Electrical Resistivity Surveys in Prospect Gulch, San Juan County, Colorado

By Robert R. McDougal

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By Robert R. McDougal[1]

Abstract

Prospect Gulch is a major source of naturally occurring and mining related metals to Cement Creek, a tributary of the upper Animas River in southwestern Colorado. Efforts to improve water quality in the watershed have focused on Prospect Gulch because many of its abandoned mines and are located on federal lands. Information on sources and pathways of metals, and related ground-water flow, will be useful to help prioritize and develop remediation strategies. It has been shown that the occurrence of sulfate, aluminum, iron, zinc and other metals associated with historical mining and the natural weathering of pyritic rock is substantial. In this study, direct current resistivity surveys were conducted to determine the subsurface resistivity distribution and to identify faults and fractures that may act as ground-water conduits or barriers to flow. Five lines of resistivity data were collected in the vicinity of Prospect Gulch, and cross-section profiles were constructed from the field data using a two-dimensional inversion algorithm. The conductive anomalies in the profiles are most likely caused by wet or saturated rocks and sediments, clay rich deposits, or high TDS ground water. Resistive anomalies are likely bedrock, dry surficial and sub-surface deposits, or deposits of ferricrete.

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Introduction

Prospect Gulch is a major source of naturally occurring and mining related metals to Cement Creek, a tributary of the upper Animas River in southwestern Colorado. In this highly mineralized sub-basin it has been shown that the occurrence of sulfate, aluminum, iron, zinc and other metals associated with historical mining is substantial, but relatively insignificant compared to contributions from areas of natural weathering of highly altered, pyritic rock (Wirt and others, 2001). While many of the streams in the area have low pH and elevated metal loads caused by acid-rock weathering, acid-mine drainage from historical mining has contributed to the degredation of ground and surface water (Church and others, in press). Efforts to improve water quality in the watershed have focused on Prospect Gulch because many of its abandoned mines and waste-rock piles are located on land managed by the U.S. Bureau of Land Management (BLM). Information on sources and pathways of metals, and related ground-water flow, will be useful to the BLM to help prioritize and develop remediation strategies.

The direct current (dc) resistivity method used in this study is a geophysical technique that uses variations in electrical resistivity of the earth to help characterize subsurface features related to geologic structures and ground-water geochemistry. The surveys were conducted to determine the subsurface resistivity distribution and to identify faults and fractures that may act as ground-water conduits or barriers to flow.

This study was conducted as part of the Process Studies of Contaminants Associated with Mineral Deposits Project by members of the U.S. Geological Survey’s Central Region Crustal Imaging and Characterization Team. The results of the electrical geophysical surveys presented here are part of an integrated effort, including seismic surveys, drilled core and monitoring wells, stream tracer injection studies, and geochemical analyses, to characterize and model ground-water flow in Prospect Gulch. These data sets will be used to help constrain the conceptual models of current ground-water conditions.

Purpose and Scope

This report describes the process and results of a geophysical investigation of subsurface geologic and hydrologic conditions as they relate to ground-water flow in a mountainous sub-basin. Four lines of resistivity data were collected at the base of Prospect Gulch using an automated multi-channel system. An additional line of data was collected near the Henrietta and Lark mines to record pre-remediation subsurface conditions. Cross-section profiles were constructed from the field data using a two-dimensional inversion algorithm.

Physical Setting

Prospect Gulch, located approximately 10 km north of Silverton, Colorado, is a steep-gradient alpine to sub-alpine mountain sub-basin that drains the southern flank of Red Mountain No. 3 (fig. 1). The stream in Prospect Gulch has an elevation change of 800 m and is approximately 2.4 km in length. The majority of precipitation in the area occurs as snowfall (94 cm/year), with an average annual precipitation of about 114 cm (Wirt and others, 2001). During the summer months thunderstorm events can produce substantial amounts of precipitation.

Much of Prospect Gulch is above tree line, which is approximately 3,536 m at this latitude. Non-forested areas primarily consist of alpine vegetation, poorly developed soils, talus, and exposures of bedrock.

Several mine adits and large waste dumps are located on BLM property in the drainage. These are associated with the Lark, Henrietta, and Joe and John mines. Other notable historical mines include the Hercules and Galena Queen mines (fig. 1).

Geologic Setting

Prospect Gulch is located on the margin of the historic Red Mountain mining district, near the northwest structural margins of the San Juan and Silverton calderas. Rocks in Prospect Gulch formed following formation of the 28.2 Ma San Juan Caldera, and are coincident with and or post-date formation of the 27.8 Ma, Silverton caldera (Yager and Bove, 2002). These intermediate- to felsic- composition igneous rocks and minor volcaniclastic sedimentary rocks were deposited on the flanks of central vent volcanoes. This igneous sequence, referred to as the Silverton Volcanics, formed from lavas and volcaniclastic sediment that infilled the San Juan caldera over an area of 14 km^2 to a thickness of nearly a kilometer (Lipman, and others 1973). In order of their relative abundance, the primary minerals of the intermediate composition porphyritic lavas of the Silverton Volcanics include plagioclase, quartz, hornblende, pyroxene, ± biotite, and opaque oxide minerals.

Following caldera formation and simultaneous with Silverton Volcanic deposition, regional propylitic alteration occurred throughout much of the study area. As the San Juan caldera cooled and degassed, the primary mineral assemblages were altered to secondary assemblages containing chlorite, ± epidote, ± calcite, ± pyrite, fine grained muscovite, and iron oxide minerals (Yager and Bove, in press).

Several small-volume plugs and dikes of dacite to rhyolite composition intruded along the structural margins of the calderas long after caldera activity ceased. Based on the isotopic ages of the intrusions near Prospect Gulch, indications are that they formed several million years after the eruption of the intermediate composition Silverton Volcanics lavas during the Miocene Epoch. The intrusions are thought to have provided the heat source for the hydrothermal alteration and mineralization of the Red Mountain mining district (Lipman and others, 1976; Bove and others, 2001).

A number of alteration types are found in Prospect Gulch and vary substantially from north to south across the sub-basin (Bove and others, in press). Near Red Mountain #3, acid sulfate mineralization is exposed and is associated with pervasive silicification that formed resistant ridges. The acid sulfate mineralization is characterized by high sulfate content and includes the mineral assemblage of quartz, alunite, pyrophyllite (QAP) and pyrite. More easily weathered argillic alteration occurs on the margins of the QAP assemblage. The most abundant alteration assemblage in Prospect Gulch is the quartz-sericite-pyrite (QSP), locally containing ten to twenty volume percent pyrite. In the lower part of the sub-basin, regional propylitic alteration is dominant.

Structural interpretation of mapped veins in the sub-basin indicates that general trends of northwest, north, and northeast are predominant. There is evidence that these veins may have formed coincident with mineralization along structural zones of weakness. East-west trending veins, although uncommon, do occur in Prospect Gulch (Bove and others, in press).

Methods of Investigation

Electrical Properties of Earth Materials

Electrical resistivity, which can be expressed inversely as electrical conductivity, is a fundamental property of all earth materials. The degree of resistance or conductance varies with rock or sediment type, porosity, clay mineral type and content, and the quantity and quality of moisture. Poorer quality ground water (that is, water with higher concentrations of dissolved solids) or sediments with higher clay content are usually more conductive (Zohdy and others, 1974). The presence of electrically conductive minerals, such as metallic sulfides can also result in higher conductivity values.

Resistivity is expressed in ohm-meters, and is an estimate of the earth's resistivity calculated using the relationship between resistivity, an electric field, and current density (Ohm's Law), and the geometry and spacing of the current and potential electrodes. When the earth is not homogeneous and isotropic, which is usually the case, this estimate is called the "apparent resistivity", which is an average of the true resistivity in the measured section of the earth (Dobrin and Savit, 1988). Often, in geophysical studies associated with ground-water characterization it is useful to convert values of resistivity to conductivity to identify or emphasize conductive anomalies or zones. The range of resistivity values from 1 to 1,000 ohm-meters collected in the field can be expressed in conductivity units of 1,000 to 1 millisiemens per meter using the conversion factor:

1000/ohm-meters = millisiemens/meter (McNeill, 1980)

Because of the many factors that affect terrain conductivity, interpretation of geophysical surveys can often result in a non-unique explanation for a conductive or resistive anomaly. Therefore, in this study, the availability of information from drilled core samples (Johnson and Yager, 2006) and seismic profiles aided in the interpretation of the resistivity data.

Collection of Resistivity Data

In July 2004, four lines of resistivity data were collected on and down gradient from the alluvial fan at the base of Prospect Gulch (fig.2). Line 1, paralleling County Road 140, starts at the north end of the Prospect Gulch alluvial fan, crosses Prospect Creek, and ends at the southern extent of the fan. Lines 2 and 3 coincide with the location of two seismic lines collected contemporaneous with the resistivity. Line 4 extends from the southern extent of the alluvial fan past an iron bog adjacent to Cement Creek. Line 5 was located below the Lark Mine on an old road grade composed of waste rock from the Henrietta Mine. Subsequent remediation at this site was supervised by the BLM. Post-remediation seismic surveys have been completed in this area, and future resistivity surveys are planned to help evaluate the effectiveness of removal of the waste rock.

The resistivity system used in this study is an Advanced Geosciences, Inc. (AGI) SuperSting R8/IP eight channel multi-electrode instrument. The system was used to record lateral and vertical resistivity variations in the subsurface. Multi-electrode systems have the capability of recording many channels of data simultaneously and allow for the collection of very dense dc resistivity data in a relatively short amount of time. The electrode array was connected to the R8 transmitter/receiver, and consisted of 76 dual mode switches in contact with the ground using stainless steel stakes. To minimize contact resistance with the ground, the stainless steel stakes were watered with salt water as needed. The dual mode electrodes are automatically switched to allow each to operate as either current or potential electrodes in the array. Equidistant spacing between each electrode varied depending upon the desired line length, depth of investigation, and data resolution.

In this study, the surveys were conducted using an inverse Schlumberger array (Telford and others, 1990). A resistivity measurement in this configuration uses from four to ten of the electrodes simultaneously, half of the electrodes on either side of a central point. The inner two electrodes transmit current, while the outer electrodes measure the electrical potential. After the instrument finishes collecting data from the electrode array, a group of electrodes can be moved from the beginning of the line to the end of the line and data collection is then re-initiated over the section of the line that had not been previously measured (referred to as a “roll-along”). This method allows for the collection of lines of data of effectively any length, without sacrificing resolution. An electronic distance meter (EDM) survey system was used to accurately record the position and elevation of the resistivity lines.

The data collected in the field were converted from apparent resistivity to inverted resistivity with depth using a numerical inversion of the data. The inversion routine used for this study was EarthImager 2D, a DC resistivity inversion program from Advanced Geosciences, Inc. The result of the inversion process is a highly detailed cross-section of resistivity corrected for changes in topography along the profile using the EDM elevation and position data. The inversion routine minimizes the root mean square (RMS) error between the measured apparent resistivity and the resistivity calculated from the inverted model. To further minimize the RMS error, multiple iterations of the inversion process were run and noisy or poorly fit data points were identified and removed after each inversion. The RMS error for all of the resistivity lines was reduced to less than five percent. Profiles of the measured apparent resistivity pseudosections, calculated apparent resistivity pseudosections, and inverted resistivity section are shown in appendix 1. Crossplots of measured versus predicted apparent resistivity are shown in appendix 2.

Results

Inverted data from the dc resistivity surveys were used to construct profiles of sub-surface electrical properties of the Prospect Gulch alluvial fan, the area along the Cement Creek road from Prospect Gulch to Georgia Gulch, and the waste rock below the Lark Mine (fig. 2). Resistivity values in ohm-meters obtained from the inversion program were converted to conductivity values in millisiemens per meter to emphasize conductive anomalies as previously described. Data grids were calculated using the minimum curvature gridding method in Surfer v.8 from Golden Software, Inc., and plotted as contoured profile maps ranging in value from 0 to 37 millisiemens/meter.

The conductive anomalies in these profiles are most likely caused by wet or saturated rocks, clay-rich sediments, or high TDS ground water. Resistive anomalies are likely bedrock, dry surficial and sub-surface deposits, or deposits of ferricrete. Identification of these conductive and resistive zones is important to help characterize ground-water flow in the sub-basin and help constrain ground-water modeling efforts. The conductivity profiles presented in this study were plotted to the same horizontal and vertical scale. The end points for each line are given in Universal Transverse Mercator (UTM) coordinates, Zone 13N, North American Datum (NAD) 1927.

It is important to note that two-dimensional lines of resistivity data are collected in three-dimensional space, and must be interpreted bearing in mind the possibility of off-survey-line anomalies. The magnitude of this “3D effect” depends upon the lateral distance of the anomaly from the survey line and can result in misinterpretation of its size and location.

Line 1

Line 1 is located along the western side of the Cement Creek road and extends from the northern end of the alluvial fan at the base of Prospect Gulch to the southern end, just past the creek draining the sub-basin (fig. 2). This survey line was positioned to identify conductive anomalies that are possibly related to ground water discharging to Cement Creek from Prospect Gulch. The line was not positioned on the east side of the road closer to the creek, as originally planned, because of the presence of a buried phone line, metal pipes, and the remnants of an old railroad line.

This line consisted of a total of 124 electrode positions (76 initial electrodes with three roll-alongs of 16 electrodes each), using 2 m spacing, for a total line length of 248 m (fig. 3). In this configuration the maximum depth of investigation was approximately 30 to 35 m. However, the data resolution and signal-to-noise generally decrease below 20 to 25 m.

The conductive zone on the northeastern end of the line between approximately 170 and 230 m occurs in the thickest part of the Prospect Gulch alluvial fan. The highest conductivity values are interpreted as wet or saturated alluvium where they occur near the surface, and wet or saturated bedrock where they occur at depth although the alluvium-bedrock interface is not well defined. Conductive anomalies occurring in bedrock may be associated with fracture controlled ground-water flow and conductive anomalies in the alluvium may be associated with increased clay content. A well-core log from an exploration well drilled near Line 1 shows that bedrock (Silverton Volcanics) in this area is highly fractured and hydrothermally altered (Johnson and Yager, 2006). The small near surface conductive zone at 130 m along the line is likely caused by a buried metal cultural object, given its size and electrical contrast with the adjacent area.

The resistive near surface anomaly between 75 and 125 m is located in an area where ferricrete and dry surficial deposits were observed near the intersection with Line 3. The resistive zone at the surface from 0 to 60 m along the survey line in the vicinity of Prospect Creek occurs where bedrock outcrops and dry surficial deposits are found along the banks of the creek.

Line 2

Line 2 extends across the alluvial fan at the base of Prospect Gulch (fig. 2). The location of this line was selected to correspond with the position of a contemporaneous seismic survey line. Line 2 consisted of a total of 92 electrode positions (76 electrodes in the initial array with one roll-along of 16 electrodes), using 2 m spacing, for a total line length of 182 m (fig. 4).

As with Line 1, Line 2 is characterized by high resistivity at the surface, which is the result of dry surficial deposits and ferricrete. In some areas near the center of the line, ferricrete was exposed at the surface. The very dense nature of the ferricrete made placement of the electrodes difficult and resulted in very high contact resistance and low signal-to-noise response from the instrument.

The large conductive zone extending laterally from 20 to 85 m is interpreted to be the result of a saturated clay-rich interval encountered in the well-core between a depth of approximately 10 to 25 m. Below this interval, a highly fractured and altered bedrock interval to a depth of approximately 40 m was recorded in the well log (Johnson and Yager, 2006).

Line 3

Line 3 extends from the break in slope at the top of the Prospect Gulch alluvial fan to the Cement Creek road, and intersects Line 2 near the test well. The location of the line was coincident with a seismic survey line. The array consisted of 76 electrodes using 2 m spacing, for a total line length of 150 m (fig. 5).

The conductive zone extending laterally from 25 to 55 m correlates with the position and depth of the conductive anomaly interpreted as the clay-rich interval in Line 2. This conductive anomaly extends semi-continuously to the northwest with another conductivity high occurring between 115 and 140 m. The relative depth of these conductive anomalies indicates that the saturated alluvial zone is deeper near the bottom of the alluvial fan and may also indicate the changing depth of clay-rich sediments. The conductive zone at the surface at approximately 120 m is near an area of saturated ground observed to be associated with an iron bog. The thin resistive layer beneath this conductive zone is interpreted as a layer of ferricrete separating the conductive shallow ground water from deeper conductive water.

The resistive zone at the surface, which extends from 0 to 100 m, is interpreted as ferricrete and dry surficial deposits. The well-core from here shows that ferricrete extends from near the surface to a depth of approximately 6 m (Johnson and Yager, 2006).

Line 4

Line 4 extends along the Cement Creek road from near the southwestern end of Line 1 to the alluvial fan at the base of Georgia Gulch. The line consisted of 92 electrode positions (76 electrodes in the initial array with one roll-along of 16 electrodes) using 5 m spacing for a total line length of 455 m (fig. 6). The line was positioned to identify conductive zones down gradient from Prospect Gulch that might be associated with an iron bog along Cement Creek.

The line is generally resistive at the surface along its length, resulting from ferricrete and extremely dry soil and surficial deposits. The highly resistive surface layer at the northeast end of the line coincides with the resistivity high at the southwest end of Line 1, and is the result of observed ferricrete and dry surficial deposits. The “cat’s eye” shaped resistive zone that extends from 120 to 140 m at a depth of 5-35 m occurs in an area of mapped mineralized veins (Yager and Bove, 2002). Therefore, given the shape and depth of the anomaly, this resistive feature is possibly a concealed fault or vein that is likely silicified.

The conductive near surface layer extending from 260 to 430 m is interpreted as wet clay and alluvium eroded off of the ridge between Prospect Gulch and Georgia Gulch. The resistive zone below this layer is likely bedrock that becomes more conductive down gradient to the southwest.

The prominent conductive zone on the southwest end of the line between 30 and 180 m is interpreted as deep circulating ground water draining from Prospect Gulch. Well and piezometer samples in this area indicate that ground-water temperatures are relatively warm and that there is a strong upward gradient in flow (Johnson and Yager, 2006). Therefore, we conclude that deep circulating ground-water flow is likely influenced by the resistive structure near the upper bog and that the near surface layer of ferricrete acts as a confining layer. The highly conductive anomaly between 40 and 110 m is interpreted as the result of concentrated high TDS ground water that is mantled and confined by the ferricrete. However, this zone could also contain clay-rich sediments, but this alternate interpretation cannot be confirmed without direct core data.

Line 5

Line 5 is located midway up Prospect Gulch on an old road grade below the Lark mine. The line was positioned to intersect ground water draining from the tailings and waste rock associated with the mine in an effort to record pre-remediation subsurface conditions. The electrode array consisted of 76 electrodes using 3 m spacing for a total line length of 225 meters (fig. 7). Several seeps and springs were observed below the embankment to the north of the line, some having orange colored water with obvious iron precipitation. The monitoring well drilled near the line shows a perched water-table system in colluvial material above fractured bedrock. The conductive zone between 30 and 110 m is likely caused by the interaction of the perched near-surface water table with mine waste rock. The well data, core, and water levels show that the colluvial material and fractured bedrock below a depth of approximately 15 m is commonly unsaturated, with a deeper water table occurring at a depth of approximately 50 m, near the limit of the depth of investigation for the resistivity data. The near-surface conductive anomaly between 155 and 200 m along the line is coincident with seeps and saturated surface soils. This zone is interpreted as a plume of conductive shallow ground water draining from the Lark mine waste rock. The sharp interface between conductive and resistive zones suggests that ground water here is perched on a resistive surface of ferricrete or bedrock.

Conclusions

The resistivity profiles presented in this study generally identify zones of varying near surface geology (for example, clay-rich sediments and ferricrete) as well as zones of conductive ground water. Conductive zones at depth indicate the presence of a deeply circulating ground-water system that occurs either in saturated bedrock or faults and fractures. Where ground water is associated with mine waste the conductivity is generally high, suggesting poor water quality.

This study illustrates the utility of combining geophysical investigations with available well-core logs to expand the interpretation and understanding of the ground-water and geologic systems in complex mountainous terrains. By correlating well and piezometer data with the resistivity profiles, the often non-unique interpretation of the geophysical data can be improved.

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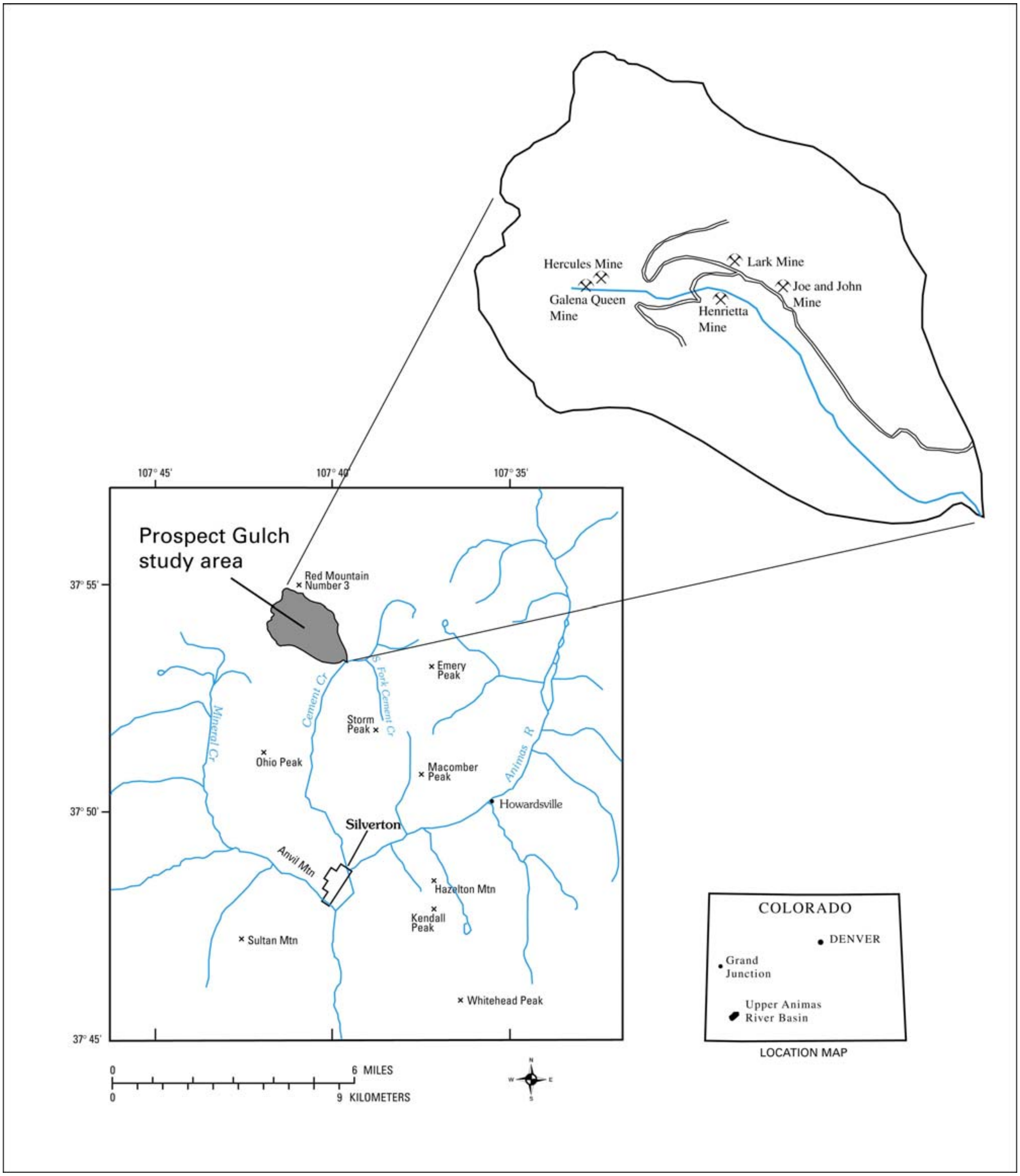


Figure 1. Location map of the Prospect Gulch study area in the upper Animas River watershed.

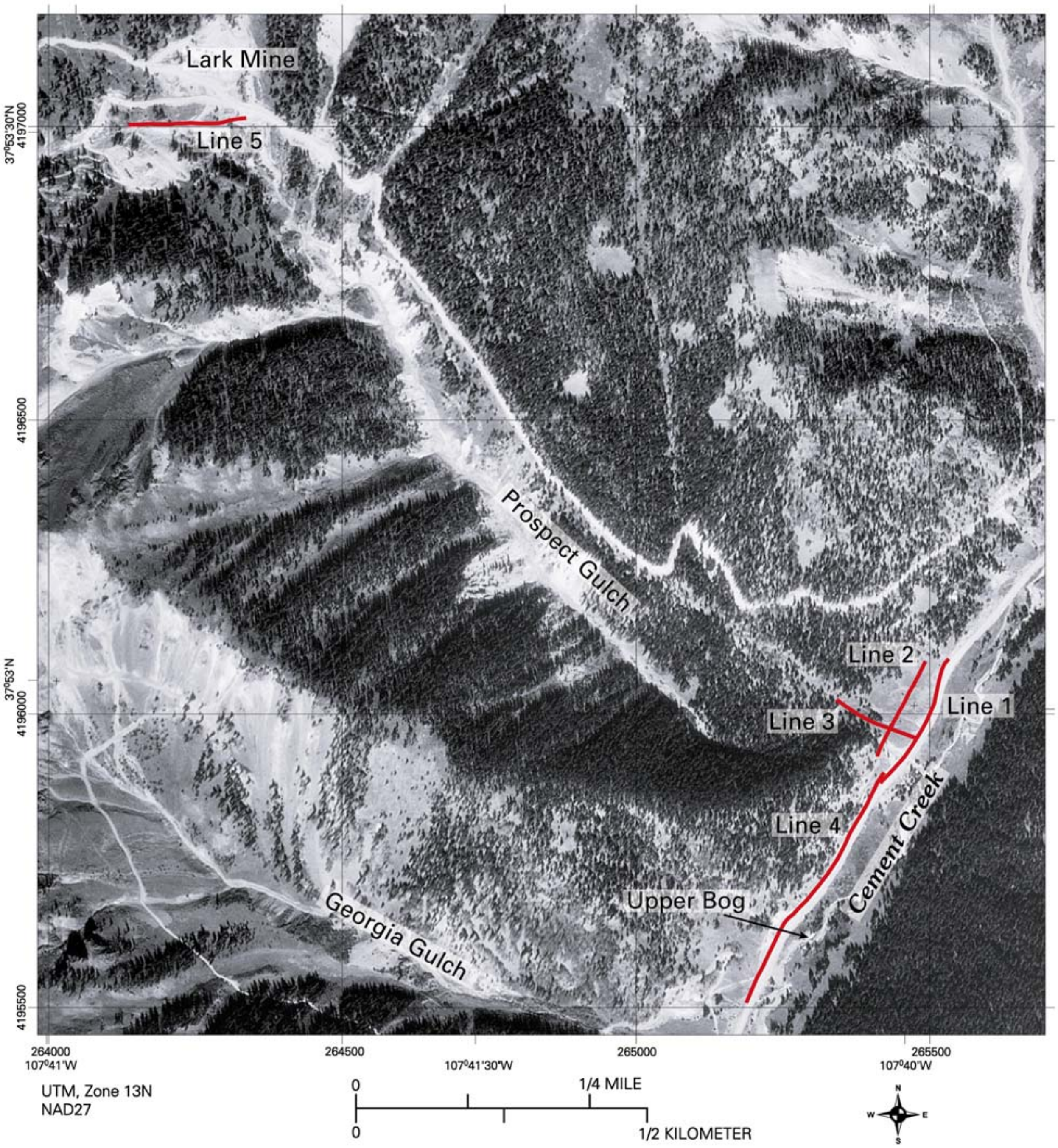


Figure 2. Location of resistivity surveys (digital ortho photo quad base image).

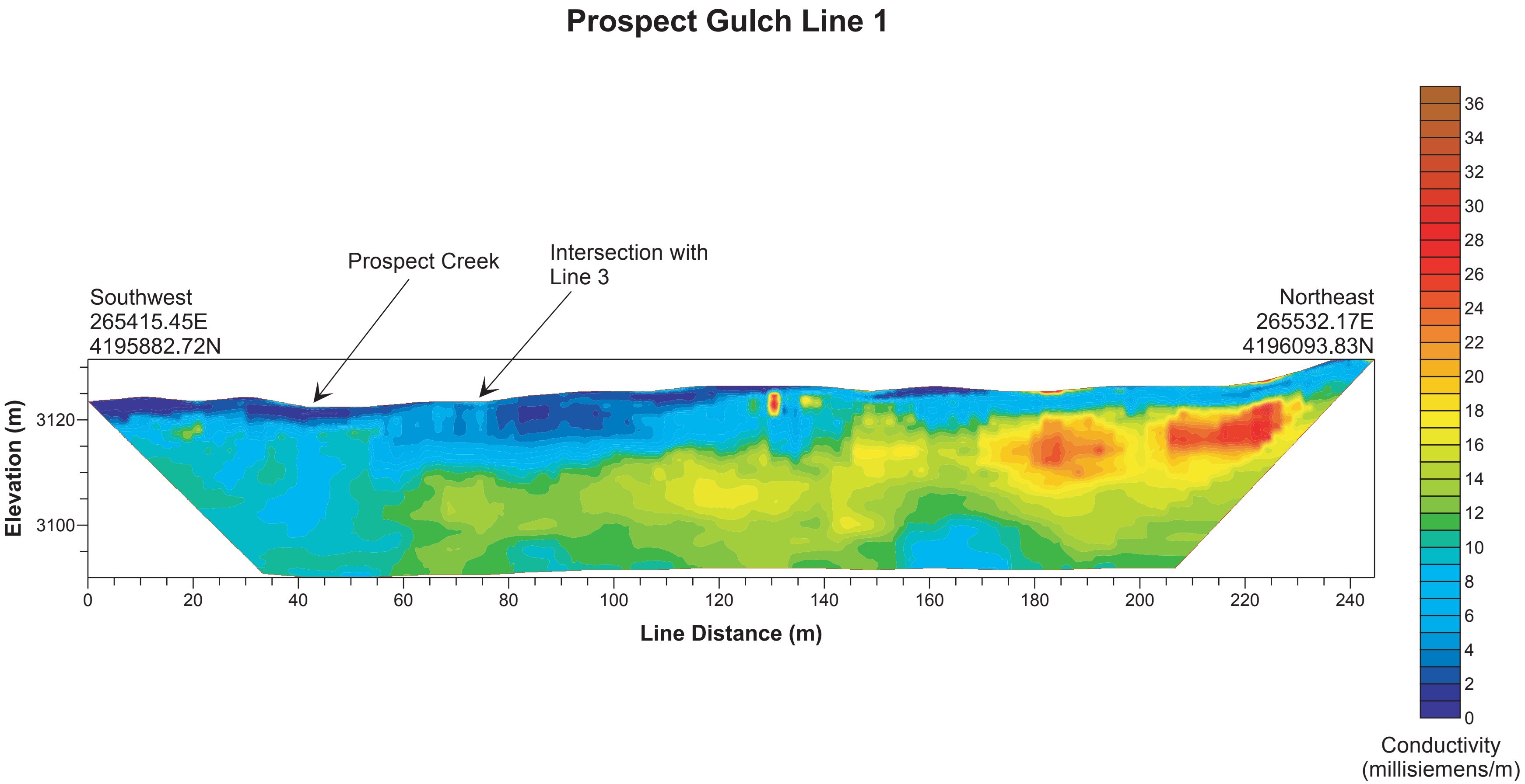


Figure 3. Conductivity Line 1.

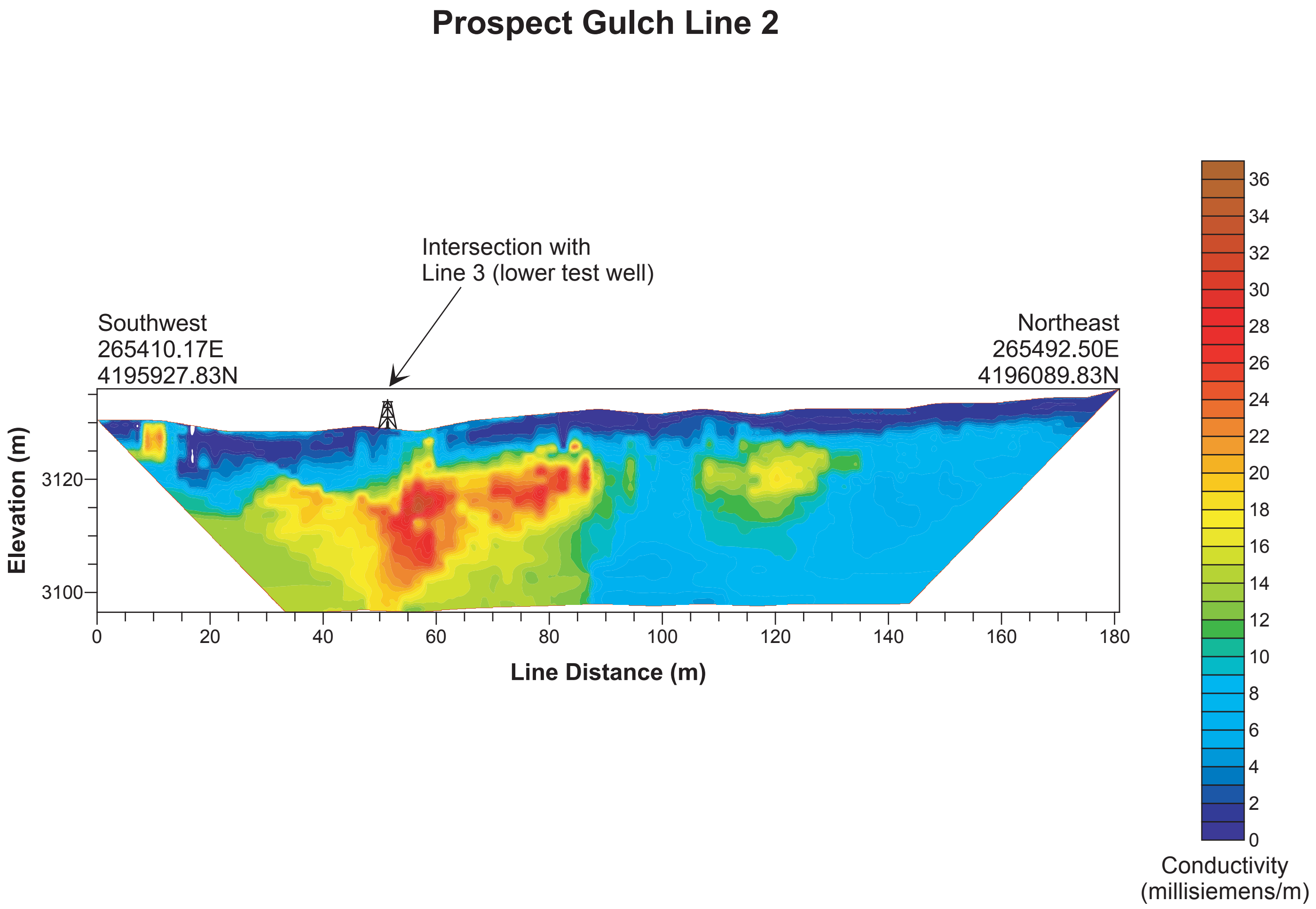


Figure 4. Conductivity Line 2.

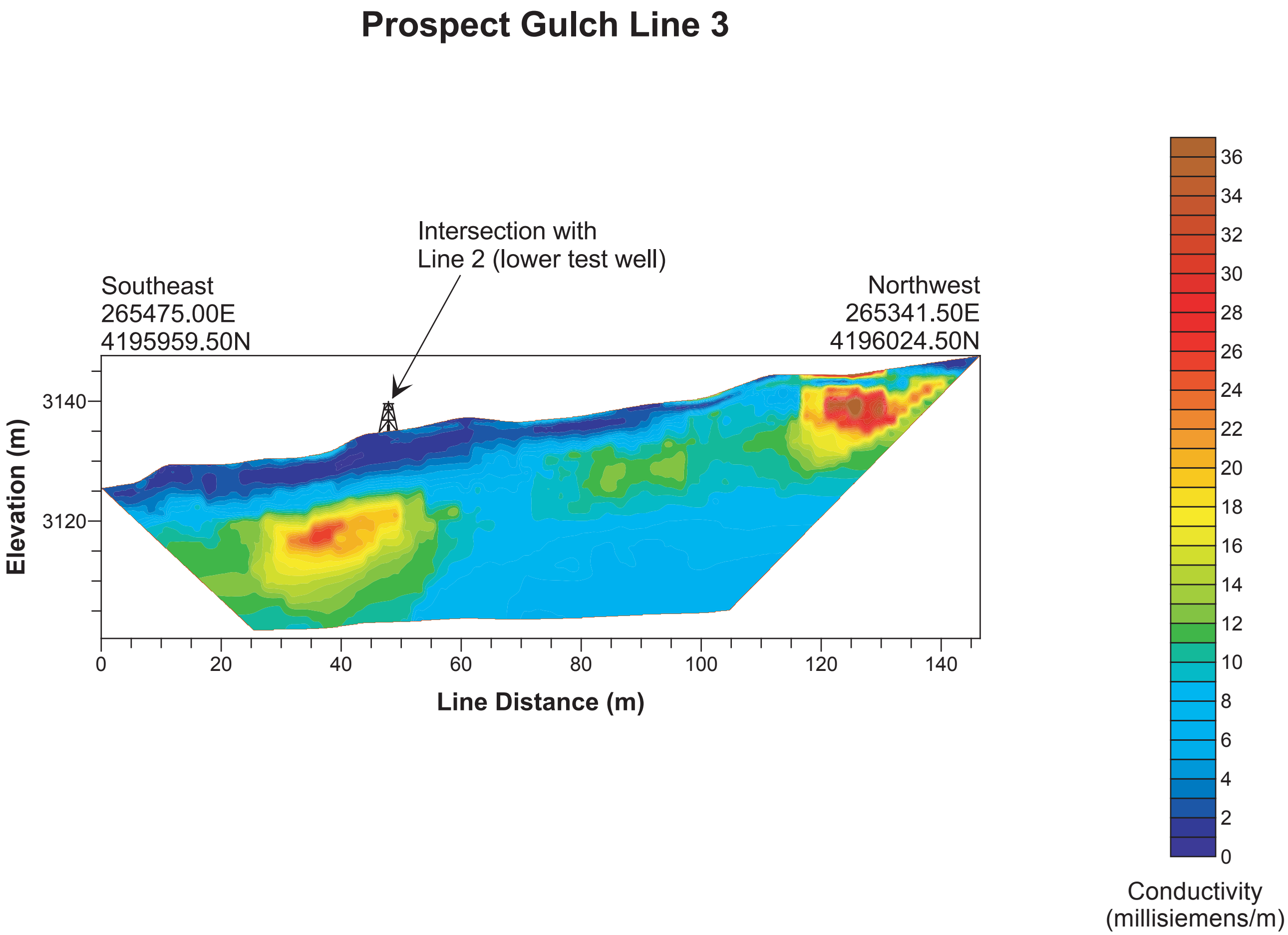


Figure 5. Conductivity Line 3.

Prospect Gulch Line 4

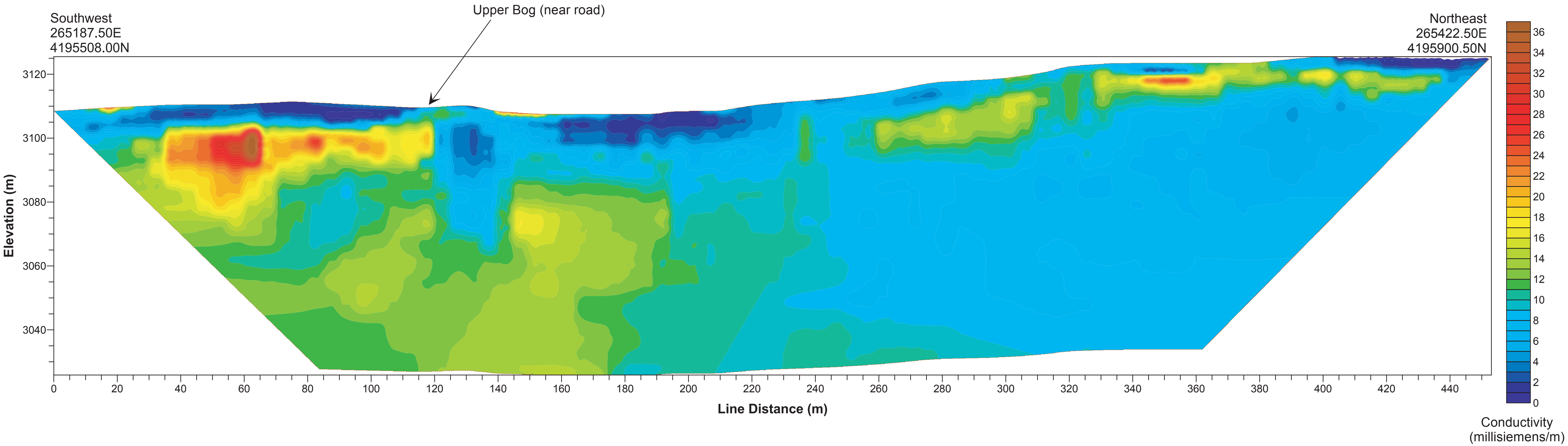


Figure 6. Conductivity Line 4.

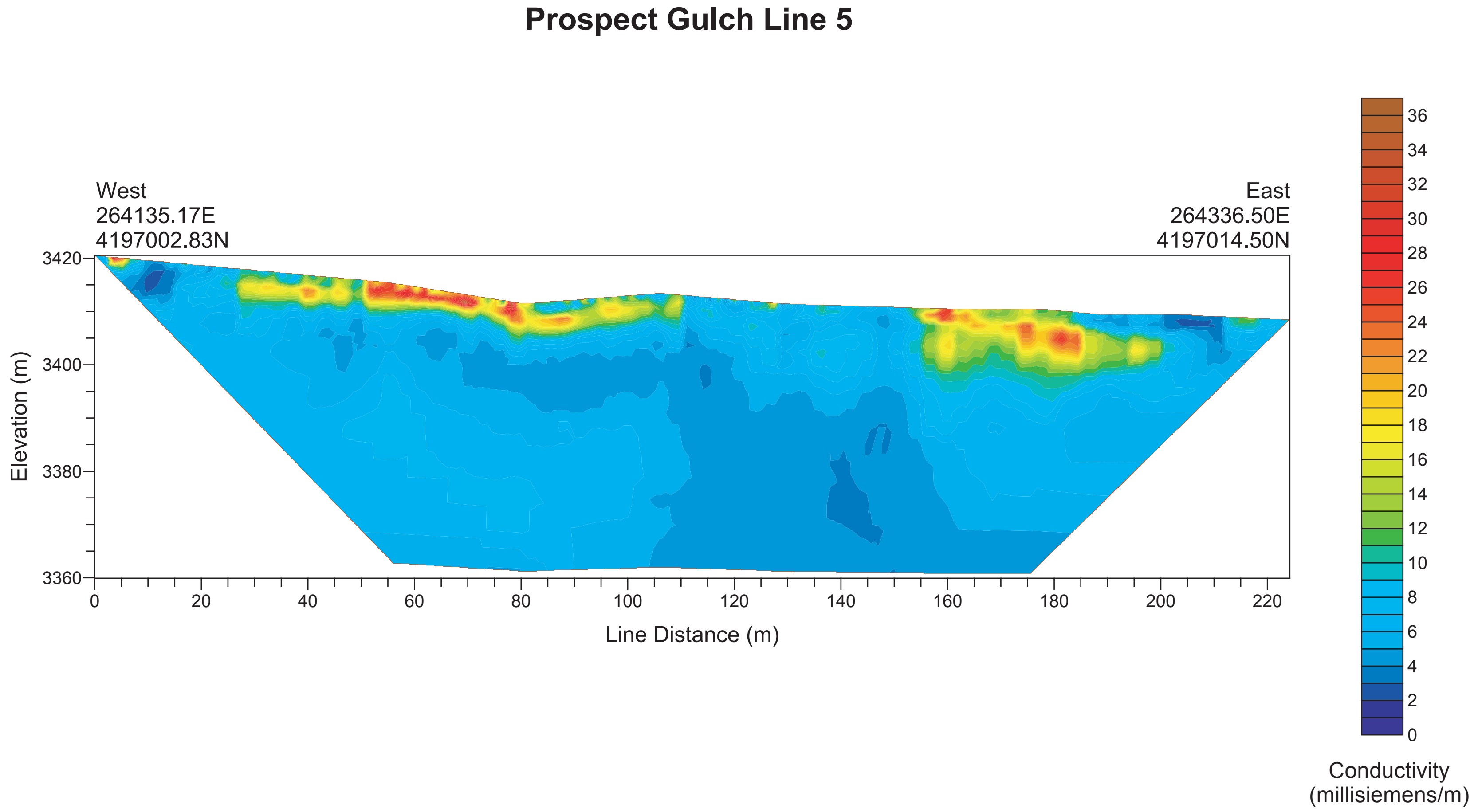
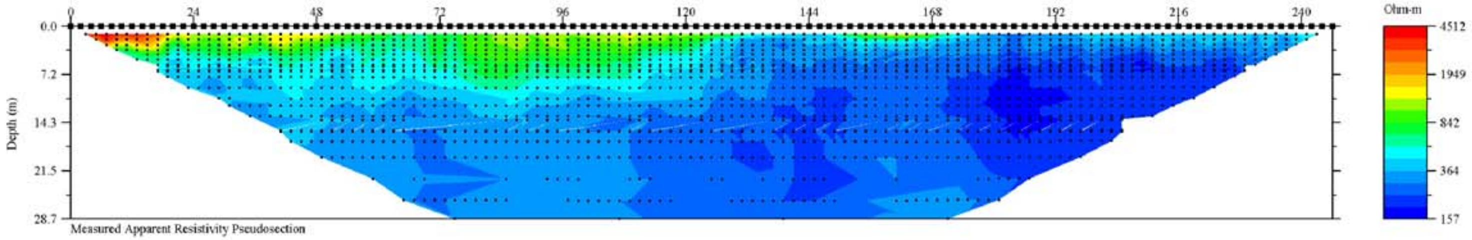


Figure 7. Conductivity Line 5.

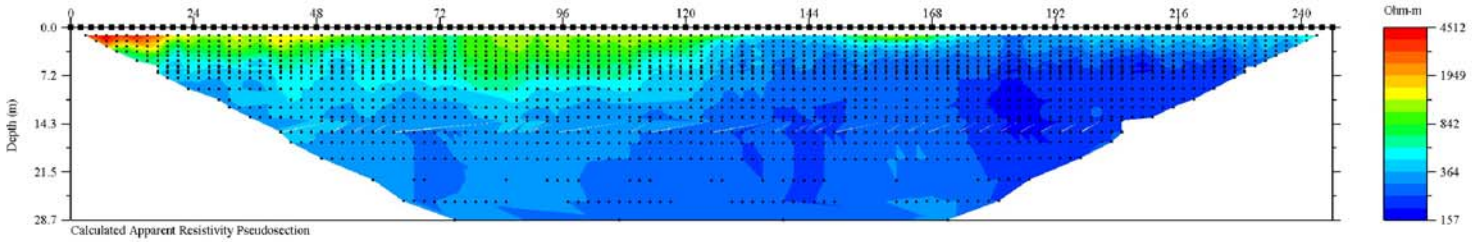
Appendix 1

Results of two-dimensional inversion of resistivity field data showing the measured apparent resistivity pseudosection, calculated apparent resistivity pseudosection, and the inverted resistivity section.

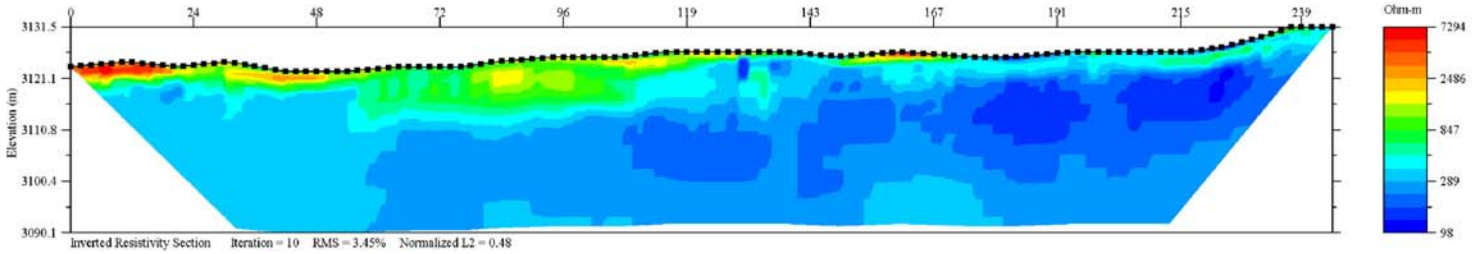
Line 1 Resistivity



Measured Apparent Resistivity Pseudosection

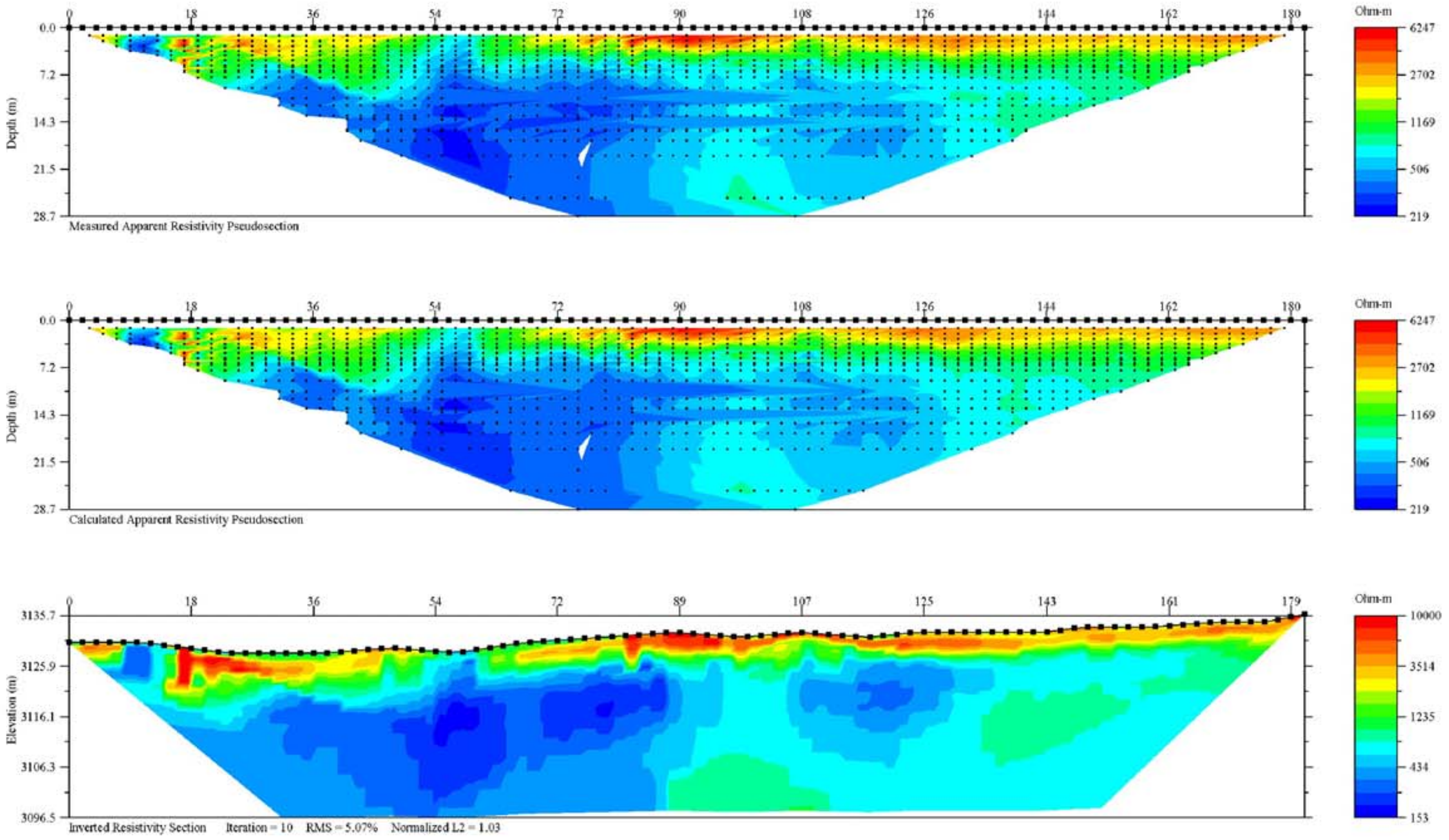


Calculated Apparent Resistivity Pseudosection

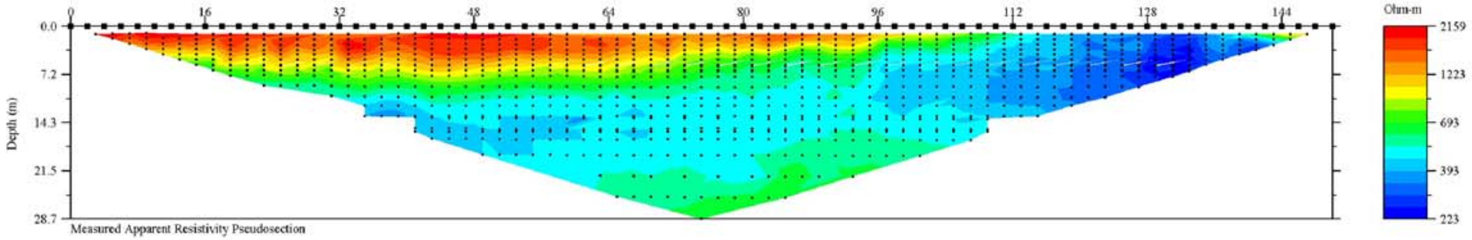


Inverted Resistivity Section Iteration = 10 RMS = 3.45% Normalized L2 = 0.48

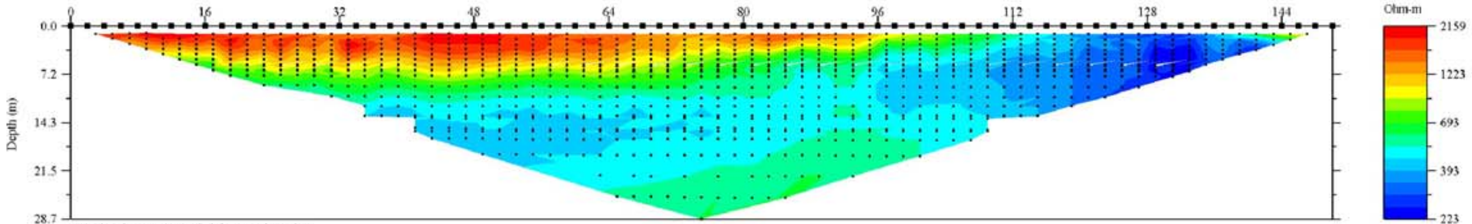
Line 2 Resistivity



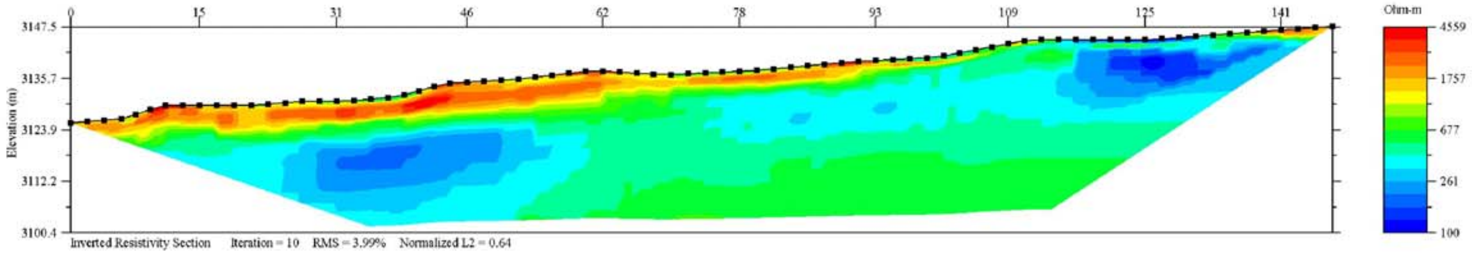
Line 3 Resistivity



Measured Apparent Resistivity Pseudosection

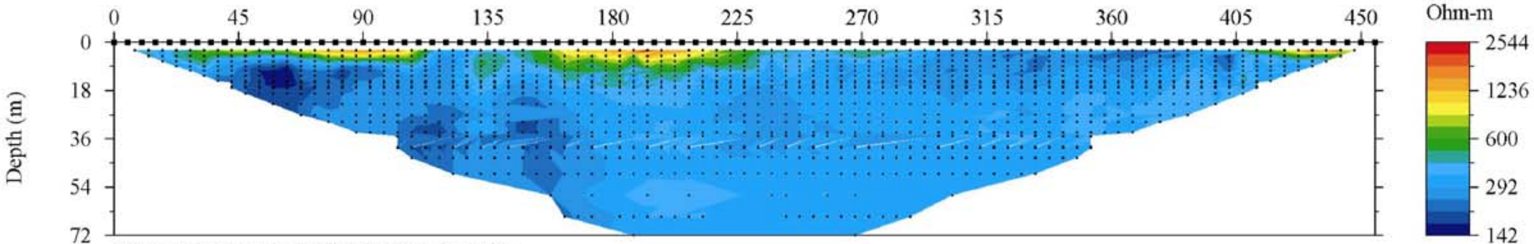


Calculated Apparent Resistivity Pseudosection

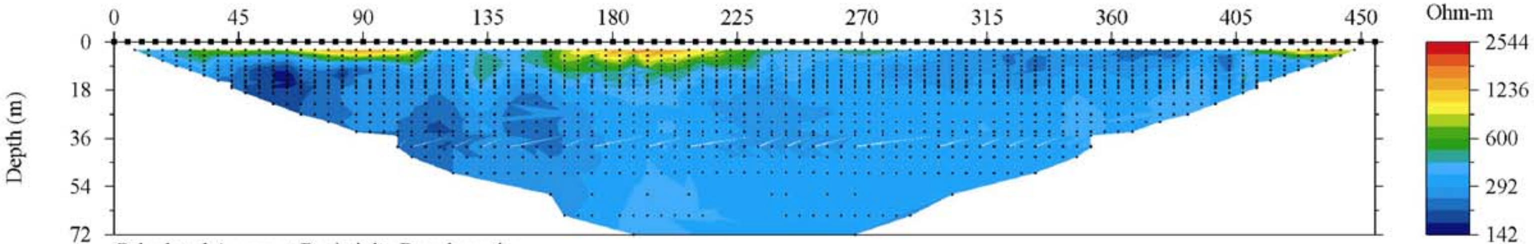


Inverted Resistivity Section Iteration = 10 RMS = 3.99% Normalized L2 = 0.64

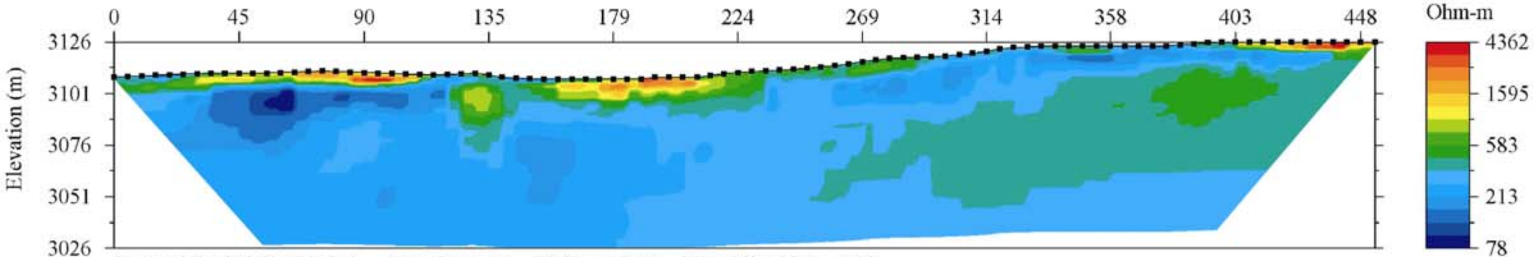
Line 4 Resistivity



Measured Apparent Resistivity Pseudosection

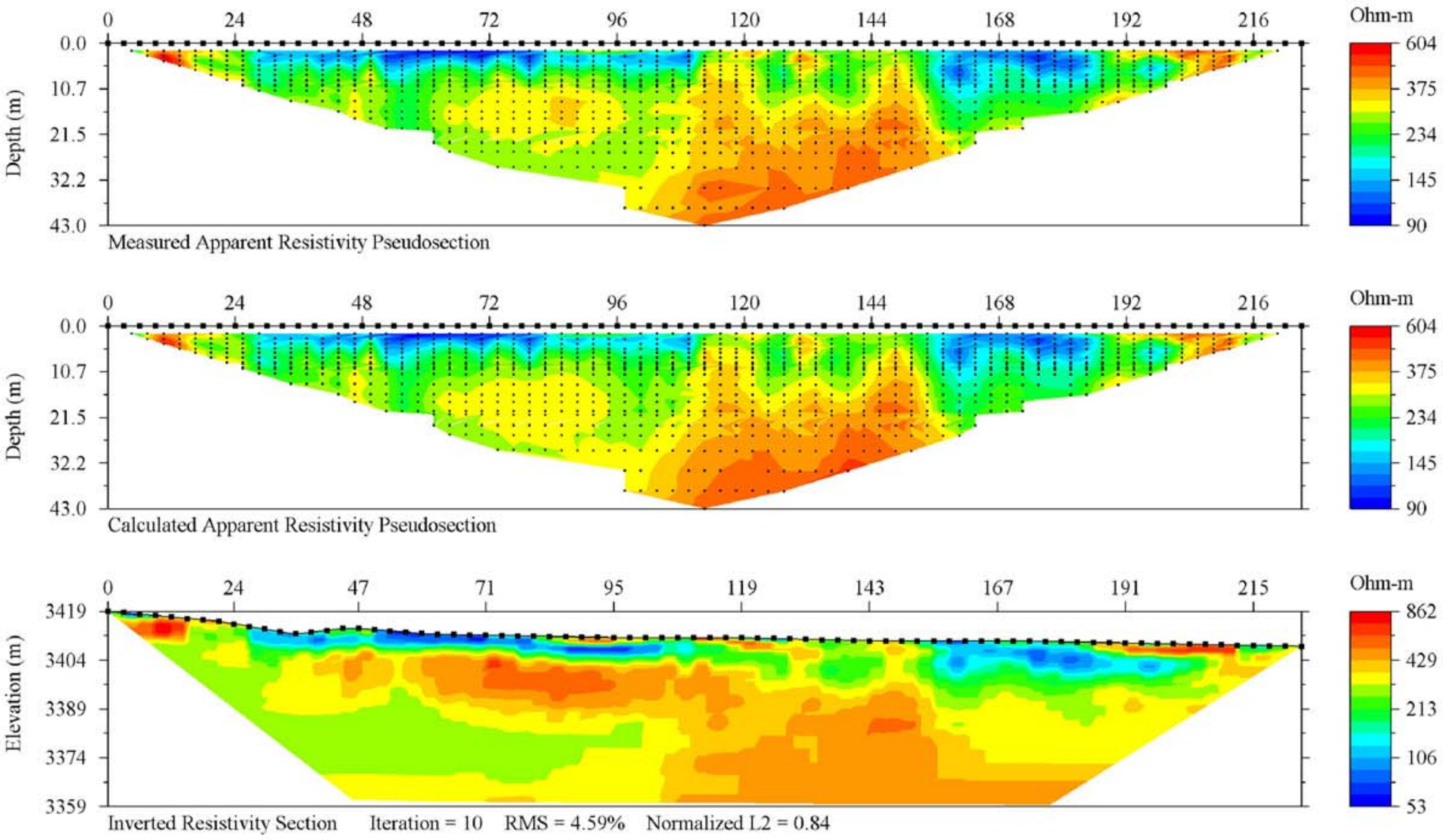


Calculated Apparent Resistivity Pseudosection



Inverted Resistivity Section Iteration = 10 RMS = 4.54% Normalized L2 = 0.82

Line 5 Resistivity



Measured Apparent Resistivity Pseudosection

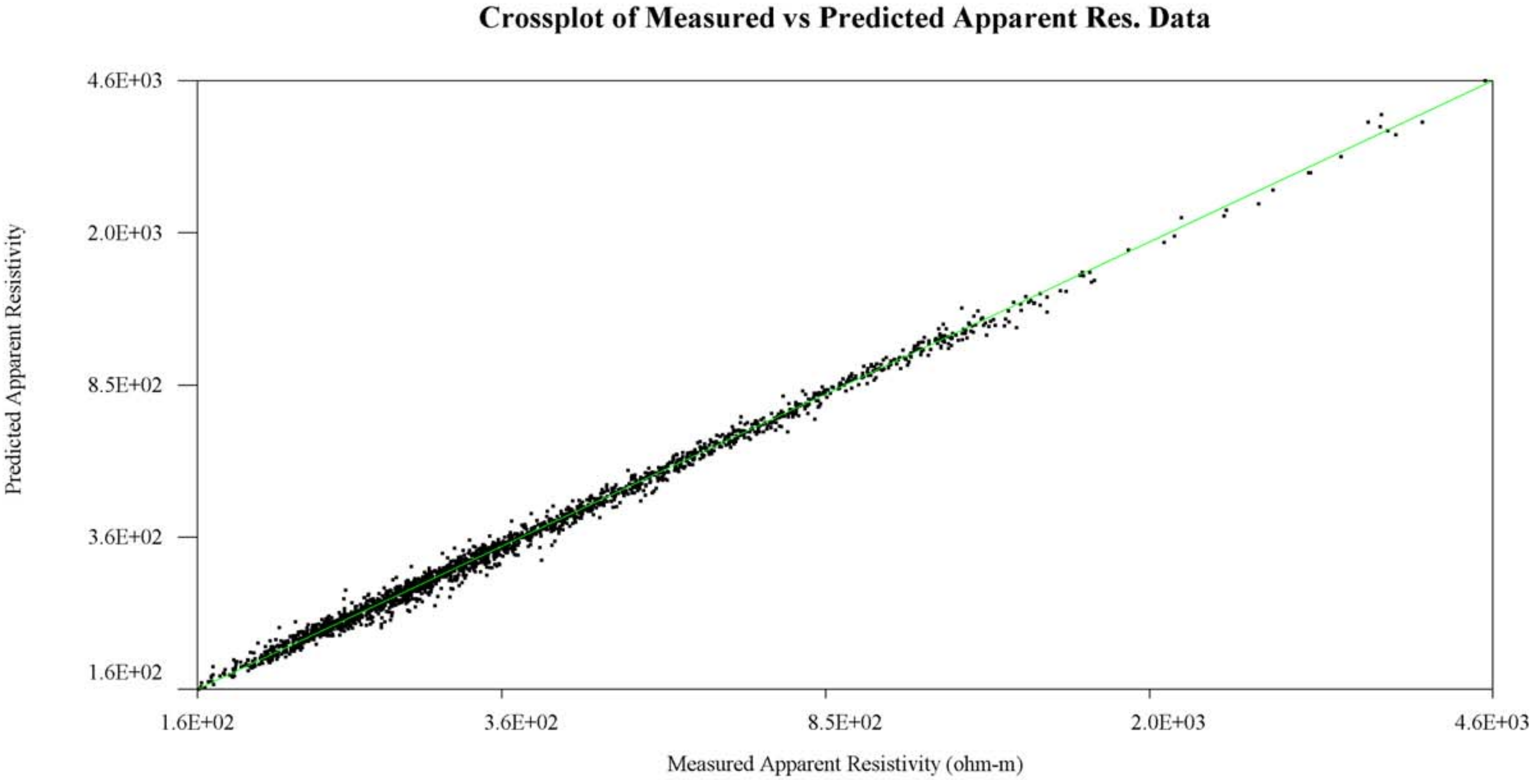
Calculated Apparent Resistivity Pseudosection

Inverted Resistivity Section Iteration = 10 RMS = 4.59% Normalized L2 = 0.84

Appendix 2

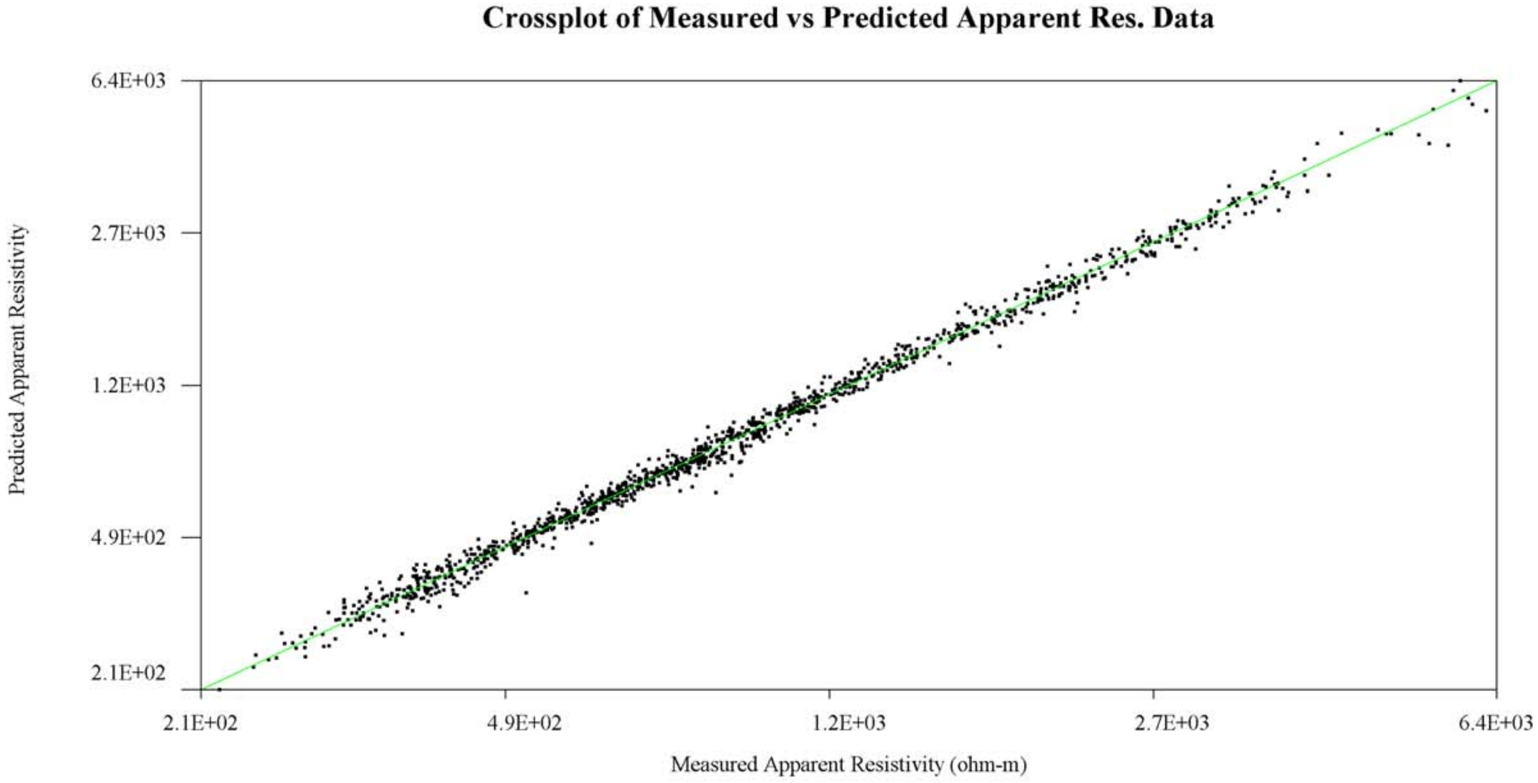
Crossplots of Measured versus predicted apparent resistivity.

Line 1



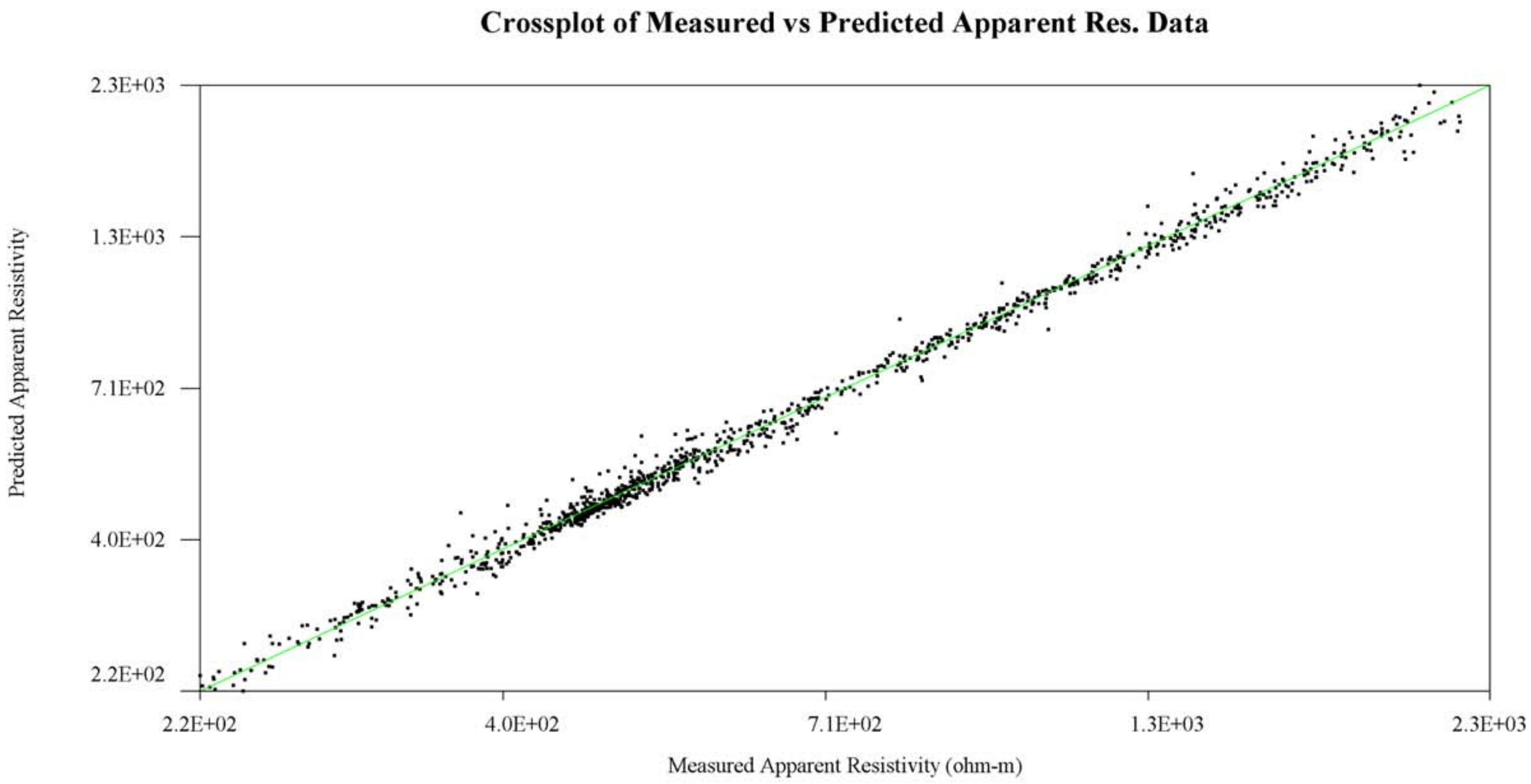
Iteration = 10 RMS = 3.45% Normalized L2 = 0.48

Line 2



Iteration = 10 RMS = 5.07% Normalized L2 = 1.03

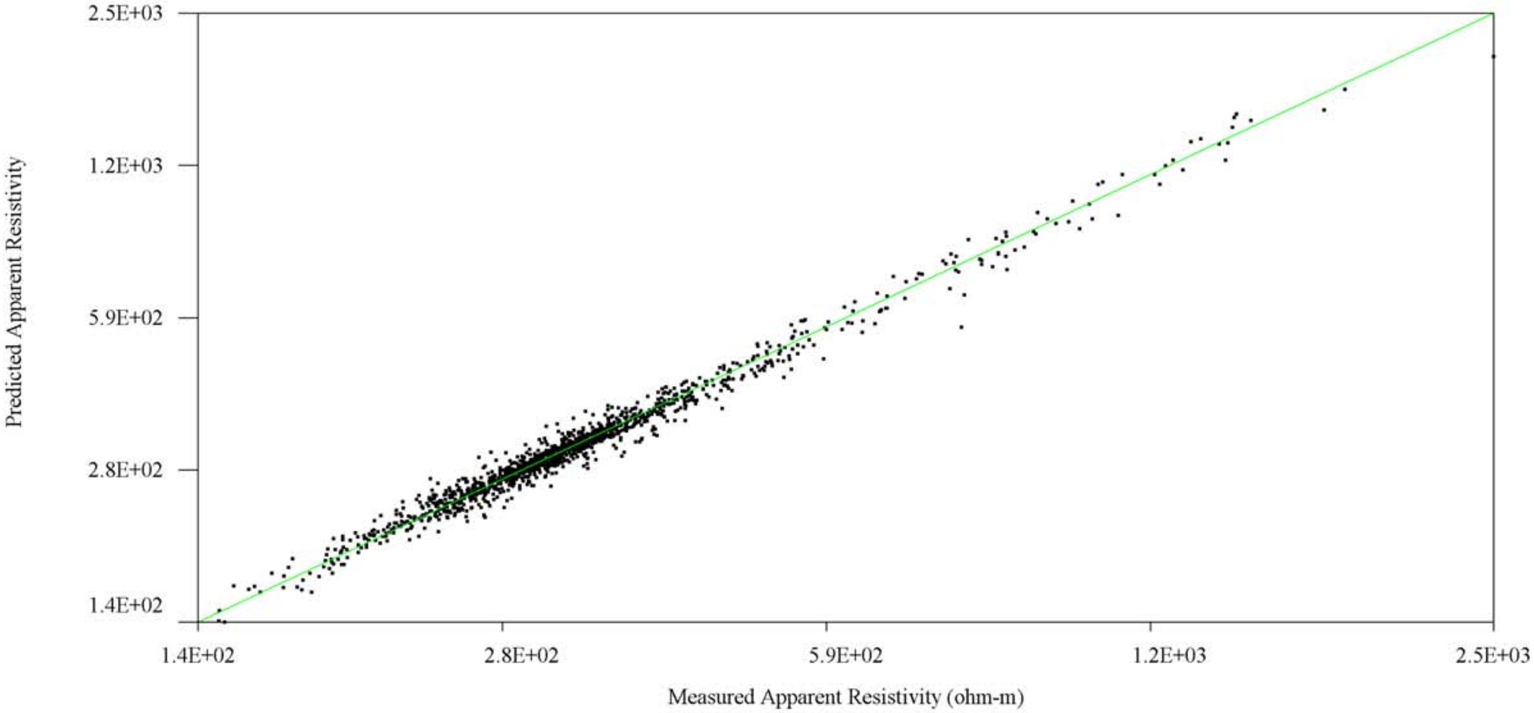
Line 3



Iteration = 10 RMS = 3.99% Normalized L2 = 0.64

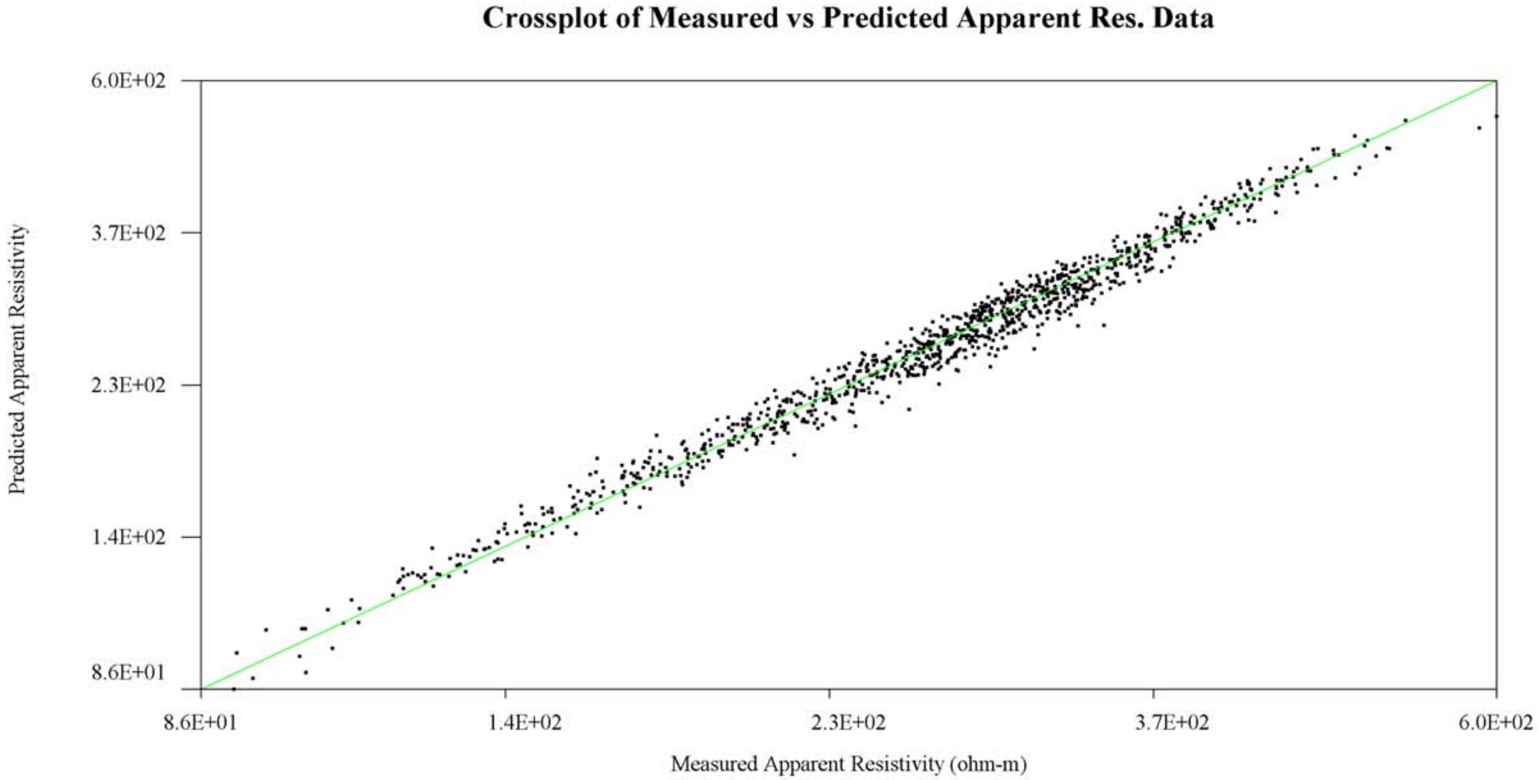
Line 4

Crossplot of Measured vs Predicted Apparent Res. Data



Iteration = 10 RMS = 4.54% Normalized L2 = 0.82

Line 5



Iteration = 10 RMS = 4.59% Normalized L2 = 0.84