpolate the data. This yielded a 3D distribution of apparent resistivity ρ_a as shown in Figure 5.

The electrical conductivity distribution acts as a surrogate for the subsurface concentration distribution. Nitrate concentrations, which may be co-located with technetium-99 and uranium at the BC Cribs and Trenches site, were shown to be correlated with resistivity measurements at the site in Serne et al. (2009).

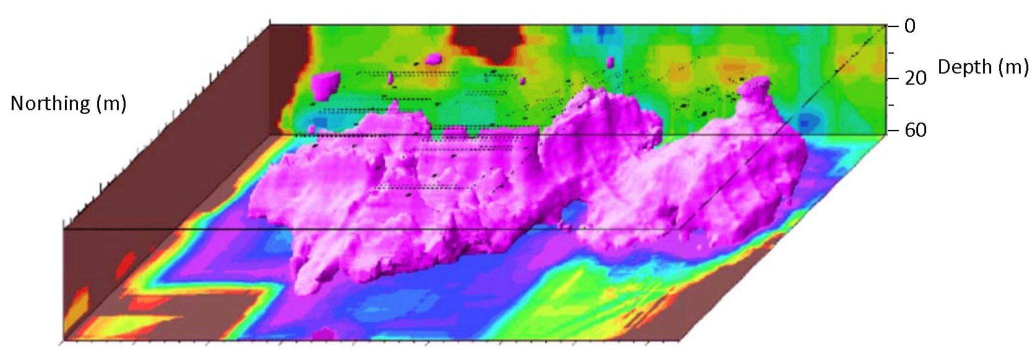

Figure 5. Initial interpretation of the HRR data visualization from BC Cribs and Trenches site (from Benecke et al. 2006).

[1] https://www.rockware.com/product/rockworks/

2.3 Data Interpretation with E4D Software

To obtain a true resistivity or conductivity, ERT data must be inverted to provide a model of the subsurface. This is an iterative process whereby all data is fit to a model, and within this process, considerations are given to adjacent regions of space and data errors. There are numerous methods used to invert ERT data, as described in a recent review by Binley and Slater (2020).

To demonstrate an additional approach for interpreting the ERT data at BC Cribs and Trenches, an early version of the E4D software (Johnson et al. 2010) was used to generate a 3D image of electrical conductivity. E4D is an open source 3D finite element modeling and inversion code, where R [Eqs. (1) and (2)] is inverted to solve for a model $\boldsymbol{m}$ of bulk electrical conductivity (BEC).

The problem was formulated as a regularized inverse optimization problem where an objective function Φ optimizes the tradeoff between the data misfit Φ_d and model constraints Φ_m through a regularization coefficient, β (Binley and Kemna 2005; Johnson et al. 2010):

$$\Phi = \Phi_d + \beta\Phi_m \tag{3}$$

where

$$\Phi_d = \|\boldsymbol{W_d}(\boldsymbol{d} - F(\boldsymbol{m}))\| \tag{4}$$

$$\Phi_m = \left\|\boldsymbol{W_m}(\boldsymbol{m} - \boldsymbol{m_{ref}})\right\| \tag{5}$$

In Eq. (3), $\boldsymbol{W_d}$ represents the data weighting matrix, which, assuming uncorrelated normally distributed noise, is a diagonal matrix containing the inverse of the standard deviations of the data $\boldsymbol{d}$ on the diagonal. $F(\boldsymbol{m})$ is the forward model operator. In Eq. (4), the model constraint matrix $\boldsymbol{W_m}$ describes the preferred relationship between parameters of $\boldsymbol{m}$ in space for the static inversion performed here. The reference model $\boldsymbol{m_{ref}}$ is a preferred solution, which for the first iteration is the average ρ_a of the dataset; $\boldsymbol{m_{ref}}$ is equal to a previous iterative solution after the first iteration. The solution is considered converged when the chi-squared statistic (e.g., representative of data fit) has a maximum value of 1 (Binley and Slater 2020). This approach solves for a smooth model with the least amount of structure so as not to overinterpret the data (Constable et al. 1987).

The E4D analysis used the data collected from all 2D ERT datasets to perform a full-scale 3D inversion, using high-performance computing to execute the analysis to produce a subsurface distribution of BEC.

3.0 3D ERT Inversion Results

Figure 6 through Figure 8 show 3D BEC images in plan and elevation views. Poorly resolved regions (e.g., regions where there are no electrodes) have been removed from Figure 6. All images are shown in Washington State Plane coordinates. The outlines of the BC Cribs and Trenches are shown in Figure 7, and all figures are shown at the same BEC scale for comparison. The original HRR survey provided results to 60 m depth; however, Figure 7 and Figure 8 show results down to 100 m. The water table was reported to be at a depth of 104 m (Benecke et al. 2006).

Given the high correlation between nitrate concentration and pore-water fluid conductivity, higher BEC regions (red in the color scale) are indicative of higher nitrate concentrations. The images show the horizontal outer edges of the plume emanating from beneath the cribs and most (but not all) trenches. In the vertical direction, a higher BEC is consistently identified to a 60 m depth. Although a higher BEC observed at a depth of 100 m, the E4D inversion did not include a rigorous analysis of the depth of investigation. Hence, there is higher confidence in the results to a depth of 60 m, based on the HGI depth of investigation (Benecke et al. 2006; Rucker and Fink 2007).

Figure 6 through Figure 8 were generated based on the results of the inversion contained in a file named *bc_cribs_ert.txt*.

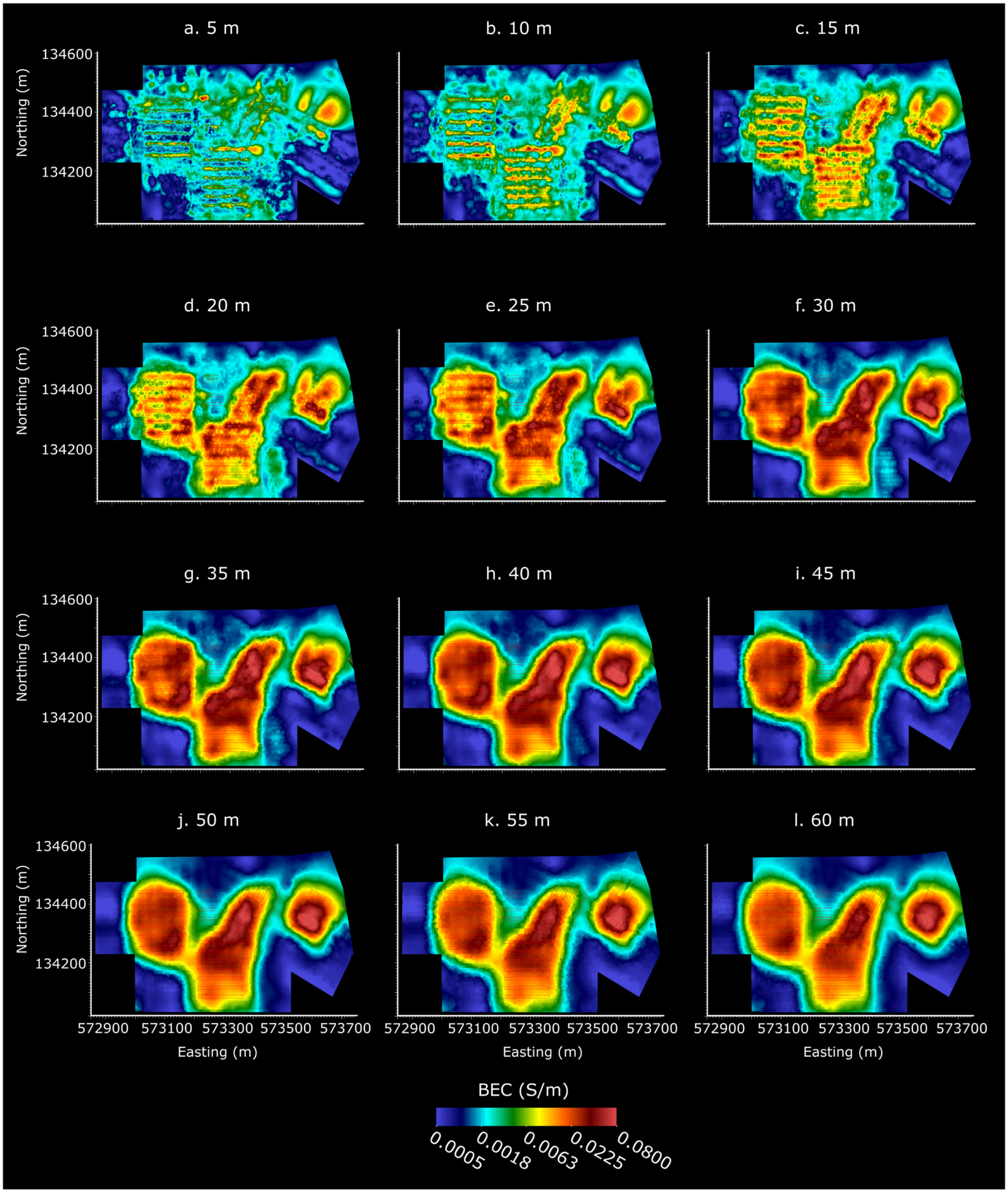

Figure 6. Aerial (top) view of 3D ERT results from a) 5 m depth to i) 60 m depth. Figure is FIO.

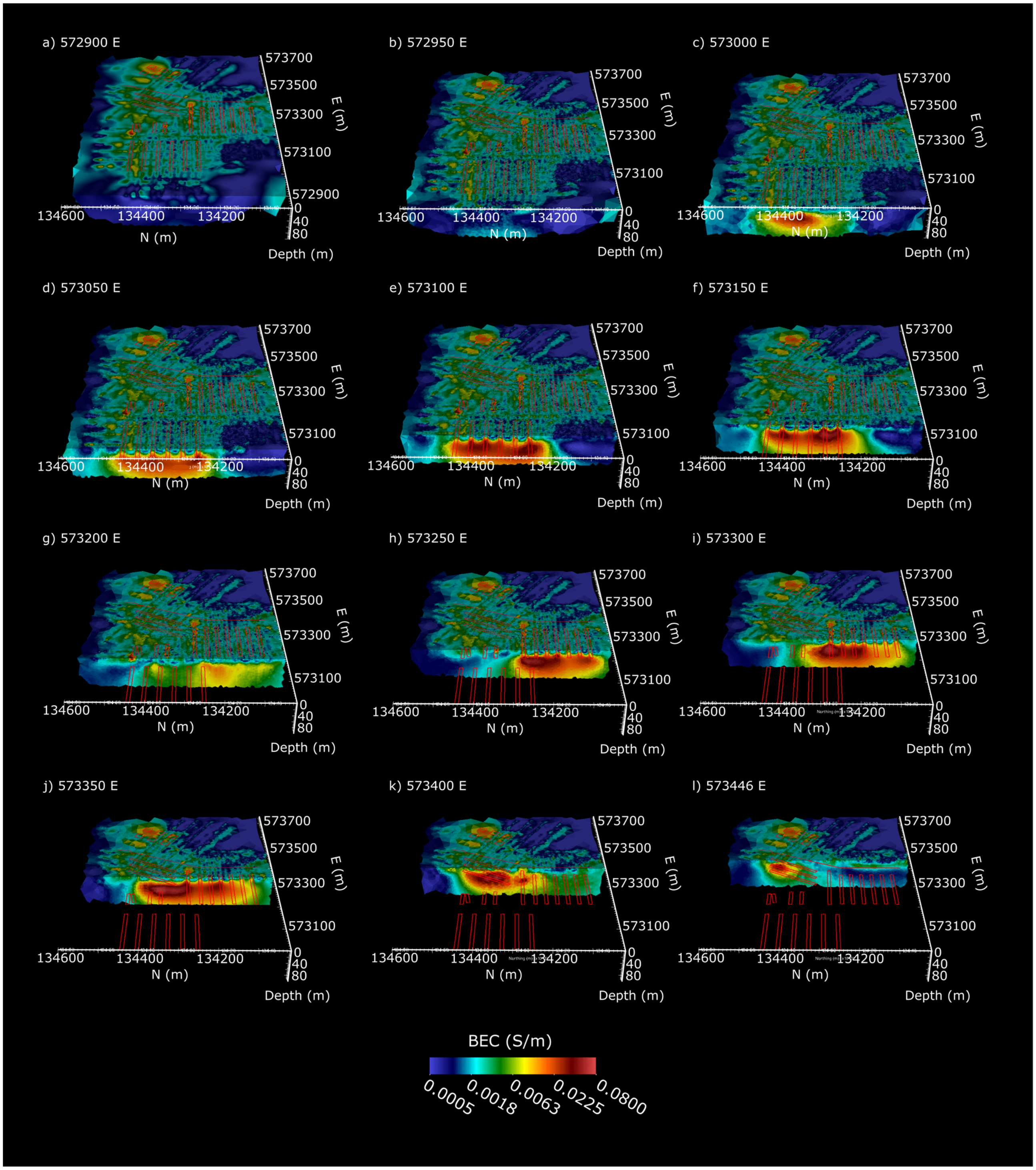

Figure 7. Eastern-facing cross-sectional views from a) 572900 E to l) 573446 E. Cribs and trenches are shown as red outlines near the surface. Figure is FIO.

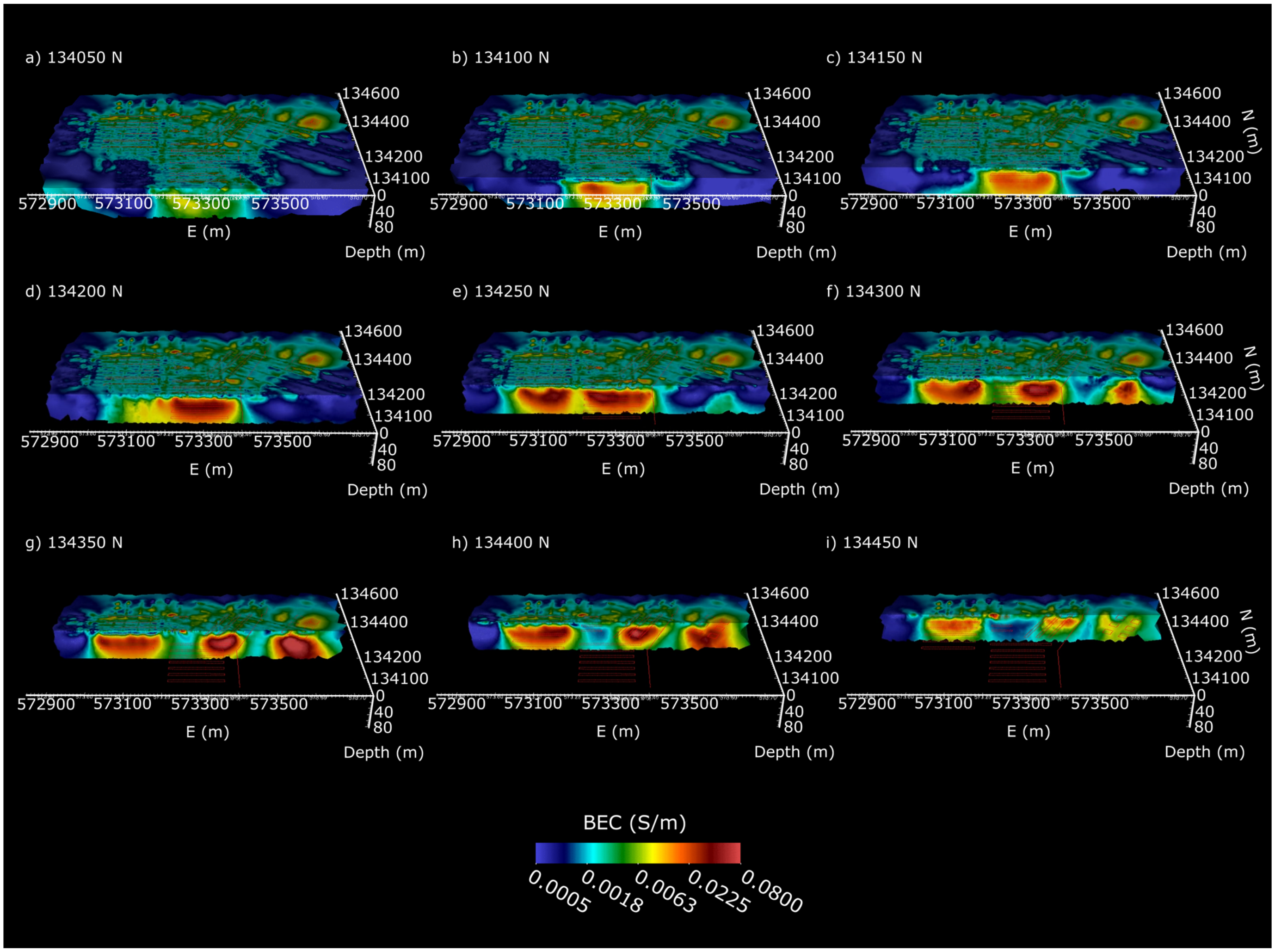

Figure 8. Northern-facing cross-sectional views from a) 134050 N to i) 134450 N. Figure is FIO.

Vertical profiles of BEC were extracted from *bc_cribs_ert.txt* surrounding wells C4161 (573842E 134146N) and C5923 (573588E 134361N). BEC values were extracted within a 5 m radial distance of the wells (Figures 9a and 10a) and averaged at 1 m depth intervals (Figure 9b and 10b).

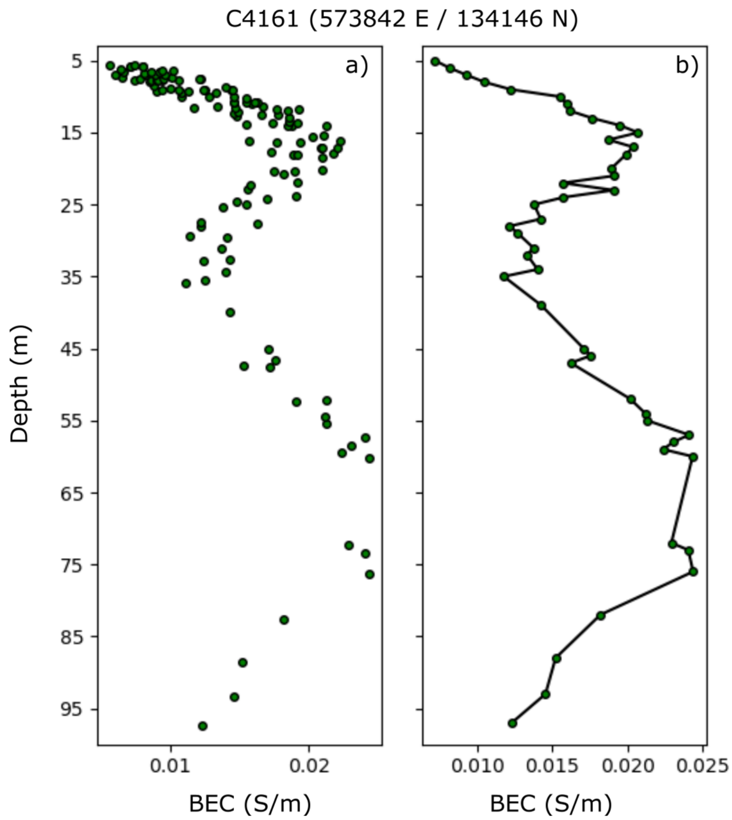

Figure 9. Vertical BEC versus depth extracted from *bc_cribs_ert.txt* within a 5 m radial distance of C4161 (coordinates shown) for a) all depths and b) averaged over 1-m depth intervals. Figure is FIO.

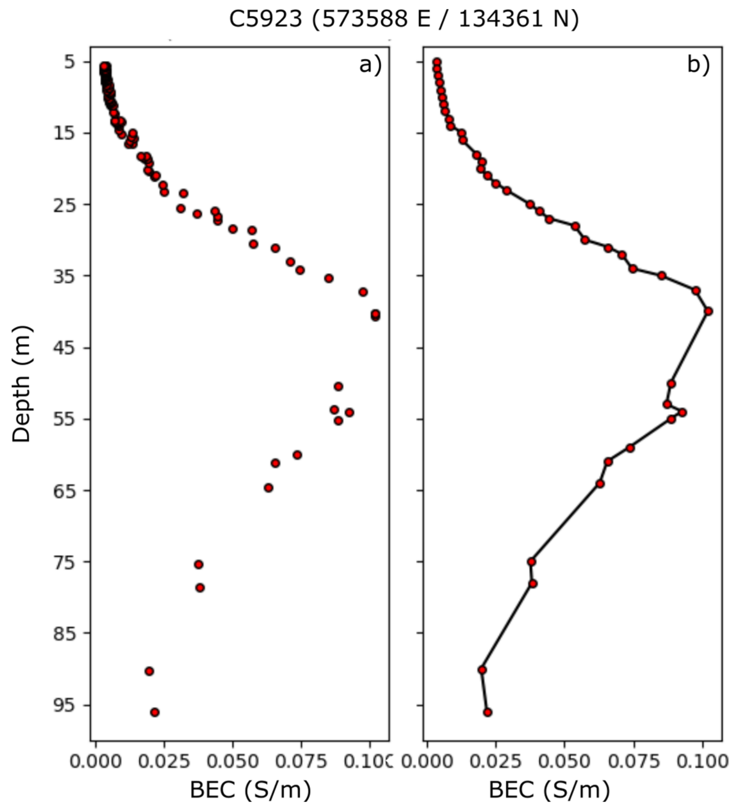

Figure 10. Vertical BEC versus depth extracted from *bc_cribs_ert.txt* within a 5 m radial distance of C5923 (coordinates shown) for a) all depths and b) averaged over 1-m depth intervals. Figure is FIO.

4.0 Conclusions

The 3D re-processing of the BC Cribs and Trenches ERT data using E4D software allowed for the true BEC to be resolved. The spatial delineation of BEC presented from this re-processing (Figure 6 through Figure 8) is based on the data from all ERT lines. This means that the BEC models shown had to fit all ERT datasets, and horizontal and vertical dimensions are true dimensions based on the data fit. This differs from the approach in Benecke et al. (2006) and Rucker and Fink (2007), which used geometric inversion to interpolate 2D lines into a 3D image. For both approaches, there was a higher BEC observed beneath most trenches and all cribs. Given the strong correlation between BEC and nitrate concentrations (Serne et al. 2009), the higher BEC is attributed to higher contaminant concentrations.

In addition to this re-processing, providing 3D spatial delineation of true BEC will allow for additional evaluations of BEC changes over time if an additional ERT survey is performed. This could provide a technical basis for reporting on contaminant movement at the BC Cribs and Trenches in both space and time.

5.0 References

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Appendix A – Formation Factor Measurements at Hanford

Slater and Ntarlagiannis (unpublished)[1] performed spectral induced polarization (SIP) measurements on twelve 4-inch cores from the 300 Area of the Hanford Site (refer to Figure 1 in the main report). SIP measurements were performed utilizing a PC-based NI-4461 dynamic signal analyzer board and external circuitry required for signal conditioning including two preamplifiers. Data were collected between the frequencies of 1000 and 0.001 Hz, although errors were encountered at frequencies below 0.01 Hz due to the discharge of batteries powering the preamplifiers.

Formation factor (F) measurements were performed for the Hanford formation cores over a frequency range of 1-1000 Hz, allowing time for proper saturation between different ionic strengths. There was some variability in the efficiency of the exchange of the fluid filling the pore space, likely due to preferential flow within the core and incomplete replacement of the pore fluid during each increase in ionic strength. This resulted in errors associated with F measurements. Table A.1 summarizes the F values and estimated errors for the Hanford 300 Area cores.

Table A.1. Formation factor, estimated errors, and surface conductivity

Well ID	Sample ID	Formation Factor (F)[a]	Error[b]	Surface Conductivity (S/m)[c]
C6189	2-12/c/40.6’-41.6’	6.1	$3.98x10^{-2}$[b]	$1.37x10^{-3}$
C6189	2-12/c/47’-48’	11.6	$1.85x10^{-3}$	$1.70x10^{-3}$
C6190	2-13/c/38’-39’	12.7	$2.68x10^{-3}$	$7.47x10^{-4}$
C6197	2-19/c/38-39	46	$3.16x10^{-3}$	$3.83x10^{-3}$
C6197	2-19/c/50-51	8.8	$1.13x10^{-1}$	$3.39x10^{-3}$
C6203	3-26/c/41’-42’	10	$1.43x10^{-2}$	$1.38x10^{-3}$
C6203	3-26/c/45.4-46.4	11.9	$8.39x10^{-2}$	$6.24x10^{-4}$
C6208	2-24/c/42’-43’	10.3	$1.98x10^{-3}$	$1.75x10^{-3}$

(a) F for this sample is estimated excluding the high fluid conductivity measurement.
(b) Error values are estimated based on the regression analysis fit standard deviation.
(c) Estimated from the intercept of the regression analysis fit.

[1] Slater L and D Ntarlagiannis. 2011. *Summary Report on Low Frequency Complex Resistivity Measurements of IFRC Wellfield Soil Cores*. Department of Earth & Environmental Sciences, Rutgers University- Newark, Newark, NJ.

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