



Three-dimensional electrical resistivity imaging of a gold heap

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ABSTRACT

A case study is presented for an electrical resistivity geophysical survey, conducted on a gold leach pad of low-grade ore. The electrical resistivity method maps the spatial distribution of electrical resistivity, which is an intrinsic property of material that measures the resistance of electrical current flow through a medium. The property is influenced by moisture content, ionic strength of the porewater, and mineralization. The geophysical method was applied to the leach pad to discern patterns of high and low moisture from past infiltration into the heap. A total of 12 survey lines were run in parallel over an 8 ha portion of the pad. The results showed that the high electrical resistivity areas, which are likely related to low moisture, could be explained by the physics of unsaturated fluid flow or evapotranspiration. The low electrical resistivity areas were thought to be related to high moisture from preferential flow along highly permeable regions of the heap. Validation of electrical resistivity was accomplished by correlating co-located geophysical data and rock samples of moisture content and total gold concentration. On an individual point-by-point basis, the correlation between the two datasets was low, due to the mismatch in measurement scales of the two characterization methods. Averaged resistivity data within discrete bins of the independent variable (rock sample), however, produced high correlations and empirical models were developed from a linear regression of averaged behavior.

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1. Introduction

Heap construction and structural non-uniformity is a main component to the movement of leachate and the recovery of metal. The movement of leachate is controlled by the permeability, a soil property that is influenced by dumping practices, geology, and ore pre-treatment. Low permeability zones, for example, may cause the leachate to bypass large portions of ore for more accessible high permeability regions by way of preferential flow. Wu et al. (2007, 2009) investigated preferential flow and channeling in heaps of low grade ore and related the phenomena to agglomeration and compaction of fine-grained material near the surface. They also proposed a secondary reason as increased bulk density at the bottom of the stack related to heap height and overburden pressure. As rock is piled higher on the leach pads, the weight of the overburden material causes the consolidation of pore space (i.e., reduction in void ratio)

which increases the density. Eriksson and Destouni (1997) discussed preferential flow in heaps and concluded the problem resulted from the wide grain size distribution, where the makeup of rock piles can be from the very finely textured silty material to large boulders.

1.1. Preferential flow

Preferential flow within the heap reduces yield due to the large amount of metal inventory that remains in unleached portions of the heap. The leachate will typically flow through those zones of highest permeability, and over a short period of time the high permeability zones are effectively leached. To gain insight in how fluid moves through heaps and possibly explain the reduced efficiency of metal capture over time, many researchers have developed flow and reactive transport models that can track the movement of the leachate. The models are based on the use of numerical or analytical mathematical codes that incorporate the physics and nonlinear nature of unsaturated flow. Orr and Vesselinov (2002) demonstrated a flow model through two types of heaps (crushed and stacked uniformly; run-of-mine and successive dumping) using the finite element code FEHM. A major finding was the application rate may vary some flowpaths within the heap. Cariaga et al. (2005) presented a multi-phase flow and physiochemical reaction model. In addition to tracking the liquid phase (leachate), the code explicitly models the gaseous phase (air),

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which most codes consider to be at atmospheric pressure. Other models, such as HeapSim (Ogbonna et al., 2005), also incorporate heat dynamics and microbial reactions.

1.2. Numerical modeling

All numerical models need hydraulic parameters that describe the physics of fluid flow. These hydraulic parameters relate, for example, how the moisture content affects the pressure head (i.e., water retention curve) or hydraulic conductivity through constitutive relationships. The van Genuchten relationship (van Genuchten, 1980) uses four hydraulic parameters to describe the water retention curve. In all cases, the parameters are dependent on the heap's makeup and are heterogeneous, requiring many unique measurements over the heap to obtain a site specific model. Unfortunately, the hydraulic parameters are expensive to obtain, are laboratory derived, and usually require long experimental times to record data at very low pressures. To by pass this expense, many modelers use published values from similar soil and rock types encountered in the heap. For example, Decker and Tyler (1999) present some hydraulic parameters of heap material from the Carlin Trend. Alternatively, a few hydraulic parameter measurements can be made and extrapolated to represent the entire rock pile (Lefebvre et al., 2007).

There are two main issues to the above prescribed modeling approach: the scale of laboratory-derived hydraulic parameter measurement and the destructive nature of the testing. Laboratory soil samples are conducted on a scale of tens of cubic centimeters, where as numerical model cells are much larger (up to tens of cubic meters). The issue of upscaling is still a heavily researched area within hydrogeology. Additionally, soil and rock samples are remolded to fit a particular laboratory apparatus such as a flow cell. These issues make the hydraulic parameter measurements appear non-representative of the heap, which can have a significant outcome on the predictive capabilities of the numeric model.

Geophysical methods offer both non-intrusive and non-destructive measurements of some hydraulic parameters at a scale relevant for validating a numerical model. In particular, methods that measure electrical properties such as dielectric permittivity or electrical conductivity can be related to the moisture content. Gloaguen et al. (2007) used cross-borehole ground penetrating radar on a waste rock pile to estimate the water content. Ground penetrating radar is a high frequency electromagnetic tool that measures the dielectric permittivity, which has been shown to be uniquely related to the moisture content (Topp et al., 1980). Orr (2002) and Orr and Vesselinov (2002) suggested that electrical resistivity could be used to measure basic hydro-chemical data for model calibration and validation. In this paper, we conduct a ground survey of electrical resistivity over a portion of a heap owned by Newmont Mining Corporation to help understand the hydraulic issues related to leaching. The work is meant as a case study to demonstrate how electrical resistivity data can be acquired and used to gain insight into a heap. The resistivity data are validated through drilling and sampling to show that the average behavior of moisture content and total gold concentration can be correlated to the measured resistivity. In this way, the electrical resistivity results could be used to advance the use of flow and transport models and increase metal recovery. Furthermore, the information would allow operators to target the unleached portions of the heap by varying application rates or using invasive methods.

2. Site description

Electrical resistivity imaging was conducted on the North Area Leach (NAL) pad at Newmont Mining Corporation's Carlin Nevada Operations. Fig. 1 shows the site location, which is 20 miles north of Carlin, NV. The NAL pad was constructed in 1987 to process low grade oxide gold ores mined from multiple open pits on the Carlin Trend. It

was constructed as a fully lined facility in a series of phased expansions.

The heap under investigation was underlain with synthetic liners placed directly on a prepared native soil base. An under-drain solution collection system, composed of 4 in perforated PVC pipe, lies on top of the synthetic liner. The ore consisted of both Run-Of-Mine (ROM) and crushed. Since 2004, however, only ROM ore has been placed. The portion of the pad characterized by the resistivity method included ROM nearest the surface and mixtures of ROM and crushed at depth. Lime is added directly to the ore and to solution for pH control. The ore is placed by end-dumping from 250 t trucks in nominal 10 m lifts with an ultimate heap-height of 100 m.

Gold is leached from the ore with a dilute sodium cyanide solution which is applied to the surface of the heap using drip emitters. Typical solution application rates of 0.005 gpm/ft² are used with a primary leach cycle lasting 90–120 days. Total barren solution flows from the heap range from 7500 to 8500 gpm. Gold is recovered from the pregnant solution by means of a Carbon-In-Column (CIC) plant. As of December 2008, over 208 Mt have been placed from which 3 Moz of gold has been recovered. The heap construction and leaching process is similar to that of pads on adjacent properties (see Bhakta and Arthur, 2002). Leaching of the pad ceased at least 1 year prior to the survey.

3. Theory

Resistivity (ρ) is a volumetric property that describes the resistance of electrical current flow within a medium. Direct electrical current is propagated in rocks and minerals by electrolytic and electronic conduction (Telford et al., 1990). Porous media can pass current through ions within the open framework of the pore space by way of electrolytic conduction, which relies on the dissociation of ionic species. Here, the conduction varies with the mobility, concentration, and degree of dissociation. By contrast, electronic conduction occurs in metallic-luster sulfide minerals, such as that found in heaps, where free electrons are available. Rocks and non-metallic minerals have extremely high resistivities (low conductivities) and direct current transmission through this material is difficult. Electrolytic conduction is relatively slow with respect to electronic conduction due to mass transfer rate limiting processes and is strongly influenced by the structure of the medium.

Field data are generally acquired using an established electrode array. A four-electrode array employs electric current injected into the earth through one pair of electrodes (transmitting dipole) and the resultant voltage potential is measured by the other pair (receiving dipole). Estimating resistivity is not a direct process. When current (I) is applied and voltage (V) measured, Ohms law is assumed and resistance is measured. The ratio of the transmitted current and observed potential is called the transfer resistance (R). Resistivity and resistance are then related through a geometric factor over which the measurement is made. The simplest example is a solid cylinder with a cross sectional area of A and length, L :

$$\rho = R \frac{A}{L} \quad (1)$$

In such cases where the actual volume involved in the measurement is known, the result is called the "true" resistivity and is considered to be a physical property of that material. However, field measurements involve an unknown volume of earth. Consequently, resistivity calculations are based on the hypothetical response for the given electrode geometry over a homogeneous, isotropic, half-space. This result is what is termed "apparent" resistivity.

Some common electrode configurations are dipole–dipole, Wenner, and Schlumberger arrays. These arrays configure the basic four-pole electrode geometry differently and their use depends upon site

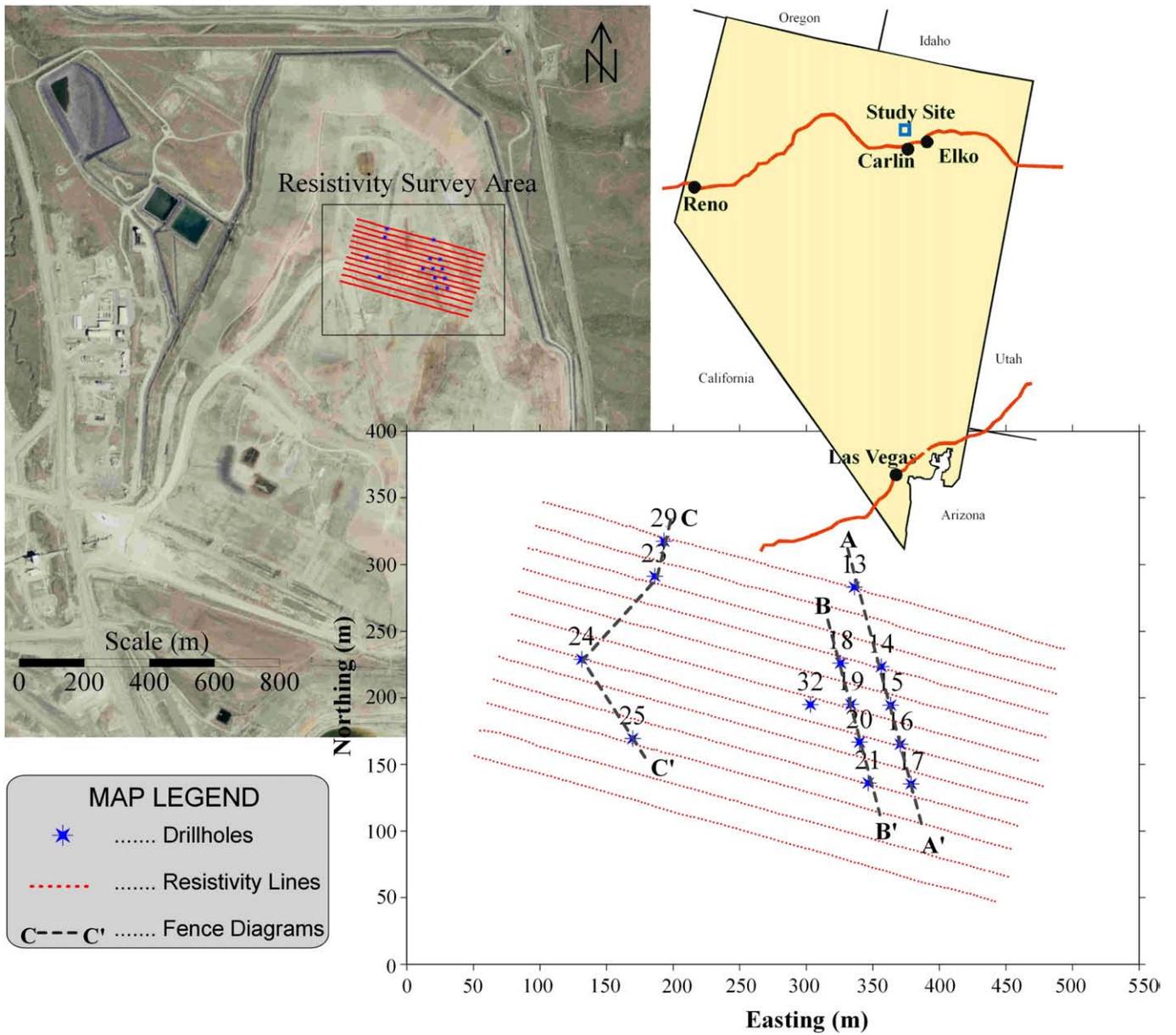


Fig. 1. North area leach pad at Newmont Mining Corporation's Nevada operation.

conditions and the information desired. Fig. 2, adapted from Telford et al. (1990), shows a schematic of the dipole–dipole configuration, where C1 and C2 are connected to the current source (i.e., transmitting electrodes) and P1 and P2 are connected to the volt-meter

(receiving electrodes). For the four-electrode array, the geometric factor, K , is

$$K = 2\pi \frac{1}{\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)}, \tag{2}$$

where r_1 through r_4 are defined in Fig. 2. Unlike the dipole–dipole array, the Wenner and Schlumberger arrays places the current electrode on the outside electrode pair and measure the voltage on the inside pair of electrodes.

Eqs. (1) and (2) are used to estimate an apparent resistivity, which assumes that each measurement of transfer resistance was a result of point electrodes on the surface of a homogeneous, isotropic, half-space:

$$\rho_a = 2\pi \frac{V}{I} K \tag{3}$$

where subscript “a” in ρ_a denotes the *apparent* resistivity. The apparent resistivity is not necessarily the true resistivity of the

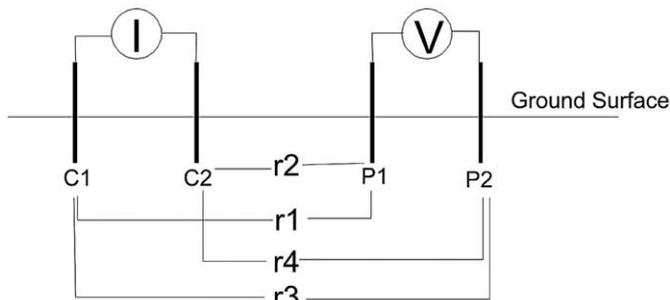


Fig. 2. Set up of the resistivity 4-pole array, with I =current (transmitter) and V =voltage (receiver).

formation, but a simplified resistivity that provides a starting point for subsurface evaluation. Other assumptions used in Eq. (3) are isotropy (i.e., no directional dependence of resistivity), no displacement currents (using a DC or low frequency current application), and that resistivity is constant throughout such that Laplace's equation can be assumed. Since the degree of heterogeneity is not known *a priori*, a true resistivity is not calculated from Eq. (3). To obtain a true resistivity, electrical resistivity tomography (ERT) is required, which generates a model of true resistivity using an iterative inverse methodology given the measurements of apparent resistivity, electrode arrangement, and other boundary conditions. Discussions of ERT and the methods by which the true resistivity is calculated can be found in several sources, including Loke and Barker (1996), LaBrecque et al. (1996), and Oldenburg and Li (1999).

4. Geophysical survey method

Methodologies for three-dimensional resistivity data collection and modeling are described in the literature (e.g. Slater et al., 2002; Dahlin et al., 2002; Rucker and Fink, 2007). The resistivity data acquisition on the NAL pad was conducted with the SuperSting R8 resistivity meter (Advanced Geosciences Inc., Austin, TX) with a multi-conductor cable and stainless steel electrodes. The electrodes are approximately 30 cm long and 2 cm in diameter, enough to provide direct contact with the earth without disturbing the ore itself. The resistivity method provides a volume measurement, thus small divots caused by electrode placement does not affect the outcome of the survey. The resistivity acquisition was conducted one line at a time, to create a series of profiles of two-dimensional data. Each line was composed of 140 electrodes, with an electrode spacing of 3 m. Data were acquired using the gradient array (a hybrid Wenner and dipole-dipole array, described in Stummer et al., 2004) for 12 lines, with a line spacing of 15 m (see Fig. 1). A total of 1780 electrode locations and 105,840 data values were collected on the heap over a period of 6 days (minimum time needed to place electrodes, move cable, and run the equipment). After noise removal and filtering of substandard data, the net data count was 81,242.

Although the electrical resistivity data were acquired along two-dimensional lines, the data can be combined into a three-dimensional data set given proper geo-referencing of the electrodes. Once geo-referenced, the data can be modeled together in an inversion code. For our study, the inversion code EarthImager3DCL (EI3DCL) was used to invert the NAL pad resistivity data. The code usage requires some familiarity with numerical modeling and the specific parameters that guide the inversion processes. Data formatting for code input is easy to replicate, but knowing exactly when the process is finished and whether the inversion was successful is quite challenging. Specifically, the EI3DCL code uses the finite element numerical method and can incorporate topography. The meshing for the heap model consisted of tetrahedral elements with 108,976 core nodes (139 rows, 56 columns, 14 layers) on which the electrical resistivity was calculated. For this application, the processing computer system comprised a Dell PowerEdge 6800 running Microsoft Windows Server 2003 64-bit with four dual core Intel Xeon 7120M processors (3 Ghz) and 32 GB of RAM.

5. Geophysical results

The measured resistivity values of the heap range from 7.8 to 500 ohm-m, demonstrating that the heap is highly heterogeneous. Fig. 3 shows the spatial distribution of the resistivity. The inversion model creates a solid block of cells, with each cell having a resistivity value and hence a color associated to it. To provide a means to look within the model, the solid block was sliced horizontally at four depths in Fig. 3a. The slices are color contoured with warm colors (red and yellow) representing high resistivity values and cool colors (blue

and purple) representing low values. An alternative view of the spatial distribution is to remove all data above (or below) a set resistivity value and show the remaining population as a solid rendered body. Fig. 3b shows a solid body of values less than 50 ohm-m and Fig. 3c shows a solid body of values greater than 75 ohm-m. These opaque bodies are presented from overhead and from the south side.

The distribution of resistivity within the heap shows high values near the surface and in the center of the measurement area. The near surface having high resistivity can be explained through evapotranspiration. The data were acquired in the middle of summer, and the reduction of moisture would cause an increase in resistivity. High resistivity values can also be seen at breaks in slope on the heap. It can be further reasoned that the bypassing of leachate along the toe of the heap is caused by a capillary barrier created by a dipping, fine-grained rock layer overlain on a coarse-grained rock. Orr (2002) modeled this phenomenon, and flow lines were shown to bypass the top portion of the coarser material. It is likely that the physics described in Orr (2002) is occurring along the sloped portion of the heap.

Low resistivity values are more common for rock with higher moisture content. The distribution of low resistivity material is observed to be along segregated portions of the measured area and extend down to the depth of investigation (about 70 m below the heap surface). The nature of the distribution could suggest preferential flow, where gravity drainage along high permeability zones allows the leachate to shortcut to the drainage system and liner. Most low resistivity regions appear to have a complete connection from top to bottom of the survey area. Orr and Vesselinov (2002) show example flow models of a heap, where vertically connected high saturation zones are also shown to exist.

An alternative hypothesis that may describe the variability in electrical resistivity is an even leachate distribution during infiltration, but differential drainage. Fine-grained soils and rock will retain higher moisture at lower pressures compared to coarse-grained material. After the cessation of leaching, the coarse-grained material drained more quickly and thus leaving the material at a higher resistivity. This is in direct opposition to the hypothesis of low resistivity related to preferential flow through zones of high permeability. The alternative suggests that the low resistivity is related to zones of low permeability. Regardless, the moisture content is likely the driving force behind the low resistivity in both hypotheses.

6. Geophysical calibration

Based on the assumption that the high resistivity material represents minimally leach ore, wells were drilled into the heap to capture additional inventory (Fig. 1). The wells were part of a patent-pending intrusive leaching process called Hydro-Jex (Seal, 2004, 2007), developed for the secondary stimulation of heap leach pads. The secondary stimulation process consists of drilling and casing holes within a heap, perforating the casing at specific depths, and injecting leachate at each depth using a straddle packer. The final stage is targeted rinsing. This secondary leaching application is extremely effective if the drilling targets are the areas left dry by ineffective primary leaching. Leachate volumes and injection pressures of the secondary stimulation system have been based on cylindrical models and refined by field testing. Actual flow paths of leachate within a heap are strongly dependent on the directional hydraulic conductivity of the heap which is, in turn, dependent on the heap construction and variability in particle sizes within the pad.

The rock samples from the wells were characterized for a number of geochemical parameters, including water content, gold, pH, sulfides, etc. Samples were extracted every 1.5 m from the top of the heap down to within 17 m of the liner. The drilling was accomplished with the dual rotary drill (Seal, 2007) and samples were prepared for offsite assaying, including the proper handling of samples for moisture analysis (sealed containers in a cooled environment). The water

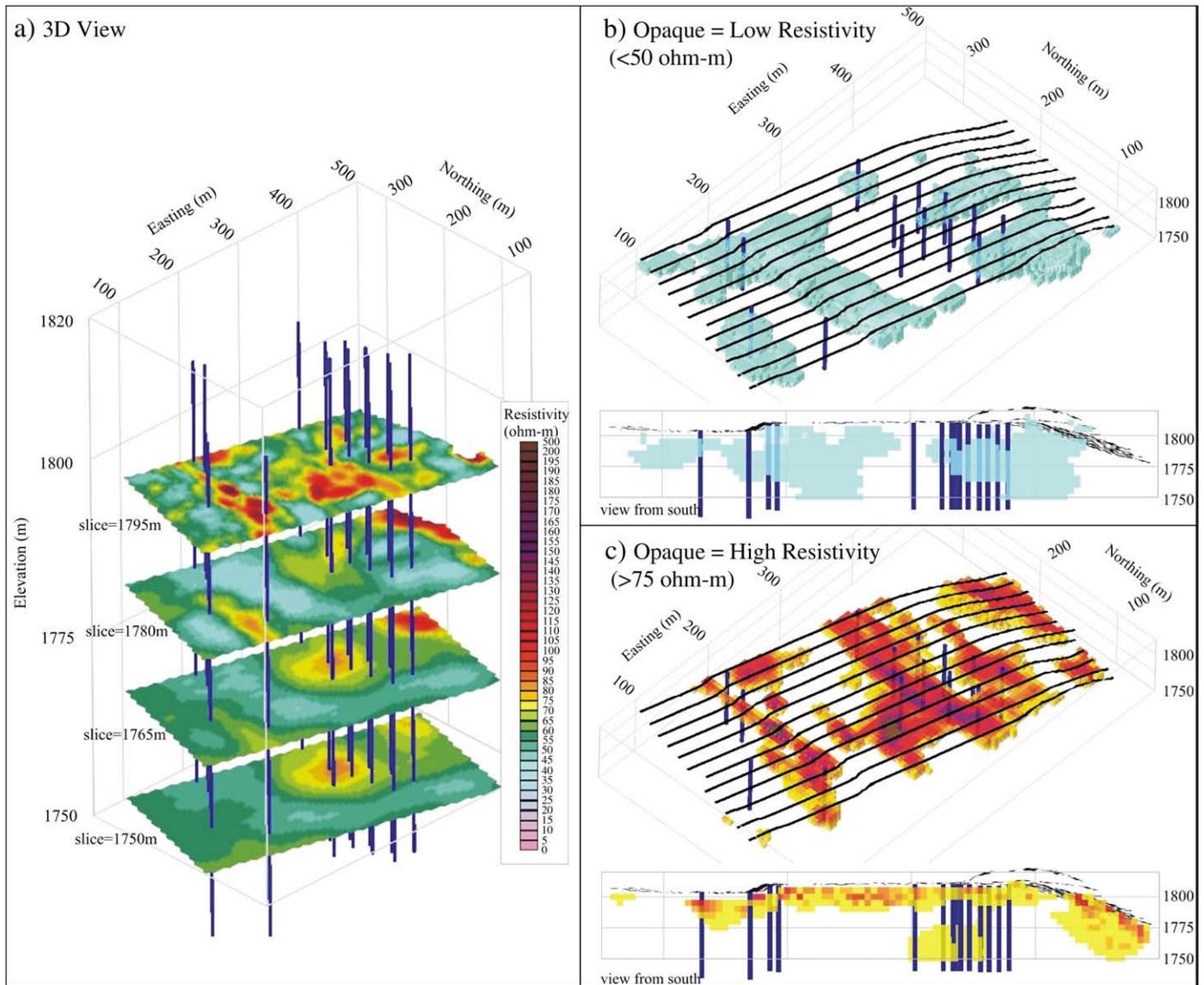


Fig. 3. Electrical resistivity distribution within the NAL pad, showing a) horizontal slices and solid model renderings of b) low resistivity and c) high resistivity material.

content and total gold concentration (fire assayed) data are presented in Fig. 4 as fence diagrams along three sections of the heap (A–A'; B–B'; C–C' in Fig. 1). To create the fence diagrams, the data from the rock samples were interpolated using the geostatistical technique of kriging through a variogram analysis. Geostatistics, in general, offers a way of describing the spatial continuity of natural phenomena by providing a means of interpolation (or extrapolation) at an unsampled location using this description (Isaaks and Srivatsava, 1989). For the kriging method, the variogram is used to estimate the spatial continuity of the sample population. These functions aim to measure the average degree of dissimilarity between an unsampled value and a nearby data value (Deutsch and Journel, 1992). Typically, larger distances equate to greater dissimilarity between data values.

For reference in the subplots of Fig. 4, the well names are along the top of each fence diagram. The data show that the moisture (Fig. 4a) generally increases from west to east with a great deal of heterogeneity. Some isolated pockets of both dry and moist zones are distributed within all of the fence diagrams. Dry zones are prevalent particularly near the surface. Fence diagram B–B' explicitly shows a high moisture zone just below the surface. Although the other two fence diagrams don't show an explicit connection of similar zones across multiple wells, there appears to be some continuity among the boreholes.

The gold concentration data of Fig. 4b also shows continuity, especially in fence diagram A–A'. White regions within the contour plots, in particular along wells 25 and 29, indicate that data do not exist for these areas. The top of well 15 shows very high gold concentrations with adjacent wells 14 and 16 also showing isolated pockets of higher values. Fence diagram C–C' appears to be less heterogeneous, with larger and more continuous features seen within the section.

The degree of similarity between electrical resistivity and moisture content or gold concentration is presented in Fig. 5. The reciprocal of resistivity (electrical conductivity) was plotted as a scatter plot with moisture content on the left and with the logarithm of gold concentration on the left. Both plots show a high degree of scatter with the electrical conductivity. Although not shown, the correlation among the moisture and gold with electrical conductivity is low with a correlation coefficient less than 0.1 for both sets of data. The low correlation is likely due to the geophysical data scale (tens of cubic meters) versus the rock sample characterization scale (tens of cubic centimeters). The geophysical data averages over much larger volumes, which minimizes the possibility of large fluctuations over short distances. Additionally, other factors are likely influencing the scatter (clay content, texture, mineralization), and a multivariate analysis may prove to be useful in reducing scatter among the variables.

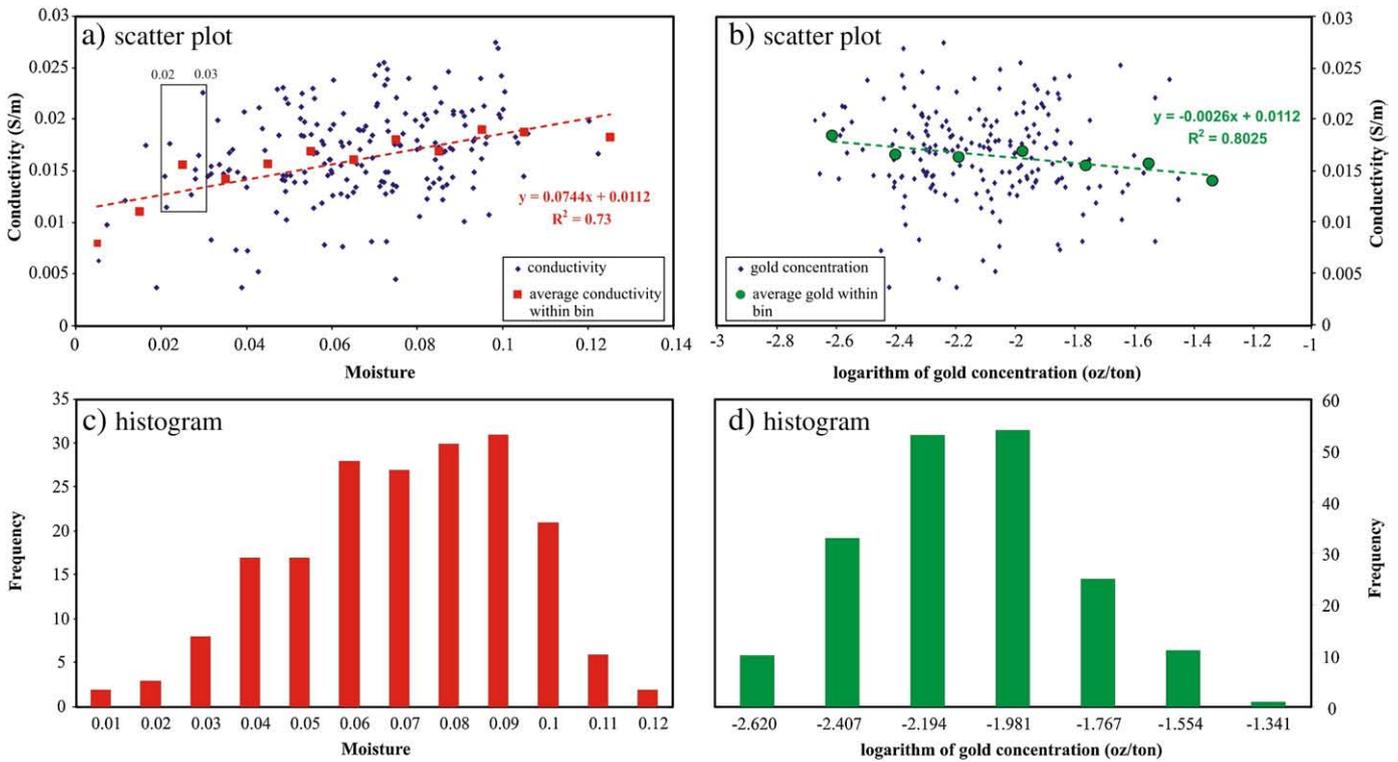


Fig. 5. Regression analysis of co-located electrical resistivity and the independent variables of moisture and total gold. a) scatter plot of electrical conductivity vs. moisture; b) scatter plot of electrical conductivity vs. logarithm of gold concentration; c) histogram of moisture showing discrete bins used for averaging conductivity; d) histogram of gold concentration showing discrete bins used for averaging conductivity.

An alternative comparison of co-located well and geophysical data was conducted through binning of the independent variable. The moisture and gold concentration data were binned into discrete groups to observe average behavior of the data at different scales. A histogram analysis presented in Fig. 5c and d, shows that the binning methodology produces slightly skewed normal distributions. These bins were then used to create a new scatter plot by averaging electrical conductivity data within the bins. Fig. 5a shows an example subset of conductivity data that were averaged in the moisture bin from 0.02 to 0.03. Eight co-located well and geophysical measurements fell within the bin with an average conductivity of 0.01563 S/m and standard deviation of 0.00343 S/m. The scatter of averaged conductivity produced a high correlation with moisture, with an R^2 of 0.73. Similarly, the average conductivity versus logarithm of gold concentration produced an R^2 of 0.80. It is unlikely that there is direct causality of high gold and low conductivity, and the statistics simply suggest a correlation among the two variables. The indirect correlation of gold and direct correlation of moisture to electrical conductivity also helps confirm the justification of targeting dry zones with secondary leaching applications.

Lastly, the empirical regression formulae, that were established between the well and resistivity data, can be used to convert all resistivity data to either moisture or gold concentration. The conversion is accomplished using an inverse procedure on the regression formulae in Fig. 5. Fig. 6 demonstrates the results of the conversion, with a contour of data from a horizontal slice through the block. The slice is at an elevation of 1790 m and the contouring intervals were created from the histograms in Fig. 5. Extrapolation outside the data bounds was not done, and so a constant color was associated to values greater or less than that associated with the scatter plot. The moisture data of Fig. 6a show some continuous regions of both high and low values. The inverse relationship between moisture and gold concentration is evident in Fig. 6b, where similar

shaped bodies of high gold and low moisture are observed in the slices. Based on the conversion of geophysical data, wells 18, 25, and 32 appears to be in a prime locations for enhanced recovery with the secondary stimulation process.

7. Conclusions

An electrical resistivity geophysical survey was conducted on a gold leach pad of low-grade ore after the cessation of the primary leaching cycle. The subject site was the North Area Leach pad at Newmont Mining Corporation's Carlin Nevada Operations, north of Carlin, NV. The resistivity survey was conducted over an area of approximately 8 ha on the surface of the heap. Twelve lines were evenly spaced over the area, and data were acquired using a two dimensional profiling method. By geo-referencing the data locations within the measurement area, all of the data can be combined into a three-dimensional model to determine the spatial distribution of electrical resistivity within the heap. Low electrical resistivity is typically associated with high moisture content, high ionic strength pore water, fine-grained soil particles, and to some extent mineralization.

The electrical resistivity data showed a complex pattern of low and high values within the measured volume. High values of resistivity near the surface of the heap were reasoned to be fairly dry due to natural evaporation of moisture during the summer measurement campaign. Additionally, high values were seen at large slope angles, which could also be explained by capillary barriers causing leachate to bypass large portions of the heap near the top of the slope. Low resistivity values were observed to be along continuous zones, with full connection from top to bottom of the survey volume. Preferential flow channeling of leachate within the heap may explain these low resistivity zones.

The heap was drilled for an enhanced recovery method using pressurized injections. The recovery method re-stimulates portions of

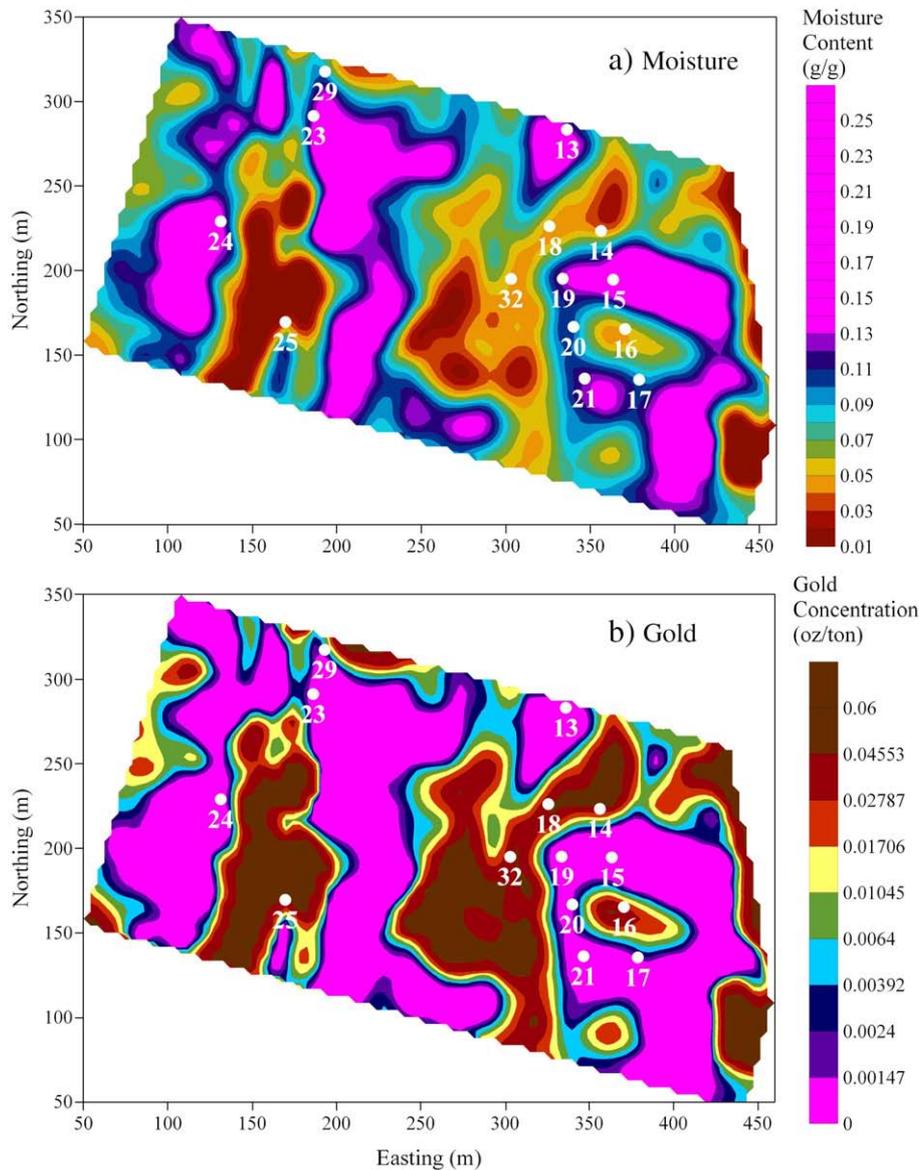


Fig. 6. a) Moisture and b) gold contours along a horizontal slice at an elevation of 1790 m, created by converting electrical resistivity to the respective parameter.

the heap that were thought to have a high degree of gold inventory remaining. The rock samples from the drilling were characterized for several geochemical parameters including moisture content, gold, pH, and others. For validation of the geophysical data, co-located resistivity–geochemical measurements were evaluated empirically through regression. Scatter plots of moisture and total gold concentration showed low correlation on a point-by-point comparison, which was likely the result of mismatched measurement scales. Geophysical data typically represent tens of cubic meters of undisturbed heap while the geochemical measurements are conducted on laboratory samples of tens of cubic centimeters. The resistivity data are averaged over a much broader volume than the moisture data. To overcome some of these issues, the independent regression variables of moisture and gold data were broadly binned into discrete categories and the resistivity data were averaged within each bin. The correlations improved with the averaged resistivity data, with R^2 values of .73 and 0.80 for moisture and gold, respectively. The empirical regression model was then used to convert all resistivity data within the heap to moisture and total gold. Knowing the spatial distribution of resistivity should provide a better methodology for targeting unleached portions of the heap with secondary leaching applications.

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