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Final Report

Geophysical Survey of the Wetland Area of Upper Sandia Canyon

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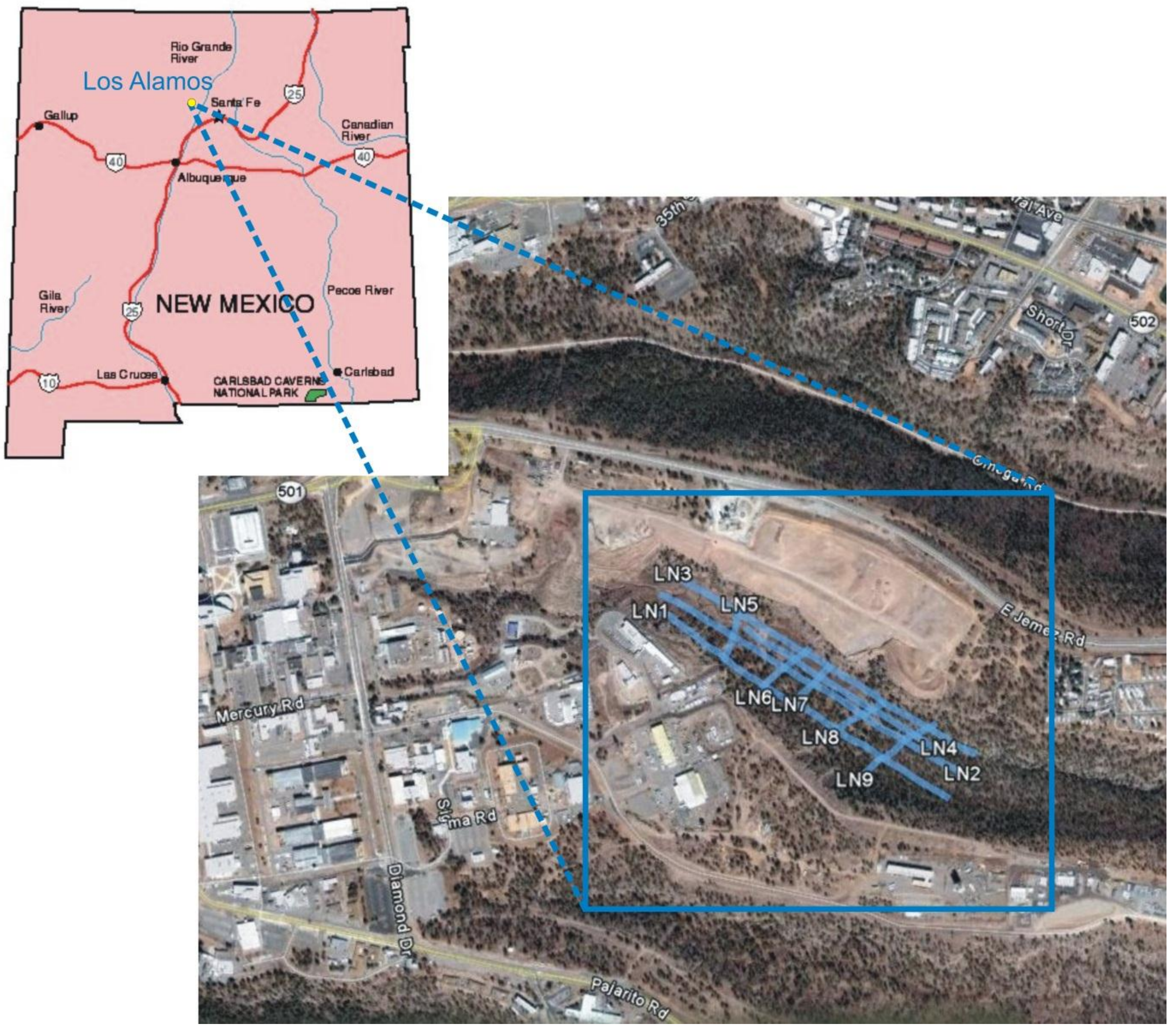
1.0 INTRODUCTION

This report documents direct current (DC) electrical resistivity-based geophysical characterization activities completed in the wetland area near the headwaters of Sandia Canyon at the U.S. Department of Energy (DOE) Los Alamos National Laboratory in Los Alamos, New Mexico (Figure 1).

Figure 1. Upper Sandia Canyon, Los Alamos National Laboratory Location Map.



1.1 SCOPE

The scope of this electrical resistivity characterization survey included:

- Data acquisition along four parallel longitudinal lines on strike with the Sandia Canyon and five supplementary lines placed orthogonally to the longitudinal lines. The five supplementary lines (and one longitudinal line) were arranged according to the results of the initial three longitudinal lines (Line 1 to Line 3),
- Data processing and inversion, including the use of methods and controls to ensure quality assurance consistent with geophysical characterization across the DOE complex
- Data visualization that included the use of two-dimensional (2D) contouring of individual resistivity profiles,
- Compilations of resistivity cross sections from three-dimensional (3D) inverse modeling results.

1.2 OBJECTIVES

The overall objective for this geophysical investigation was to collect and analyze electrical resistivity data to identify low resistivity regions in the wetland of upper Sandia Canyon. Low resistivity values are indicative of increased moisture content, changes in geologic lithologies, perched water, or an increased concentration of electrolytes compared to background conditions.

The three specific objectives for the survey were:

- Determine if electrical resistivity data can be used to identify features that may represent infiltration zones beneath the upper Sandia Canyon wetland,
- Identify horizontal electrical features in bedrock that may represent perched zones in the upper vadose zone beneath the upper Sandia Canyon wetland,
- Determine if electrical resistivity data can be used to identify planer geological structures (e.g. faults or fracture zones) that may localize infiltration and/or affect potential groundwater pathways.

2.0 BACKGROUND

Sandia Canyon is located at Los Alamos National Laboratory (LANL) in north-central New Mexico. This canyon was contaminated by past Laboratory operations. The "Investigation Report for Sandia Canyon" (LANL-UR-09-6450) documents the contamination history and sources since the Laboratory began operation in 1943 and includes relevant information to this project located in TAs 03, 60, and 61:

- Effluent water releases to Sandia Canyon have occurred since the early 1950s and continue today, with the primary sources being treated sanitary wastewater and cooling tower blowdown.

- Potassium dichromate was used from 1956 to 1972 to treat cooling tower blowdown from a power plant, resulting in the release of approximately 31,000 to 72,000 kg (69,000 to 160,000 lb) of hexavalent chromium into upper Sandia Canyon. Because of its relative mobility, hexavalent chromium is the primary contaminant of concern in groundwater.

- Since 1992, Laboratory treated sewage effluent and releases from TA-03 steam plant boilers were major sources of surface water released to upper Sandia Canyon. Currently, effluent releases to the canyon average 1700 m^3/d (390,000 gal./d).

- The long-term discharges and runoff support the thriving wetland near the head of Sandia Canyon and have supplied a sufficient water volume to facilitate contaminant transport in the canyon. The wetland contains abundant solid organic matter that serves both as a chemical reductant and as an adsorbent to contaminants, particularly chromium, that flow through the wetland.

- Based on surface-water balance study conducted from July 2007 to June 2008, an average water flux of 15,000 m^3/yr (12 acre-ft/yr) is estimated to infiltrate into bedrock beneath the wetland, along an area that includes splays of the Rendija Canyon fault zone. This volume represents approximately 2% of the surface water (both effluent and runoff) flowing into the canyon during the period of the study and indicates that faults and fractures in this area may be secondary pathways for deep infiltration.

The Pajarito Plateau is located in the western part of the Española basin where rocks of the Jemez and Cerros del Rio volcanic fields overlie and interfinger with Neogene basin-fill sedimentary rocks. The plateau is an east-sloping tableland bounded on the west by the Jemez Mountains volcanic field and on the east by the Rio Grande valley. The plateau is deeply dissected, and it consists of numerous fingerlike mesas separated by deep canyons containing east- to southeast-draining streams that are mostly ephemeral and intermittent. The Sandia Canyon wetland is located near the headwaters of one of these deep and narrow drainages incised into the welded tuff units that cap the plateau. Geologic units in the vicinity of the wetlands include, in descending order, Quaternary ignimbrites of the Tshirege and Otowi Members of the Bandelier Tuff (separated by volcaniclastic deposits of the Cerro Toledo Formation), Pliocene dacite lavas, and Pliocene fanglomerate deposits of the Puye Formation. The vadose zone in the vicinity of the wetlands is approximately 365 m (1200 ft) thick. Shallow groundwater occurs within canyon-floor alluvium beneath the wetland. Perched intermediate-depth groundwater may occur within bedrock units of the vadose zone, but there are no deep wells to determine its presence or absence near the wetlands. Regional groundwater saturation occurs at depths greater than 365 m (1200 ft) in coarse-grained sedimentary rocks of the Puye Formation.

3.0 DATA ACQUISITION AND PROCESSING METHODOLOGY

3.1 SURVEY AREA AND LOGISTICS

The acquisition of electrical resistivity data involves the injection of current into the ground between two electrodes, and the measurement of electrical potential between two other electrodes, repeated for multiple combinations of the available electrodes. Data acquisition along two-dimensional (2D) profiles within the upper section of the Sandia Canyon began on September 12, 2011 and was completed on September 20, 2011. A total of nine 2D profiles were collected; survey layout is displayed in Figure 2. Table 1 lists the details of the acquired profiles.

Table 1. Two-dimensional Resistivity Profile Details (Start and End Positions Reported in State Plane, New Mexico Central)

Profile #	Electrode spacing (feet)	Length (feet)	Orientation	Start Position (Easting and Northing, feet)		End Position (Easting and Northing, feet)	
1	20	2343	NW-SE	1621211	1773814	1623197	1772572
2	20	2399	NW-SE	1621268	1773932	1623332	1772710
3	20	2354	NW-SE	1621363	1774064	1623389	1772866
4	10	1578	NW-SE	1621850	1773707	1623188	1772870
5	10	404	SW-NE	1621704	1773477	1621813	1773867
6	10	500	SW-NE	1621908	1773236	1622284	1773566
7	10	374	SW-NE	1622153	1773186	1622422	1773445
8	10	509	SW-NE	1622359	1772966	1622805	1773210
9	10	653	SW-NE	1622590	1772677	1623119	1773060

3.2 EQUIPMENT

Data were collected using a Supersting™ R8 multichannel electrical resistivity system (Advanced Geosciences, Inc. (AGI), Texas) and associated cables, electrodes, and battery power supply. The Supersting™ R8 meter is commonly used in surface geophysical projects and has proven itself to be reliable for long-term, continuous acquisition. The stainless steel electrodes were laid out along profiles with a constant electrode spacing (Table 1). Multi-electrode systems allow for automatic switching through preprogrammed combinations of four electrode measurements. A pole-pole electrode configuration was used for the acquisition of profiles 1 through 9. For further details on the electrode configuration, see Binley and Kemna (2005). The pole-pole electrode configuration involves positioning one pole from both the transmitter (Tx) and receiver (Rx) pairs at a fixed and distant location from the survey area. Table 2 lists the remote electrode coordinates for the pole-pole electrode configuration profiles. In general, the pole-pole electrode configuration provides improved overall depth penetration than other configurations of data acquisition; typically a result of the current pathways being steeper inclined due to the effect of the distance remote electrodes.

Table 2. Remote Reference Electrode Locations for the Pole-Pole Electrode Configuration Profiles (State Plane, New Mexico Central)

Remote	X (feet)	Y (feet)
Tx	1616458	1775044
Rx	1630250	1771962

Electrode locations were surveyed using a Leica® 1200 Global Positioning System (GPS). Elevations for each electrode were then obtained from Light Detection And Ranging (LIDAR) data provided for the area and incorporated into the subsequent inverse modeling.

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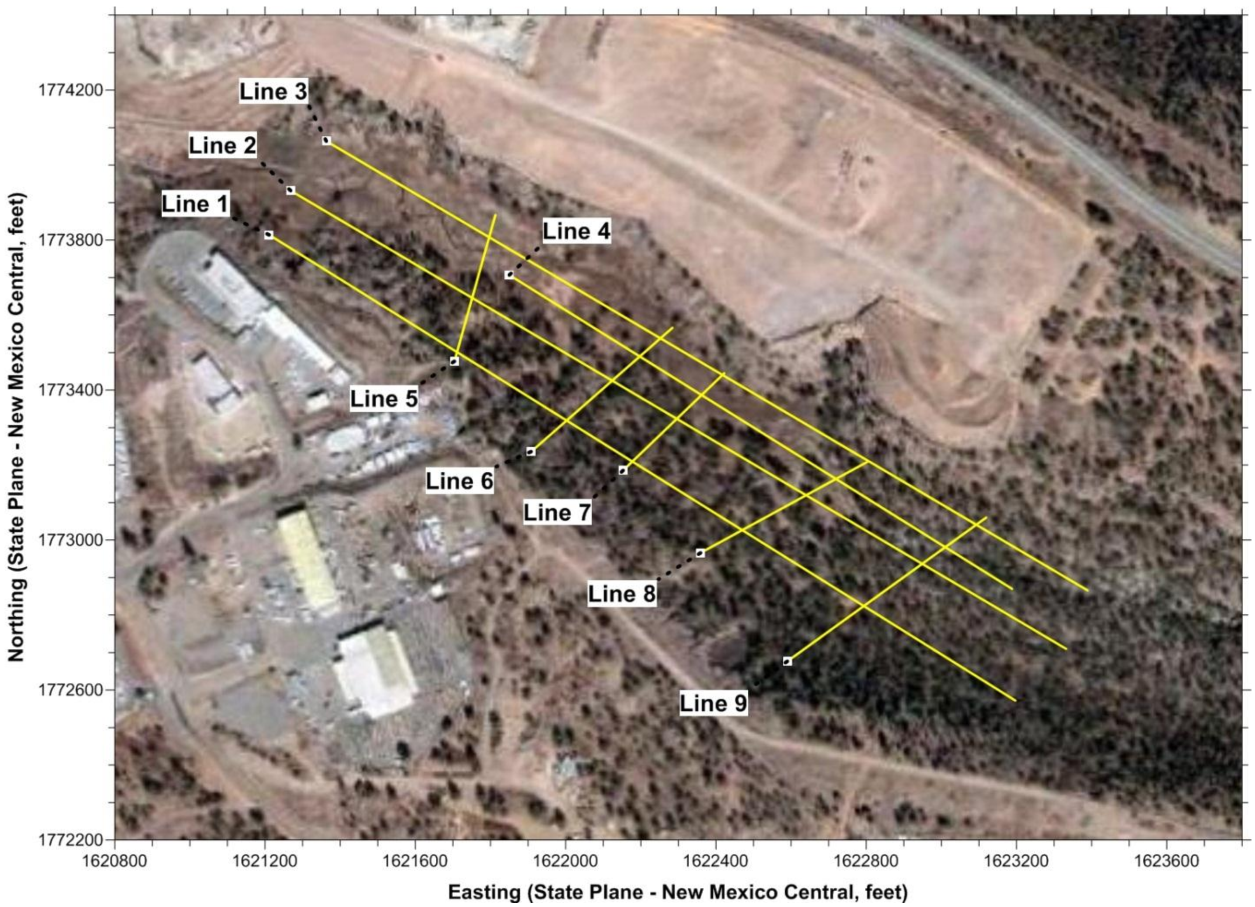
Figure 2. Two-dimensional Resistivity Profile Layout for the Upper Sandia Canyon Survey Area.



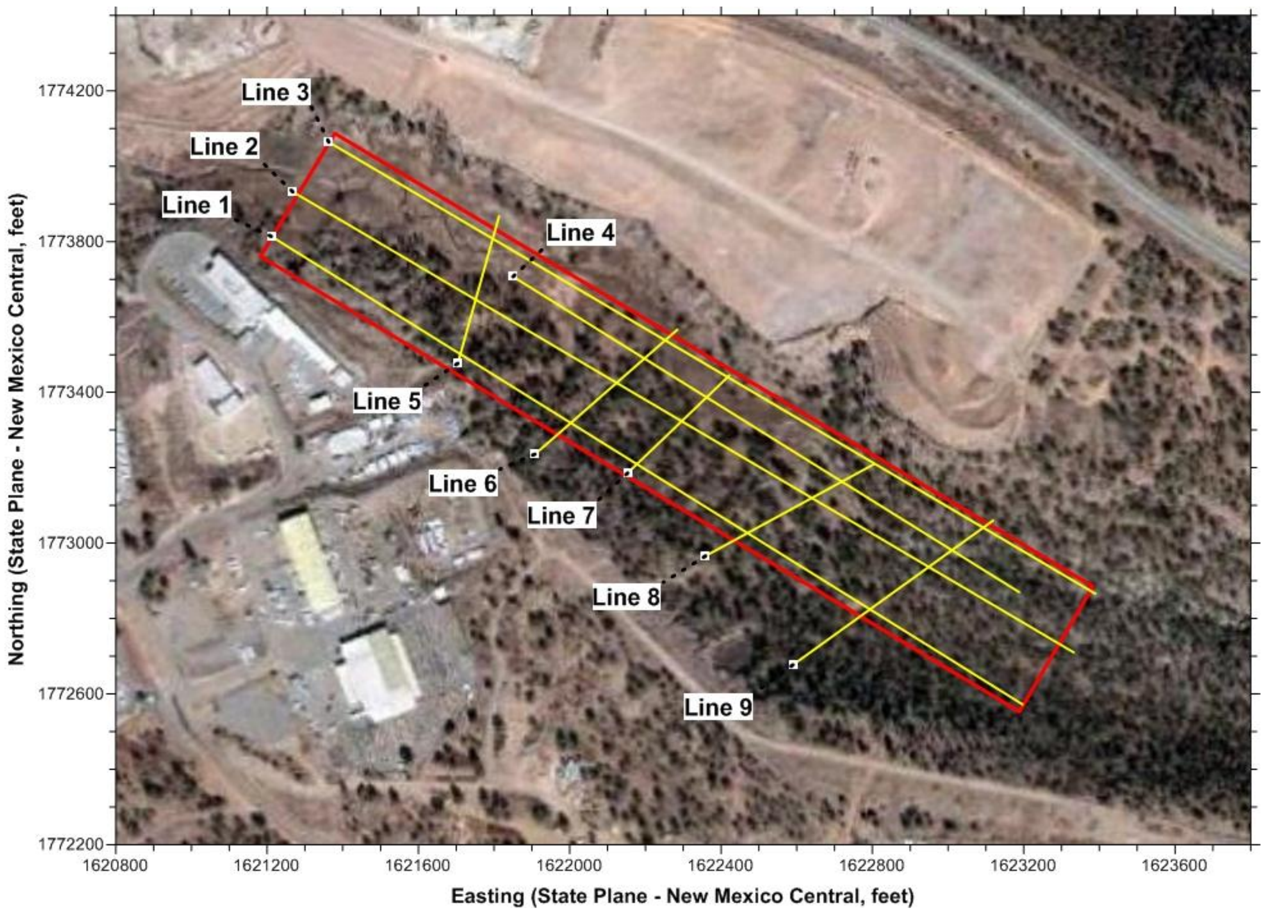
3.3 DATA PROCESSING

Measurements of electrical resistivity with ERT systems inevitably contain errors from a variety of sources, including poor electrode contact, random device errors, and external effects. An assessment of these errors provides some means of quality control of the data. The process of data editing identifies and eliminates erroneous data points, but no data modification (rounding, averaging, smoothing, or splining) is performed.

The recorded electrical resistivity data were downloaded each day for analysis. Error statistics are computed within the Supersting™ R8 for multiple readings (or stacks) on each electrode configuration. The error values on these multiple readings are used as rejection criteria, where data with errors greater than 5% were removed from the data set. Additional important diagnostic data parameters from the raw data include voltage/current (V/I, or transfer resistance, in ohms), voltage (Volts), and electrical current (Amps) output. The rationale is to seek out and remove spurious points that do not conform to the data population or points that violate potential theory. The aim was to remove data outside of the statistical population – measurements with negative V/I, low voltage (<0.01 V), or low current (<10 mA) were removed from the data set.

The data were inverse modeled using the Res2Dinv and Res3Dinv software packages. The software uses an 'Occam's' style inversion (Constable *et al.*, 1987) which produces a smooth model of the subsurface electrical resistivity that fits the acquired data within certain tolerances. The inversion proceeded in an iterative manner until the data misfit was below an acceptable level, 10% for all cases presented in this report. A built in assumption of 2D inverse modeling is that the resistivity in the cross-line direction is constant. At sites with complex resistivity structure, the 2D assumption may introduce significant error, and the resulting 2D images can contain significant distortions (Bentley and Gharibi, 2004). Hence, in areas with the potential for complex three-dimensional (3D) electrical targets, i.e. faults, fractures, perched water tables, etc., whose dimensions out of the plane of the 2D resistivity profile cannot be assumed to remain constant, it is possible that distortions will be observed in the resulting inversion models. The distortions can take the form of under- or over-estimation of the modeled resistivity value of features, location errors for electrical conductive features, or incorporating out-of-plane features into the 2D profiles. One method to reduce the distortions caused by the 2D assumption is to incorporate the individual 2D profile data into a 3D inverse model. This was achieved using the Res3Dinv software package. The data from the individual 2D profiles was georeferenced and incorporated into a 3D grid format. The outline of the 3D grid is displayed in Figure 3. A number of the original 2D profiles were truncated to reduce regions of the model with anticipated poor sensitivity due to low data density. The model grid cell size was chosen to be 40 by 40 by 40 feet, the latter determines the increment for the resulting model resistivity depth slices. The 3D inverse modeling included a total of 28,391 measurements, with the chosen final model taking 3 iterations with an acceptable data misfit of 9.8%.

Figure 3. Three-dimensional Inverse Modeling Grid Outline (Red Rectangle) Overlain onto the Two-dimensional Resistivity Profile Layout for the Upper Sandia Canyon Survey Area.



As a 'rule of thumb' the maximum depth to which the resistivity model is well constrained by the data is approximately 20% of the length of the line. To obtain a more quantitative estimate of the maximum depth we used the "Depth Of Investigation" (DOI) method outlined in Oldenburg and Li (1999). The method measures how sensitive the inverted resistivity model is to the initial starting model as a ratio, the R-value, of two different starting models. Due to the limited additional information to constrain the geophysical data we used three homogeneous models with single resistivity values of 40, 100, and 4000 ohm-m. The different starting models did not produce significantly different final resistivity models, with resulting R-values close to zero.

The resulting output resistivity model was subsequently processed and visualized using the Surfer (Golden Software, Inc., Golden, CO) and Rockworks (Rock Ware, Inc. Golden, CO) software.

4.0 DISCUSSION OF RESULTS

4.1 2D RESISTIVITY PROFILE RESULTS

The 2D resistivity model results are presented as 2D profiles in Plates 1 through 11 found in Appendix A at the end of this report. Common color contouring scales were used throughout and there is no vertical exaggeration in the 2D profile figures. Electrically conductive (low resistivity) subsurface regions are represented by cool hues (purple to green) and electrically resistive regions are represented by warm hues (orange to red). To help emphasize particular features in each section a log scale of model resistivity is used in the profile figures. When data span multiple orders of magnitude, it is appropriate to display a log transformation. Table 3 lists the data statistics for each profile.

We also present annotated 2D profiles in Figures 4 through 12 in this section of the report. The locations of the points of intersection for the various profiles are indicated along the ground surface contour for reference. In addition, fault and monocline locations are indicated by colored diamonds along the ground surface contour; these were taken from the regional geological map (Lewis *et al*, 2009 – Animation 1). They are used for comparison with interpreted features in the model resistivity profiles.

Fracture, fault, and fissure mapping with electrical resistivity is fairly common, and has been presented in numerous studies. The main component to finding these structural features is the offset in model resistivity contouring or a large change in resistivity values along a lineation consistent with a change in geology. Considering the small throws along the faults identified in Lewis *et al* (2009), we would most likely interpret the presence of a fault based on an offset in model resistivity contours. In our interpretations, we cannot determine if low resistivity associated with faults and fractures is the result of increased water content, compared to surrounding material, or represents higher clay content associated with fault gouge.

Borehole investigations further downstream of the current survey area in lower Sandia Canyon have identified perched water at several locations; including within the alluvium layer, on the top surface of the Cerros del Rio basalt, and at the base of the Cerros del Rio basalt formation (LA-UR-09-6450). In the wetland, shallow perched groundwater occurs in the alluvium above the welded bedrock tuffs. There are no boreholes in the wetland deep enough to characterize potential vadose-zone perched groundwater zones. However, within the electrical resistivity profiles we might expect perched groundwater to be represented by horizontal lenses of low resistivity, based on the increase in the degree of saturation in these normally unsaturated geological units.

Table 3. Two-dimensional Resistivity Profiles Data Statistics.

Profile #	Raw data count	Rejected data count	Measured Apparent Resistivity (ohm-m)		
			Minimum	Maximum	Median
1	7871	1984	817	836.2	271.5
2	7751	996	91.4	1184.3	297.0
3	7878	780	28.7	4481.1	224.0
4	3484	367	123.6	2930.4	306.3
5	925	11	74.1	900.1	360.1
6	1378	64	90.7	928.7	355.8
7	930	39	63.4	2337.7	287.1
8	1483	63	124.1	2932.5	351.2
9	2336	216	132.5	3347.4	506.1

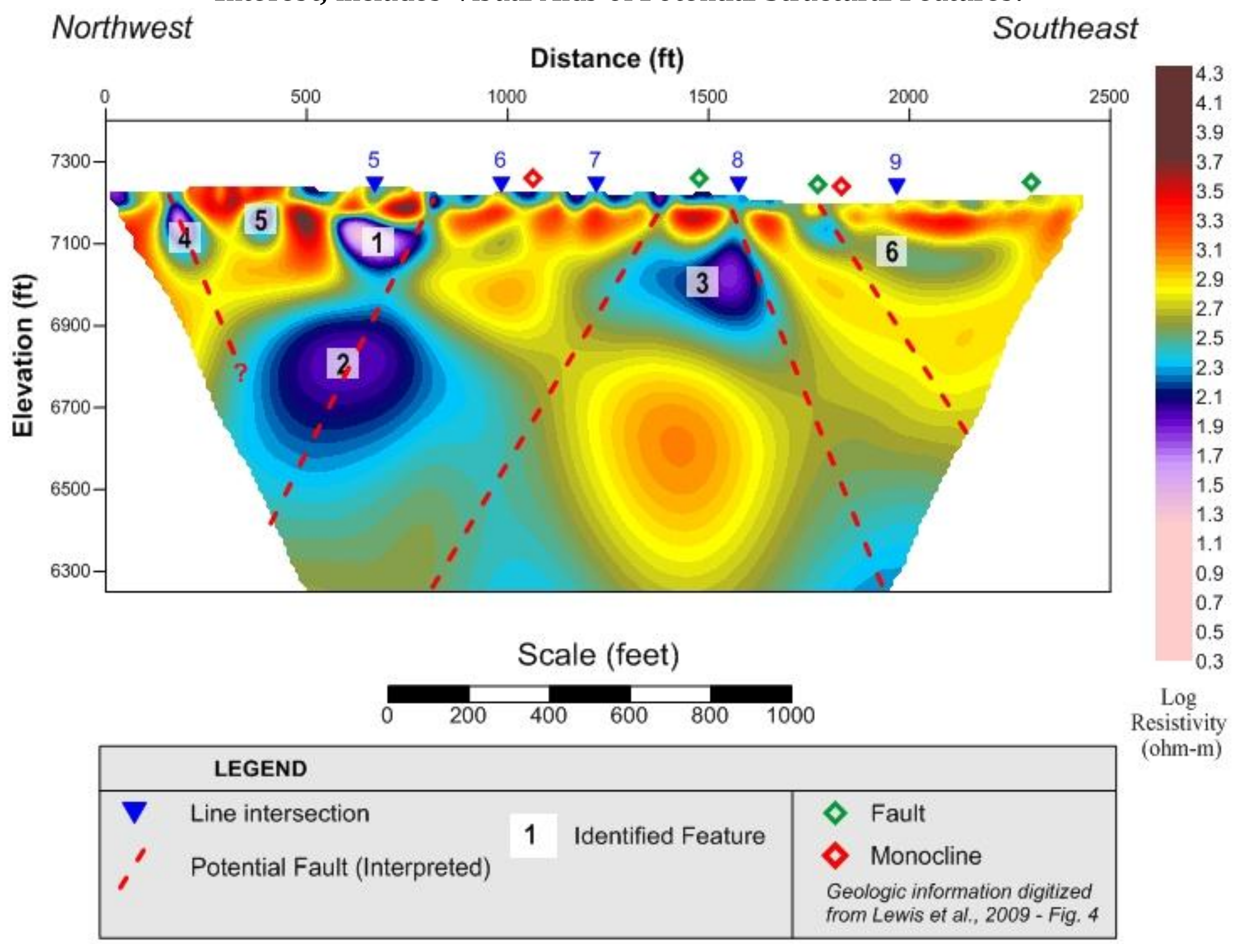
In general the nine profiles display a number of comparable features across the surveyed area. A near-surface conductive layer is observed in the western half of the surveyed area and extends from the land surface to approximately 40 feet depth. The conductive layer is observed along varying lengths of profiles 1 through 4 along the long axis of the canyon, and across the majority of profiles 5 through 8. This conductive layer appears to be absent in profile 9, where alluvium is thin to absent as Sandia Canyon begins to incise a narrow canyon into bedrock tuffs farther down canyon. The near-surface conductive layer generally corresponds to the wetland area of the canyon, although patchy regions of near-surface conductivity also occur beneath the canyon-floor alluvial slope south of the wetland (see profile 1). A resistive region is observed directly beneath the conductive layer in the models that extends down to the depth limit (approximately 6900 feet elevation) of the shorter profiles (5 through 9), and to approximately the 6600 feet elevation contour for the longitudinal profiles (1 through 4). The upper part of the resistive region, above 7000 to 7100 feet elevation, contains long segments of horizontal, highly resistive values that probably correspond to welded tuffs of the Tshirege Member that underlie the alluvial deposits in this area. The resistivity values for this resistive feature, corresponding to areas not overlain by the alluvium deposits, range between approximately 1250 and 20,000 ohm–m.

Where continuous, the highly resistive rocks of the Tshirege Member probably represent a significant barrier to the infiltration of surface and alluvial water into the subsurface near the wetland. Conversely, conductive zones extending from the surface through the upper bedrock units may indicate clay- and/or moisture-rich areas where the tuff is penetrated by infiltration pathways, including faults or fractures. Beneath the 6600 feet elevation contour, a more conductive layer is observed for profiles 1 through 4, extending to the penetration depth limit of the resistivity models, possibly relating to a change in lithology. A number of conductive anomalies are superimposed over this general structure for the nine profiles and are discussed in more detail in the following sections.

4.1.1 2D Resistivity Profile 1

Figure 4 displays the modeled resistivity results for profile 1. Profile 1 parallels the axis of Sandia Canyon, but does not cross the canyon floodplain or wetlands except at the extreme western end of the line. A near-surface conductive layer extends from approximately 800 to 1600 feet along the profile length, with an average thickness of 10 feet. This potentially relates to elevated moisture in near-surface alluvium that makes up the alluvial slope south of the wetlands. The base of this layer appears undulated in areas, the effect is also apparent to a lesser extent in the near-surface region of the model between 1600 to 2500 feet along the profile, this is possibly resulting from a combination of poor electrode coupling and high contact resistance, due to ground surface conditions and heterogeneous surface materials, affecting the modeling results. A highly resistive layer underlies this conductive layer and appears to outcrop between approximately 200 and 500, and 1800 and 2500 feet along the profile. Between 500 and 1800 feet along the profile, the resistive layer appears discontinuous in places due to a number of conductive features. A number of conductive anomalies are observed in this profile. The most notable of these is the conductive feature labeled (1), located between 600 and 750 feet along the profile length, at an elevation of 7100 feet. The feature appears to be connected to a much broader conductive feature at depth, labeled (2). These two features may be manifestations of a fault, with the ranges of resistivity values representing possible differences in saturation or varying clay content along the fault plane. The conductive feature labeled (3) is located above several offsets in the contouring of the underlying resistive layer. This may indicate a number of faults running through this region of the resistivity model, as indicated in the figure. The two conductive features labeled (4) and (5), located at approximately 200 and 400 feet along the profile, are slightly more near-surface than the previous anomalies. The feature labeled (4) may represent another fault, being located above an offset in the model resistivity contours. In addition, both features may be related to a perched water table, potentially associated with the base of the alluvium layer. Feature (4) appears to extend to the ground surface in an otherwise resistive near-surface layer, suggesting a potential flow pathway. While feature (5) appears to be isolated within a resistive background, these are 2D representations and these features may extend out of the plane of the resistivity model. The final feature, labeled (6), is located between 1800 and 2200 feet along the profile and tends to dip slightly towards the east. There are several faults identified in Lewis et al (2009) that project through the beginning and end of this feature, suggesting this conductive region may represent one or more faults. Alternatively this conductive region may represent enhanced water or clay contents in an east-dipping stratigraphic unit; the western end appears to connect to alluvium near the eastern end of the wetland and may represent an infiltration pathway.

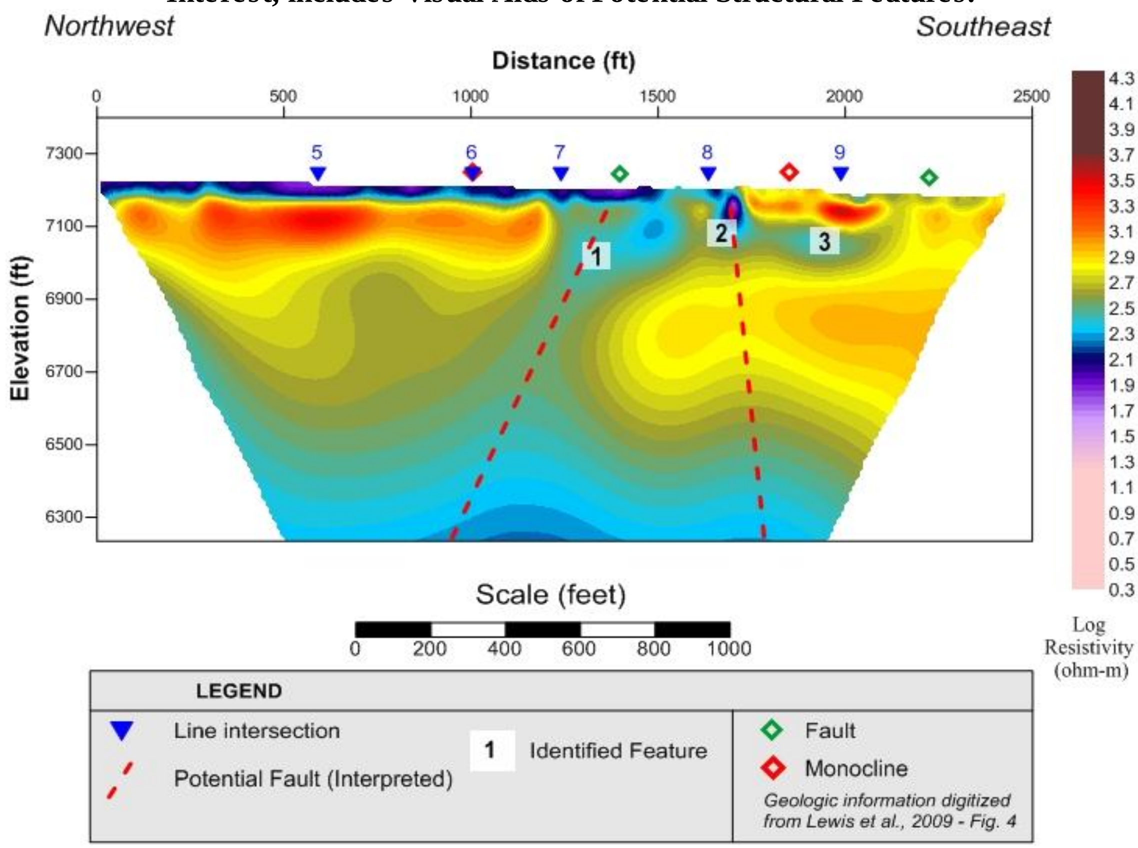
Figure 4. Profile 1 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.1.2 2D Resistivity Profile 2

Figure 5 displays the modeled resistivity results for profile 2, acquired parallel to and to the north of profile 1. The near-surface conductive layer discussed previously extends between 0 and 1700 feet along the profile, located within the canyon-floor flood plain and southern margin of the wetland, displaying an average thickness of 25 feet. East of 1700 feet, the near-surface rocks are resistive where the canyon becomes incised and the line crosses bedrock exposures of welded tuff. The main anomaly in this profile is a conductive linear feature, labeled (1), at approximately 1400 feet along the profile. This feature dips toward the west and extends down to the underlying conductive layer at approximately 6600 feet elevation. A clear offset in the resistivity model contours can be observed for this feature, potentially indicating a fault structure. Even though profile 2 is more proximal to the canyon axis the resistivity values of this feature are higher than those discussed for profile 1, possibly suggesting a lower degree of saturation or less clay content along the potential fault. The conductive feature labeled (2), located at the eastern terminus of the wetland, extends down from the ground surface to the 7000 feet elevation contour. A slight offset in the underlying model resistivity contours could indicate a fault at this location. The final conductive feature in this profile, labeled (3), which corresponds to the general location along the profile of the feature labeled (6) in profile 1. In this case the feature is not associated with significant offsets in the model resistivity contours and may represent enhanced water or clay contents in an east-dipping stratigraphic unit.

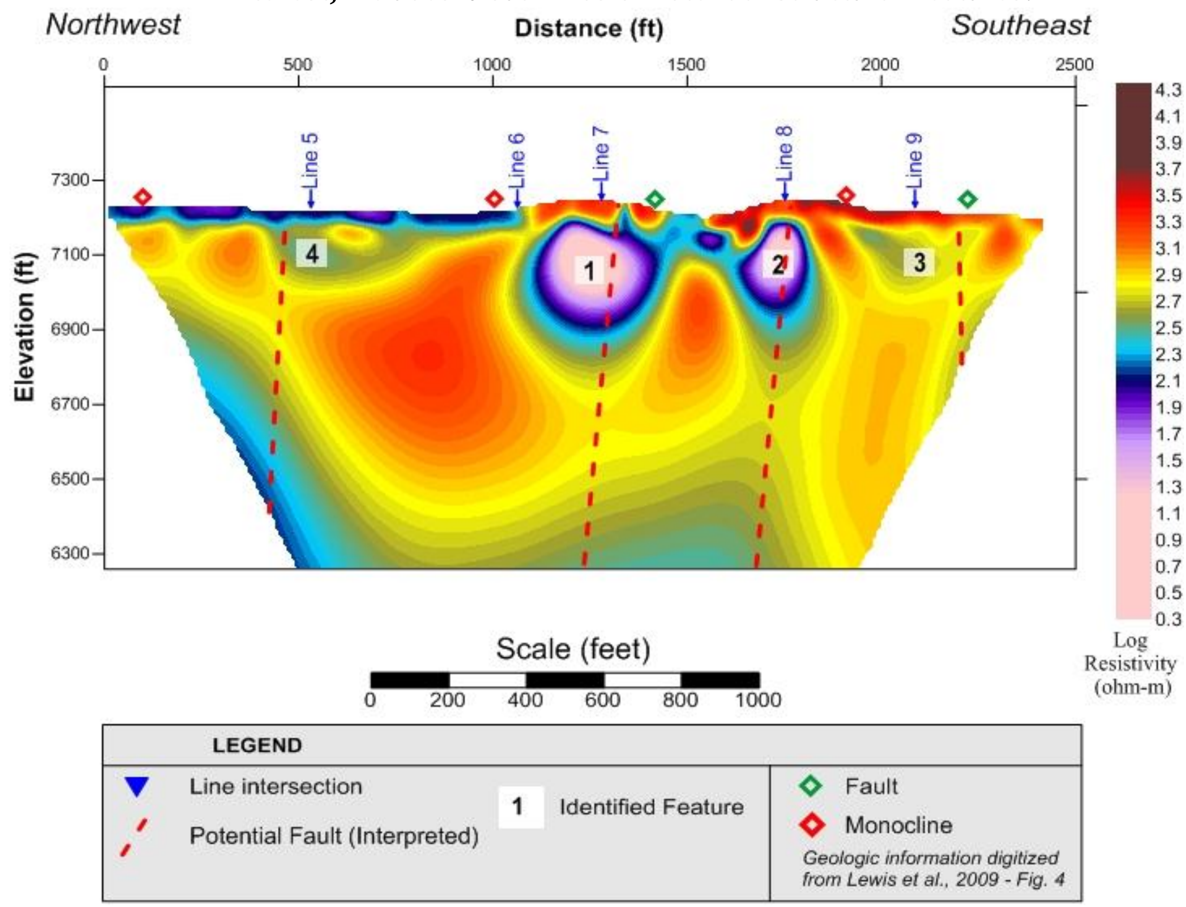
Figure 5. Profile 2 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.1.3 2D Resistivity Profile 3

Figure 6 displays the modeled resistivity results for profile 3, acquired parallel to and to the north of profile 2. The near-surface conductive layer discussed previously extends between 0 and 1100 feet along the profile, located within the northern part of the canyon floor floodplain and wetland, and it has an average thickness of 20 feet. East of 1100 feet, the near-surface rocks are largely resistive, where the line crosses a high talus slope along the north wall of the canyon before ending on bedrock exposures of welded tuff. A small near-surface conductive zone at 1500 feet appears to correspond to a tributary drainage on the side of Sandia Canyon. At depth, there are two obvious conductive anomalies, labeled (1) and (2), centered on 1300 and 1750 feet along the profile respectively. The offset in the model resistivity contours associated with these two features continues to extend to depth beneath these bulls eyes in low resistivity. The location of these two features corresponds well to previously identified potential fault traces and hence could represent fault planes. The low resistivity, 2.5 to 250 Ωm ($\log_{10}$ resistivity 0.4 to 2.4) associated with the upper sections of these features, the lowest values observed for the 2D profiles, may reflect high clay contents, high water contents, or lower resistivity values for the pore water. The latter may originate from an increase in the ionic concentration of the groundwater. The conductive feature labeled (3) on the profile, located at a distance of 2000 feet along the profile, generally corresponds to the locations along the profiles of feature (6) in profile 1 and feature (3) in profile 2. It is also associated with an offset in the underlying model resistivity contours. This combined with the proximity to the projected location of a previously identified fault trace indicates this feature may represent a fault. The final feature, labeled (4), is a sub horizontal zone with a westward dip located directly underneath the near-surface conductive layer. The depth (~125 feet) and sub horizontal orientation of this feature suggest it is stratigraphically controlled bedrock zone with enhanced water or clay contents. However, we also observe an offset in the underlying model resistivity contours possibly indicating another fault in this region. The edge of the model resistivity in this region indicate more conductive values below the 6900 elevation contour, potentially reinforcing the fault interpretation of feature (4). It should be remembered that the edges of these models are the least sensitive due to the low data density.

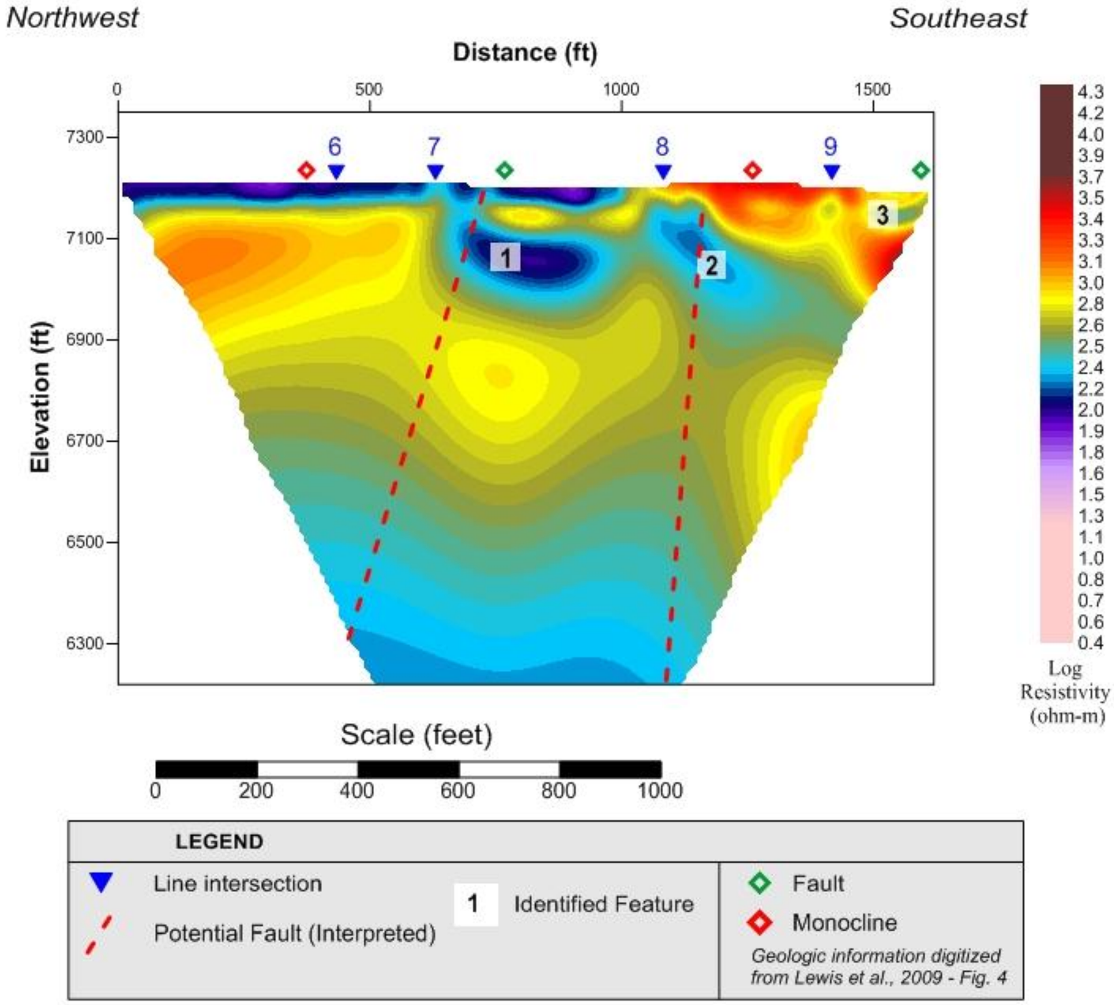
Figure 6. Profile 3 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.1.4 2D Resistivity Profile 4

Figure 7 displays the modeled resistivity results for profile 4, acquired parallel to, and in between profiles 2 and 3. The near-surface conductive layer discussed previously extends between 0 and 1000 feet along the profile, located within the central part of the canyon floor floodplain and wetland, and it has an average thickness of 25 feet. East of 1000 feet, the near-surface rocks are resistive where the profile crosses a talus slope and bedrock exposures of welded tuff. At depth, there are two significant conductive features of interest, labeled (1) and (2). Both of these features appear to be associated with offsets in the underlying model resistivity contours, and may represent faults. In addition, feature (1), located at 800 feet along the profile, is in close proximity to the projected location of a previously identified potential fault trace. Another conductive feature, labeled (3), is observed in the near-surface at 1600 feet along the profile. It is difficult to identify what may be causing this feature due to its location at the edge of the model where sensitivity is lowest.

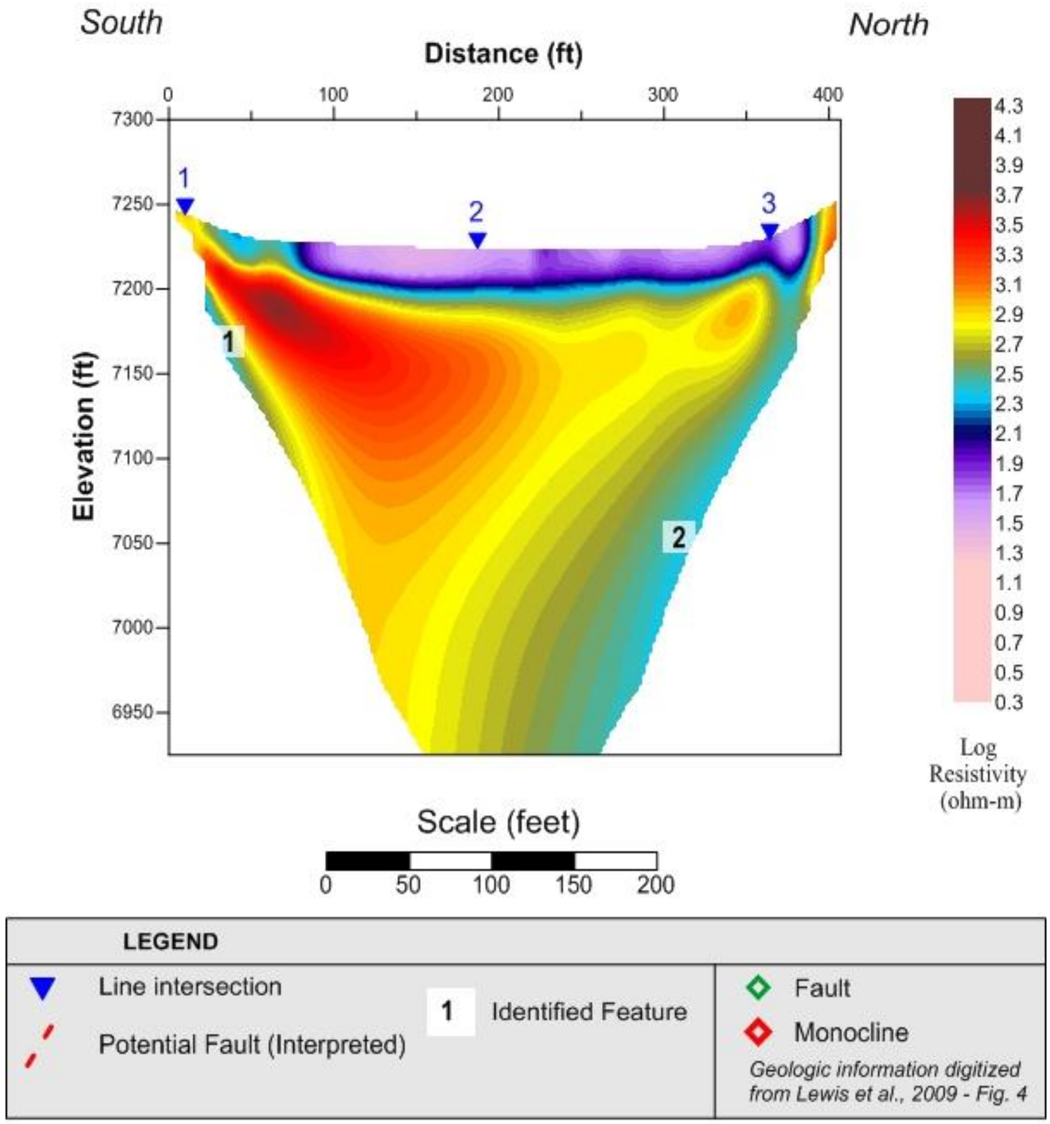
Figure 7. Profile 4 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.1.5 2D Resistivity Profile 5

Figure 8 displays the modeled resistivity results for profile 5, acquired perpendicular to profiles 1 through 4. The dominant feature in this profile is the near-surface conductive layer discussed previously, which extends across the majority of the profile with an average thickness of 20 feet. Although the wetland occurs between approximately 180 and 375 feet along the profile, the near-surface conductive layer is uniformly conductive as far south as about 75 feet along the profile. This may indicate that alluvial groundwater beneath the canyon floor floodplain extends south beneath the adjacent alluvial slope or that the near-surface conductive layer is mapping silt- and clay-rich alluvial deposits. Deep resistivity values can be observed becoming more conductive at the edges of the model; between 7200 and 7100 feet elevation on the southern edge, labeled (1), and quite clearly at all depths on the northern edge, labeled (2). The feature on the southern edge of the model coincides well with the location of the conductive feature labeled (1) in profile 1, although unfortunately there is little overlap of these regions of the two models. These are regions of the model where we have the lowest sensitivity and hence it is difficult to draw any reasonable conclusions as to the origin of such features.

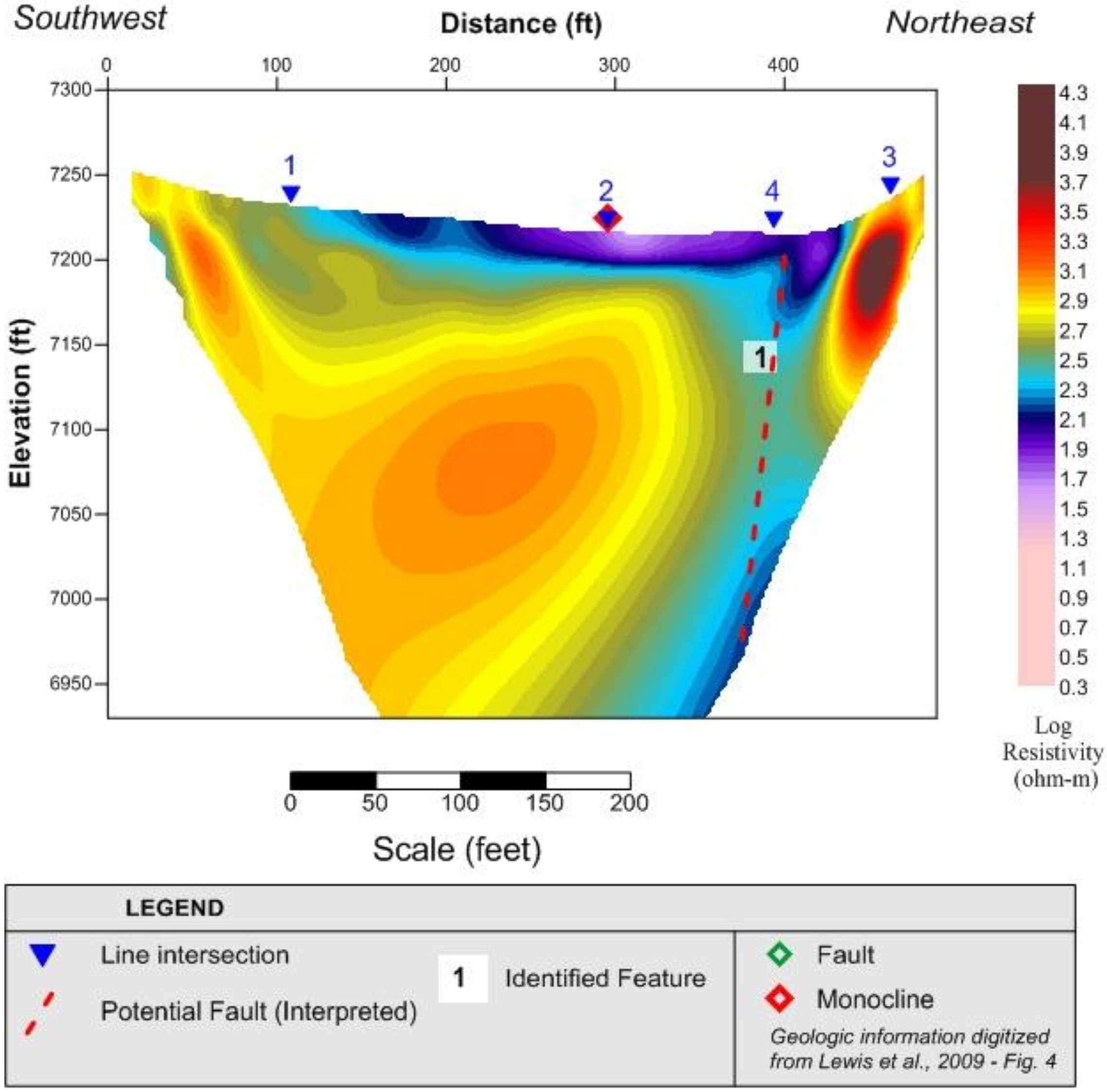
Figure 8. Profile 5 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.1.6 2D Resistivity Profile 6

Figure 9 displays the modeled resistivity results for profile 6, acquired parallel to and to the southeast of profile 5. The near-surface conductive layer discussed previously extends between 100 and 450 feet along the profile, with an average thickness of 25 feet. Similar to profile 5, the wetland occurs between approximately 300 and 430 feet along the profile, but the near-surface conductive layer extends farther south to about 140 feet along the profile. Maximum conductivity values are somewhat less than that in profile 5. Beneath this layer we observe one significant conductive feature, labeled (1). This feature is located beneath the north margin of the wetland and is associated with an offset in the model resistivity contours which extends to the limit of the penetration depth for the model. This could potentially represent a fault running through this profile.

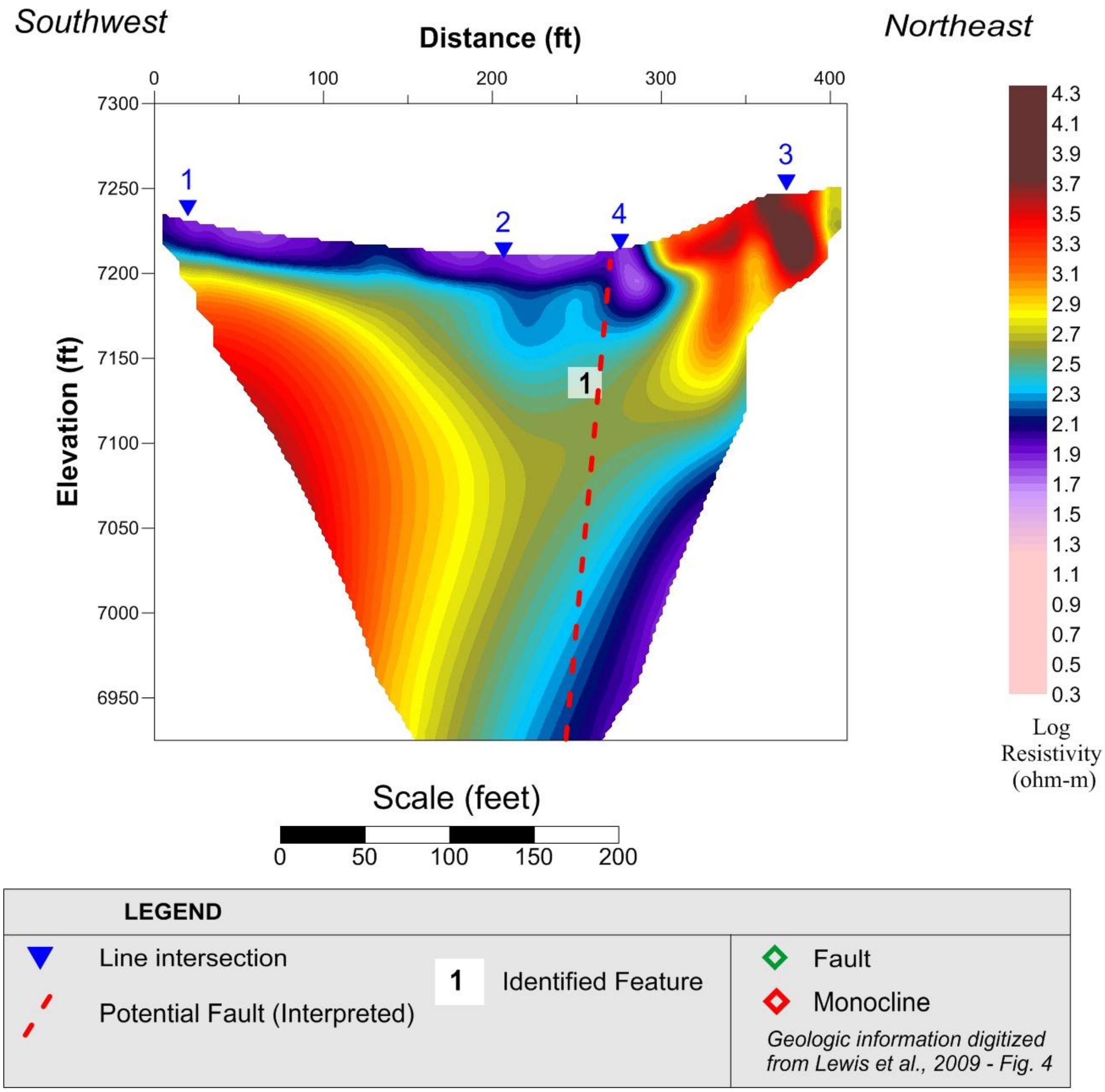
Figure 9. Profile 6 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.1.7 2D Resistivity Profile 7

Figure 10 displays the modeled resistivity results for profile 7, acquired parallel to and to the southeast of profile 6. The near-surface conductive layer discussed previously extends between 0 and 300 feet along the profile, with an average thickness of 25 feet. The wetland occurs between approximately 170 and 270 feet along the profile, corresponding to the north end of the near-surface conductive layer. As in profile 6, the near-surface conductive layer extends farther south than the wetlands and dips northward towards the canyon axis. At depth we observe one significant conductive feature, labeled (1), which may extend from the surface to the depth penetration limit of the resistivity model. This feature is again associated with an offset in the model resistivity contours that may represent a fault running through this profile. This feature could also represent two separate features; an alluvium-filled (and possibly saturated) channel inset into the bedrock tuffs that corresponds to the base of the previously described near-surface conductive layer, and a deeper conductive feature existing beneath 7100 feet elevation. The latter feature is on the edge of the resistivity model in a region with the lowest model sensitivity, so confidence is low.

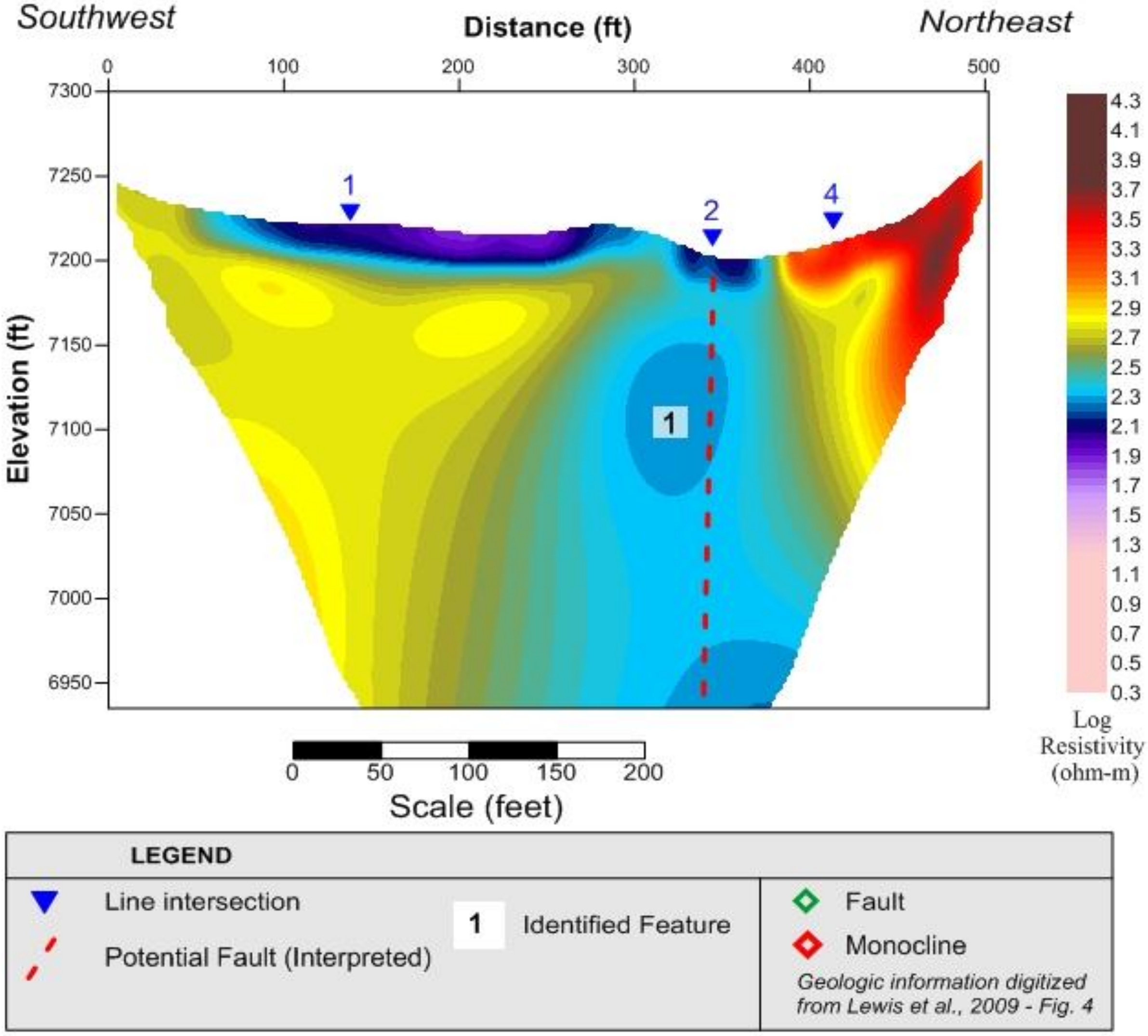
Figure 10. Profile 7 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.1.8 2D Resistivity Profile 8

Figure 11 displays the modeled resistivity results for profile 8, acquired parallel to and to the southeast of profile 7. The near-surface conductive layer discussed previously extends between 50 and 380 feet along the profile, with an average thickness of 25 feet. The profile crosses the eastern end of the wetland, which occurs between approximately 310 and 365 feet along the profile. South of 310 feet, the near-surface conductive layer may represent silt- and clay-rich alluvial deposits. At depth we observe one significant conductive feature, labeled (1). This feature is centered under the wetlands and is associated with a clear offset in the model resistivity contours, with the conductive feature extending unbroken from the near-surface to the penetration depth limit of the resistivity model. The feature may represent a fault running through this profile.

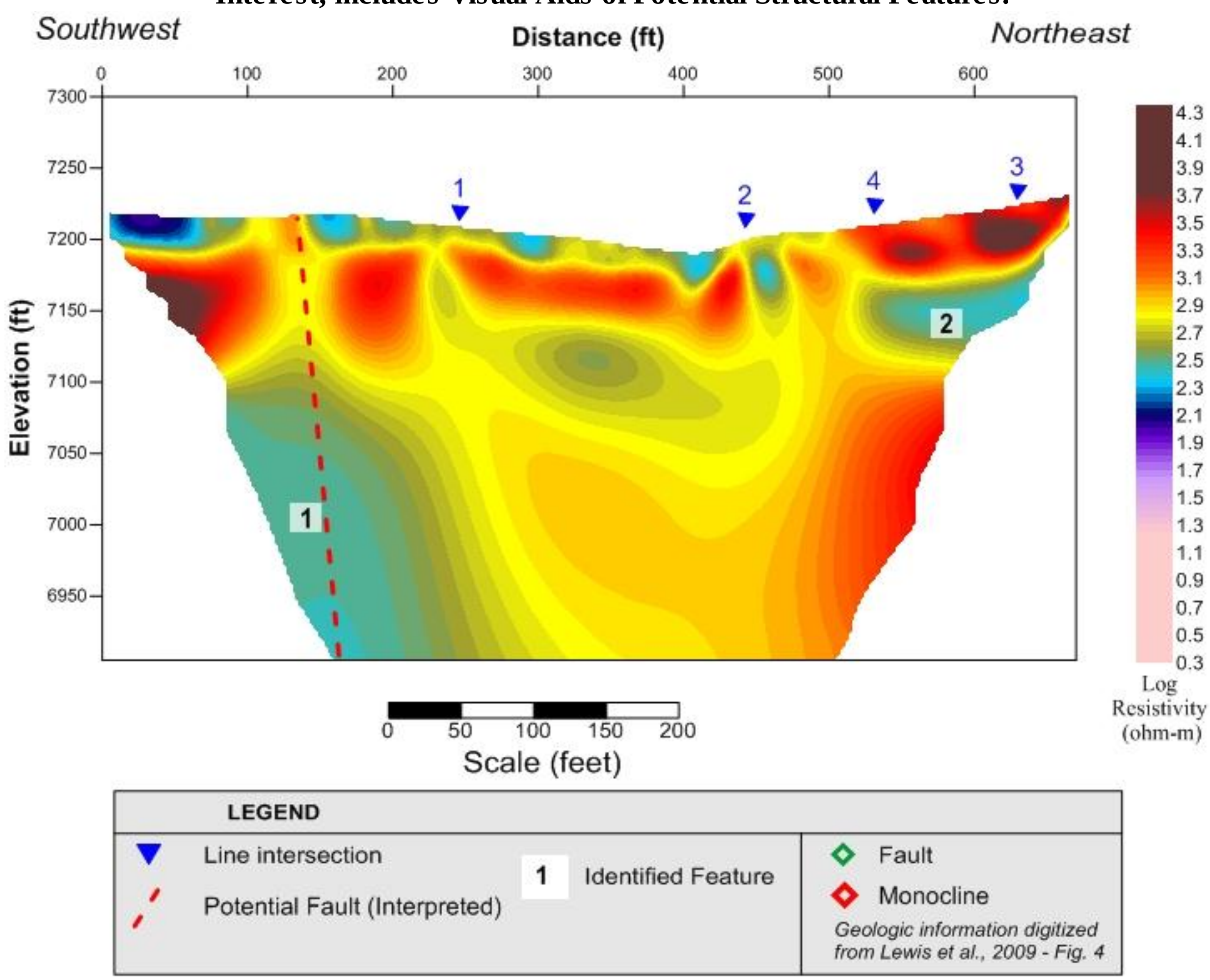
Figure 11. Profile 8 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.1.9 2D Resistivity Profile 9

Figure 12 displays the modeled resistivity results for profile 9, acquired parallel to and to the southeast of profile 8. This profile is located east of the wetlands in an area dominated by surface bedrock exposures and thin talus-slope deposits. The near-surface conductive layer discussed previously is absent in this profile. The stream, which incises a narrow bedrock channel into the welded tuffs approximately 400 feet along the profile, is a minor shallow conductive feature. Two conductive features are labeled within this profile; number (1) is located at 150 feet along the profile between approximately 7100 and 6900 feet elevation. This feature is located at the edge of the resistivity model so confidence is low based on the low sensitivity in this region. An offset in the model resistivity contours is observed above this feature through the higher resistivity values, possibly indicating a fault in this location. The second conductive feature, labeled (2), is located between 520 and 630 feet along the profile at an elevation of approximately 7150 feet. This feature does not seem to be associated with any offset in the model resistivity contours and its horizontal nature is similar to feature (6) in profile 1 and feature (3) in profile 2, although it is about 100 feet higher in elevation. This feature occurs in bedrock and most likely represents strata with enhanced water and/or clay content.

Figure 12. Profile 9 Model Resistivity Results - Identifying Electrical Resistivity Features of Interest, includes Visual Aids of Potential Structural Features.



4.2 3D RESISTIVITY MODEL RESULTS

The results of the 3D inverse modeling are displayed in Figure 13, displayed as a series of slices at selected depths within the model domain. The elevations (depths) are indicated in the lower left corner of each subplot within the mosaic of different slices. The maximum and minimum values of model resistivity for the 3D inverse modeling are approximately an order of magnitude smaller and larger than the 2D results, reflecting the improved ability of the 3D modeling to cope with complex structure. This is to be expected since we are including the regions between the 2D profiles in the 3D modeling, rather than assuming them to be constant as was the case for the individual 2D profile models. Hence, we can expect improvements in the model resistivity values and resolution of the features.

Within Figure 13, for the top two depth slices (7210 and 7170 feet elevation) the main feature of interest is the electrically conductive region stretching from the upper northwest corner of the model grid down to the intersection with profile 8, labeled (1). This region is concentrated in the canyon bottom, and appears coincident with the wetland and floodplain areas of upper Sandia Canyon. This region could be reflecting more conductive sediments associated with the alluvium or low resistivity associated with an alluvial groundwater. The remainder of the model domains displays resistive values outside of this region.

The conductive region discussed above becomes more resistive by the depth slice at 7130 feet elevation, possibly reflecting a change from alluvial deposits to bedrock tuffs. There are several areas along the canyon that remain slightly more conductive than the background resistive values, labeled (2) and (3). The main feature at this level is the conductive bull's-eye located between profiles 7 and 8, labeled (4). Two more conductive features can be observed on the southeast edge of the model domain in this area, to the north and east of feature 4, labeled (5) and (6). As we proceed through the depth slices the region of the model domain with these three features remains consistently more conductive than the surrounding resistive background. A number of potential faults have been mapped in this region which are displayed on the base map of Figure 13 (taken from Lewis et al, 2009, faults are shown as black lines). These appear to coincide well with the location of these features and the area of conductive model values.

Another conductive feature, labeled (7), can be observed in the upper northeast corner of the model domain. This feature first becomes apparent at an elevation of 7050 feet and remains evident down to an elevation of 6650 feet. This feature is apparent in profiles 1 and 5 of the 2D resistivity models, with the 3D resistivity model appearing to confirm that this feature is confined to the southeast corner of the survey area. It is interesting to note that a northwest – southeast trending canyon-parallel fault was identified in Lewis et al (2009) on the plateau area just to the northwest of the resistivity survey area.

Below the depth slice at 6650 feet the majority of the model domain has become more conductive suggesting a change in lithology across the survey area of the canyon. The conductive features of interest are very difficult to distinguish from the background resistivity from this point.

Figure 13. Plan View Depth Slices of Three-dimensional Model Resistivity (2 sheets).

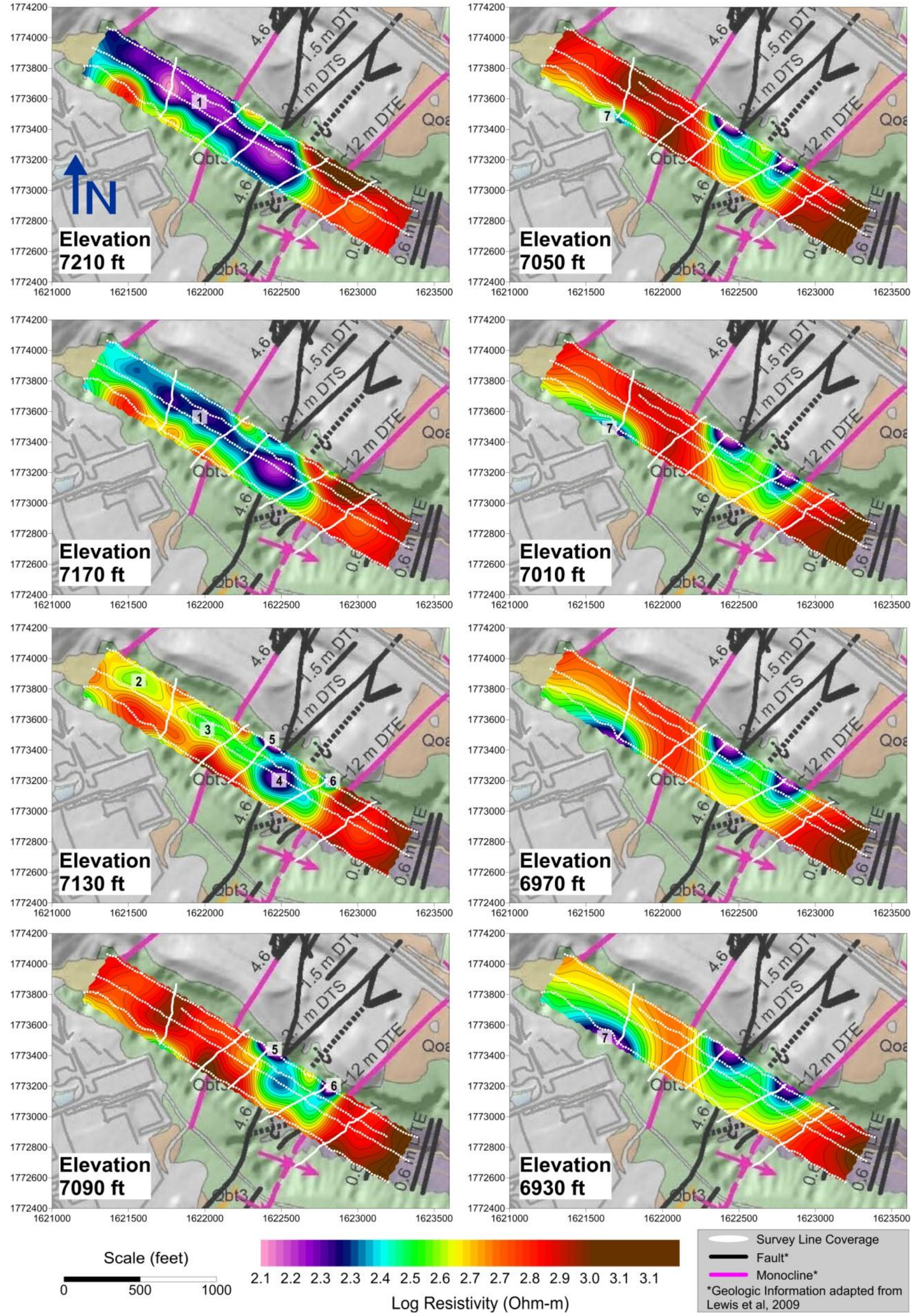


Figure 13 continued. Plan View Depth Slices of Three-dimensional Model Resistivity (2 sheets).

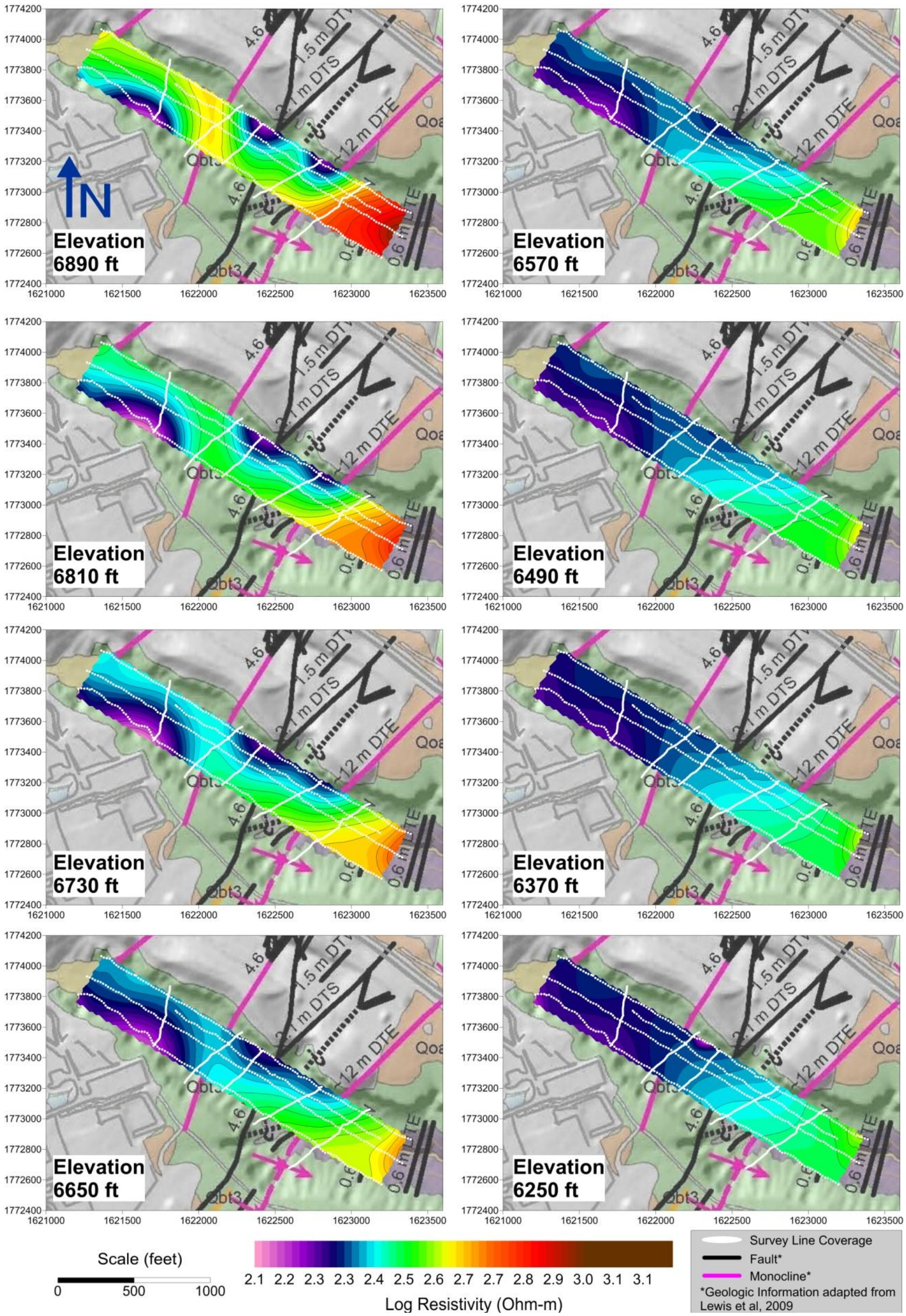
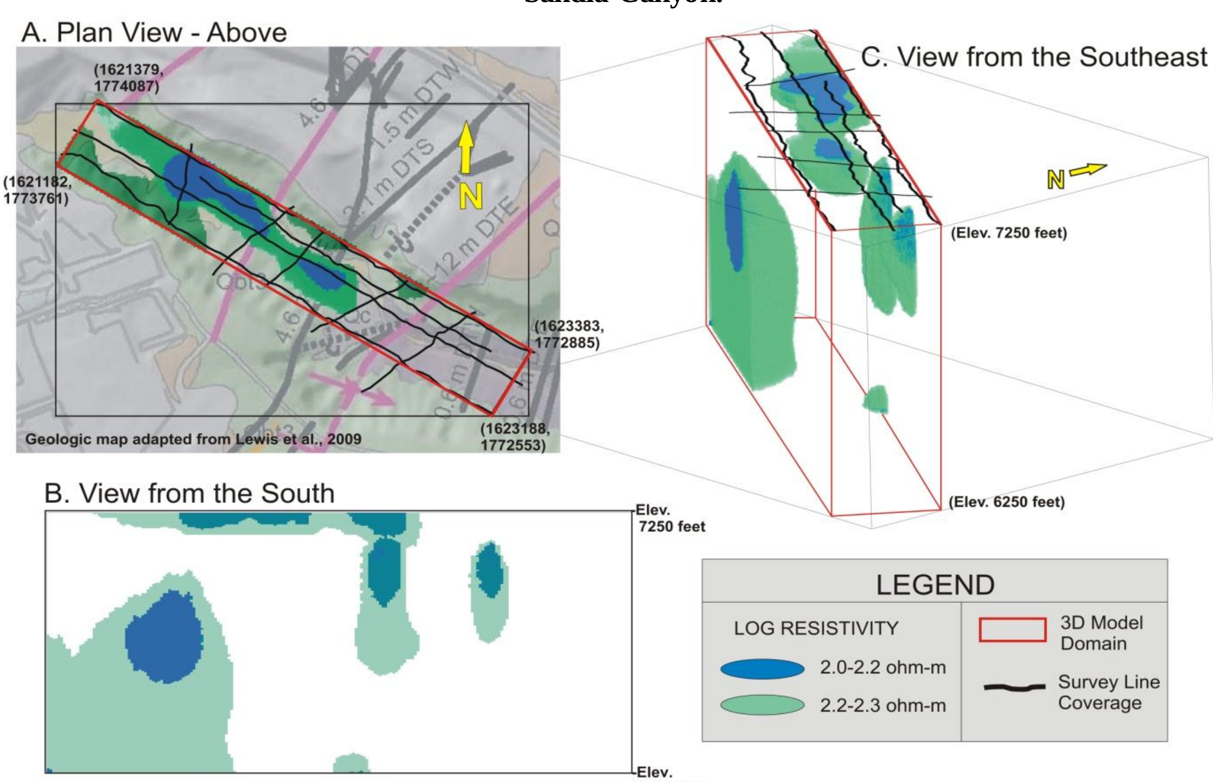


Figure 14 displays three-dimensional renderings of the low resistivity features along the Upper Sandia Canyon covered by the 3D inverse modeling. Figure14(a) displays a plan view of the 3D model domain and results from above, figure 14(b) displays a profile view from the south (looking north), and figure 14(c) shows the isometric view along the long axis of the canyon, as viewed from the southeast (looking towards the northwest). Two levels of resistivity values are presented, with the small opaque resistivity body in blue (resistivity value of 100 to 150 ohm-m) and the larger transparent higher resistivity body in green (resistivity value between 150 and 200 ohm-m). The main regions of interest in the figure are the low resistivity feature in the near-surface, stretching downstream from the northwest corner of the model domain, labeled as feature (1) in Figure 13. In addition, there are several low resistivity regions, one approximately in the middle of the model domain and a second on the upper southwest corner of the model domain, which can be seen extending to depth. The feature in the middle of the model domain is coincident with an area of the upper Sandia Canyon where a number of potential faults have been mapped (Lewis *et al*, 2009).

Figure 14. Three-dimensional Renderings of the Low Resistivity Features Along the Upper Sandia Canyon.



5.0 CONCLUSIONS

Geophysical characterization activities, in the form of electrical resistivity, were completed in the wetland area of upper Sandia Canyon at the U.S. Department of Energy (DOE) Los Alamos National Laboratory in Los Alamos, New Mexico. Data were acquired between September 12 and September 20, 2011. Resistivity data were collected in two-dimensional (2D) profiles and inverted in both 2D and three-dimensional (3D) format, the latter producing a model that reduces distortions possibly seen in 2D profiles for complex 3D electrically conductive targets. The main conclusions of this study are:

- 2D and 3D inversions of DC resistivity data provide a model of electrical properties of subsurface materials of the region beneath and adjacent to the wetland in upper Sandia Canyon.
- Resistivity features are expected to correspond to, among other factors, variations in water content; ionic strength of pore water; and clay content.
- Numerous high- and low-resistivity features correspond to observed or reasonably inferred geological features. For example, a very conductive layer extending from the surface to 20-25 feet (6.1-7.6 m) below ground level in the upper Sandia Canyon wetland correlates well with an alluvial aquifer perched on a welded unit (Qbt_2) of the Bandelier Tuff.
- "Offsets" in horizontal resistive units may indicate structural features such as faults or zones of intense fracturing. The magnitudes of the offsets are much greater than displacements of mapped faults in the area and probably do not correspond to vertical offsets of rock units; rather, they may correspond to lateral differences in water or clay contents within units.
- Several areas of low resistivity correlate generally with mapped fault and/or fracture zones (as detailed in Lewis *et al*, 2009).
- In general, there is a widespread resistive layer beneath the wetland that may correspond to the near-surface welded Bandelier Tuff that lies below the wetland alluvium. This

resistive layer may represent an aquitard beneath much of the wetland. Several areas of subvertical low-resistivity structures that penetrate the potential Bandelier Tuff aquitard were identified in this survey; these low-resistivity structures may represent infiltration zones through the potential welded Bandelier Tuff aquitard, allowing moisture from the surface to reach depths of several hundred feet.

- At present, a significant limitation to the interpretation of these data is the ambiguity between the positive effects on electrical *conductivity* of clay and water content of rocks. For example, it is not possible to determine what values of resistivity might correspond to full saturation.

- These geophysical data provide important new information for the hydrogeologic model of the wetlands and will help inform future investigations.

6.0 REFERENCES

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Lewis, C. J., Gardner, J. N., Schultz-Fellenz, E. S., Lavine, A., Reneau, S. L., and Olig, S., 2009, Fault interpretation and along-strike variation in throw in the Pajarito fault system, Rio Grande rift, New Mexico: Geosphere, **5**, No. 3, 1-18.

Oldenburg, D. W., and Li, Y., 1999, Estimating depth of investigation in DC resistivity and IP surveys: Geophysics, **64**, 403-416.

APPENDIX A

Plate 1 Profile 1 - Two-dimensional Model Resistivity Results

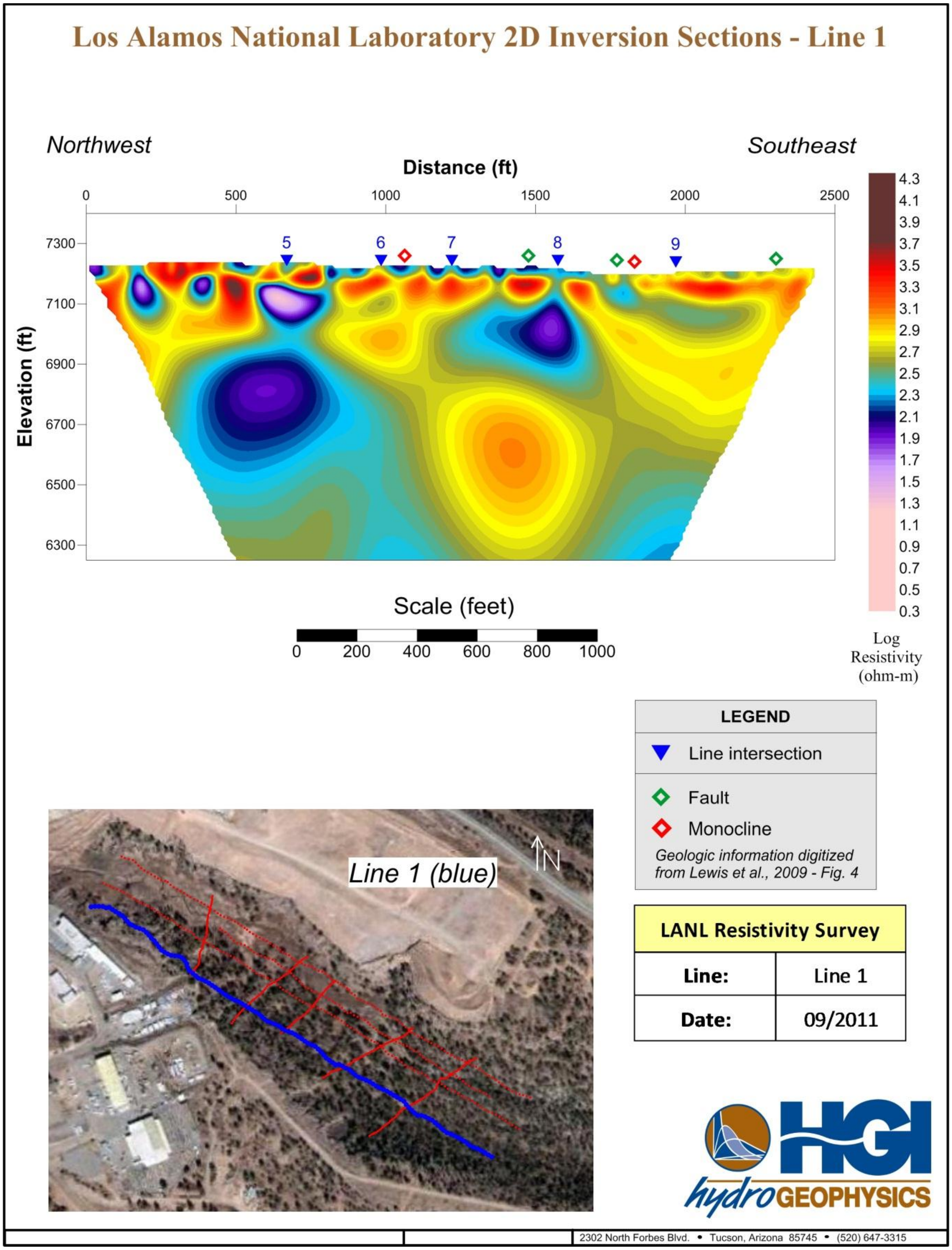


Plate 2Profile 2 - Two-dimensional Model Resistivity Results

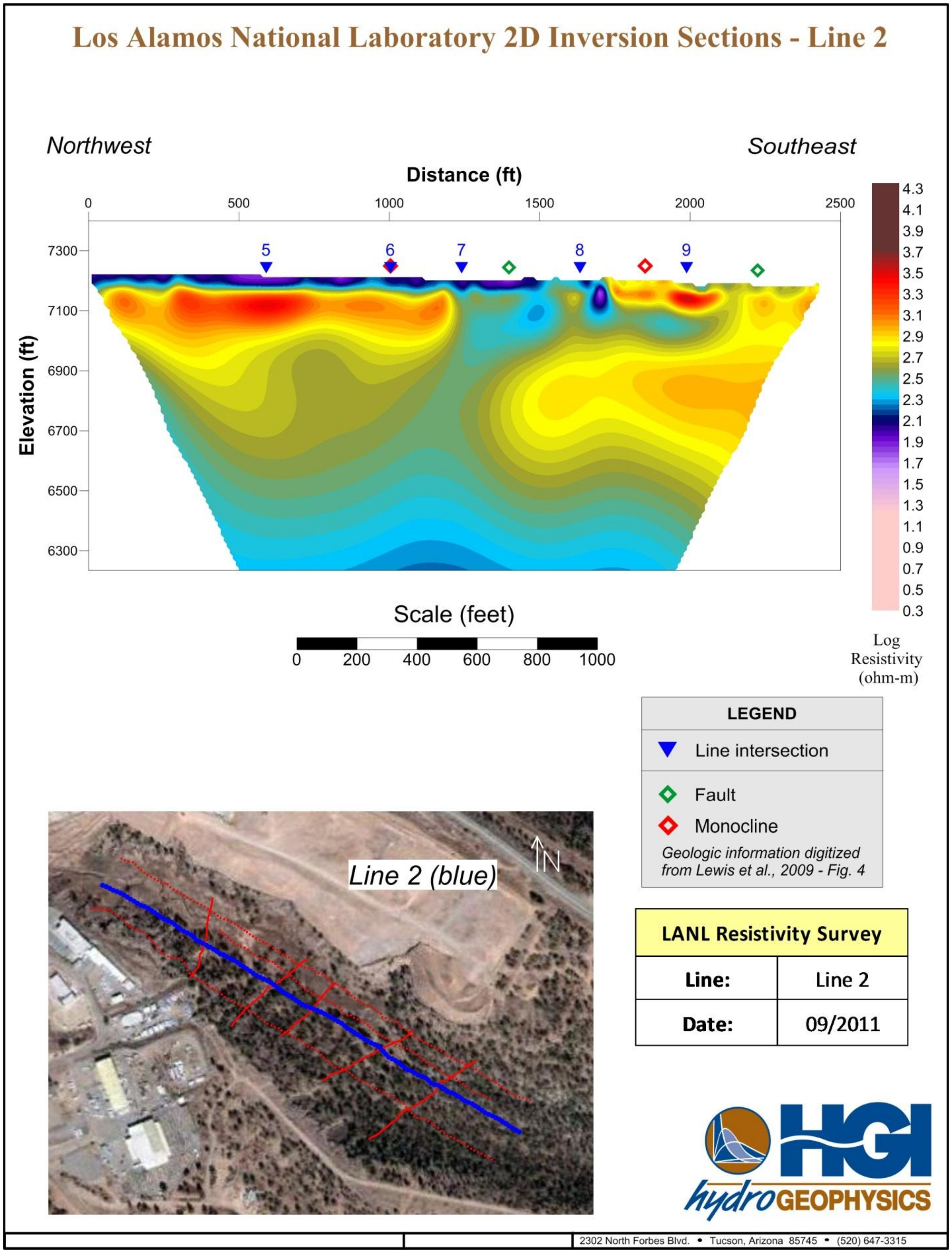


Plate 3Profile 3 - Two-dimensional Model Resistivity Results

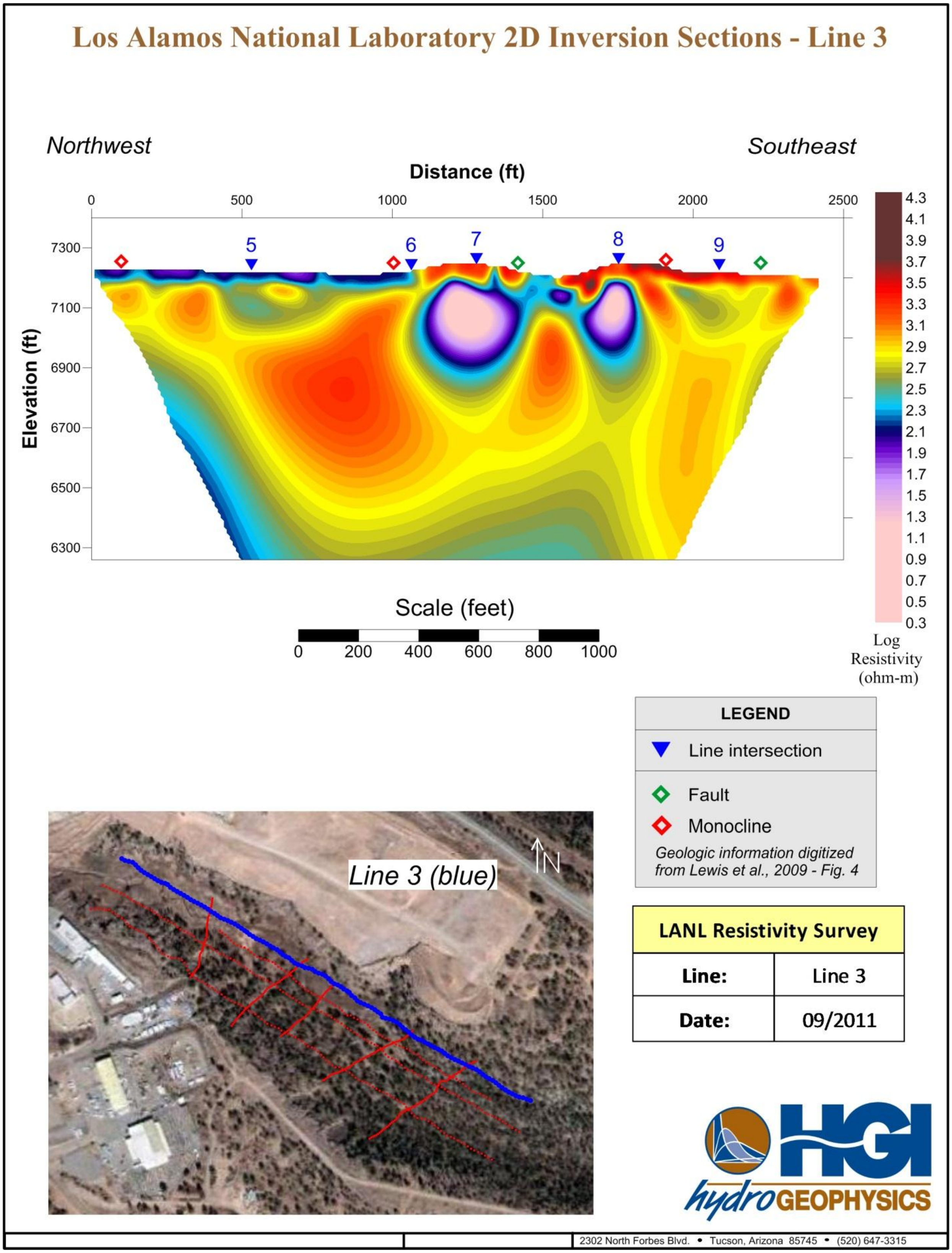


Plate 4Profile 4 - Two-dimensional Model Resistivity Results

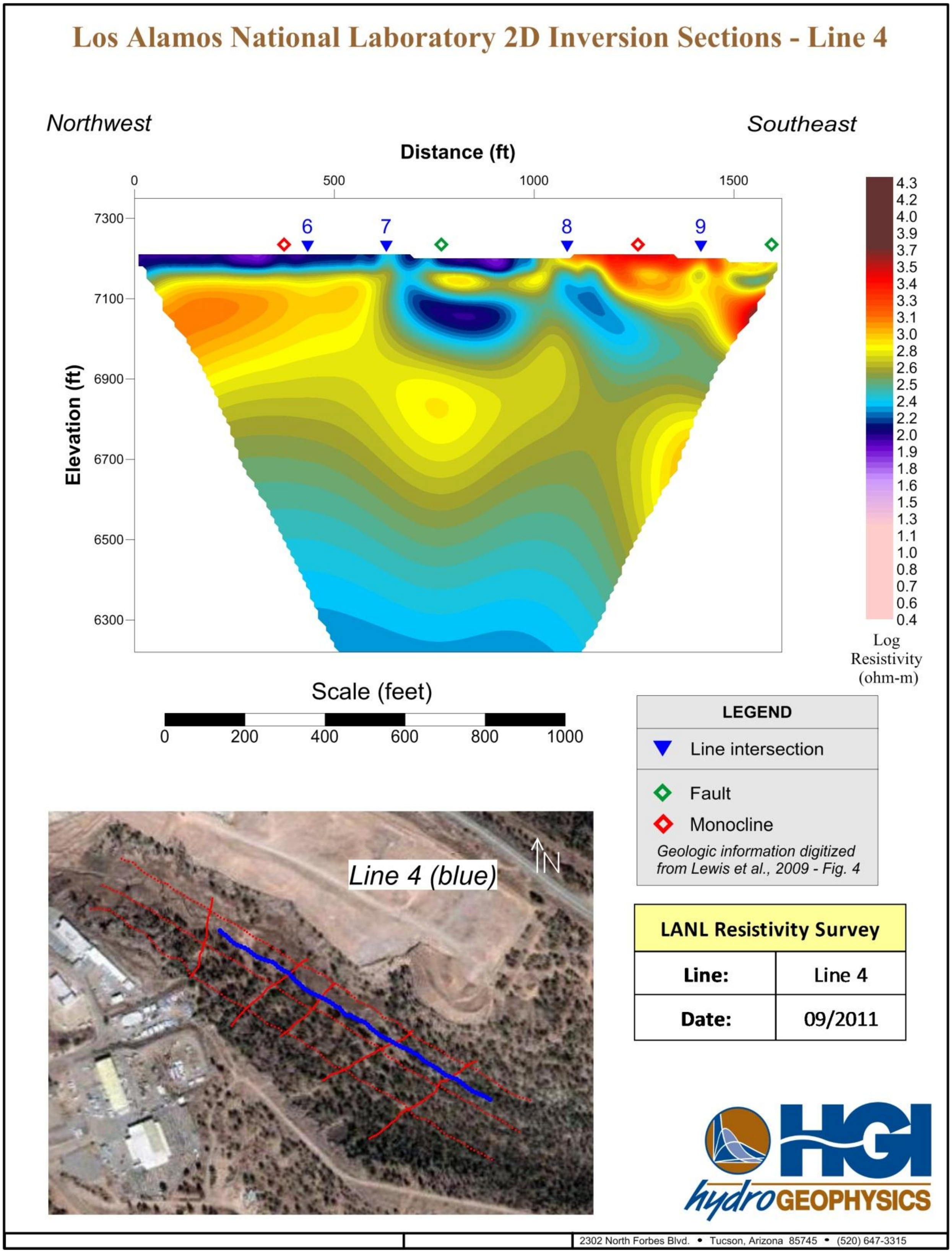


Plate 5 Profiles 1 through 4 Fence Plot - Two-dimensional Model Resistivity Results

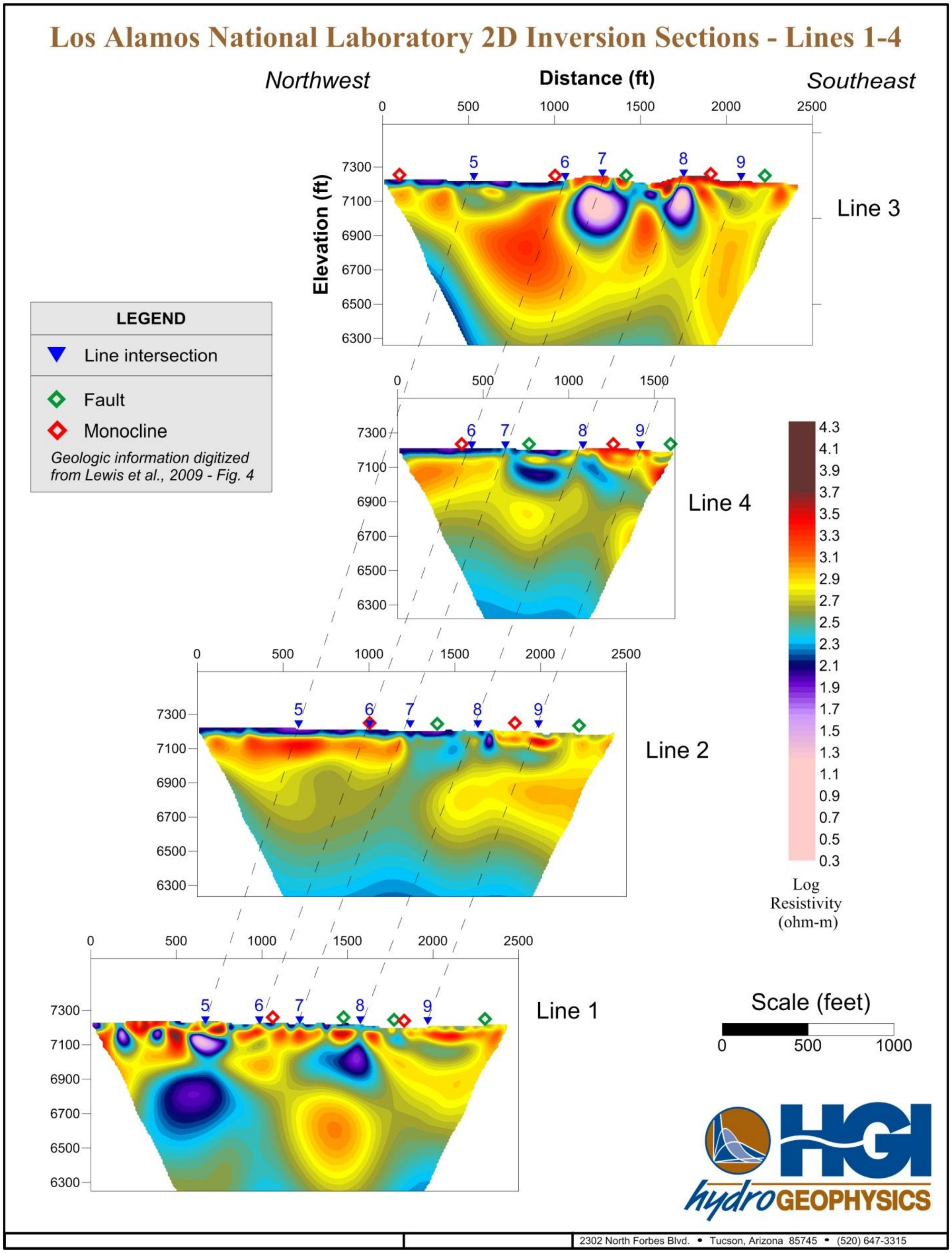
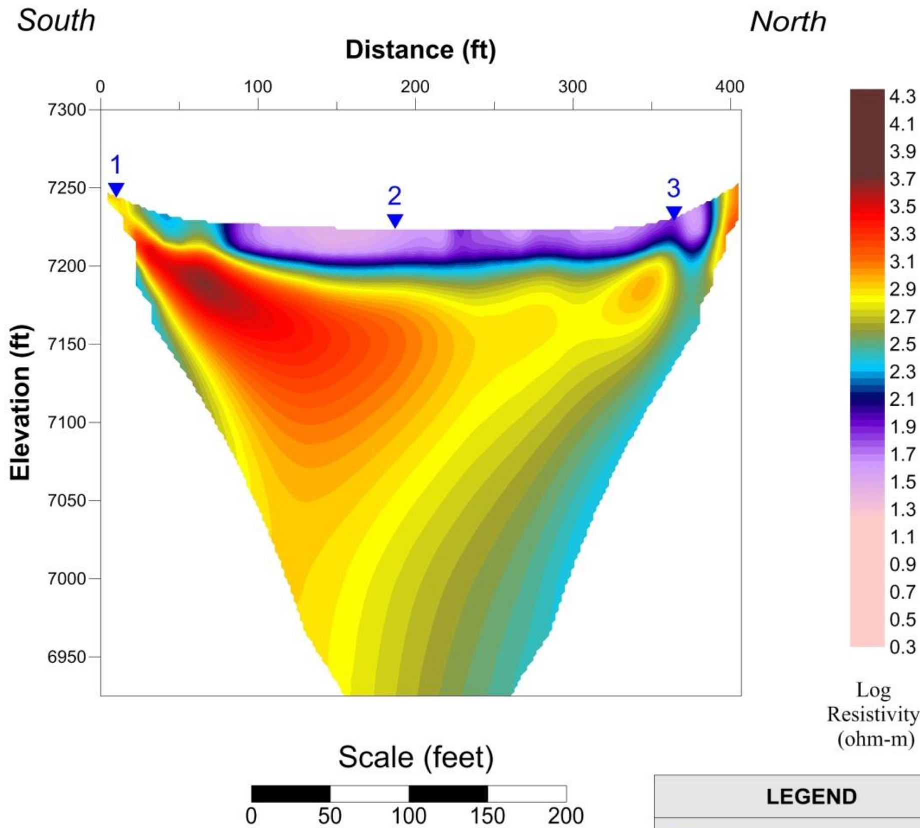


Plate 6 Profile 5 - Two-dimensional Model Resistivity Results

Los Alamos National Laboratory 2D Inversion Sections - Line 5



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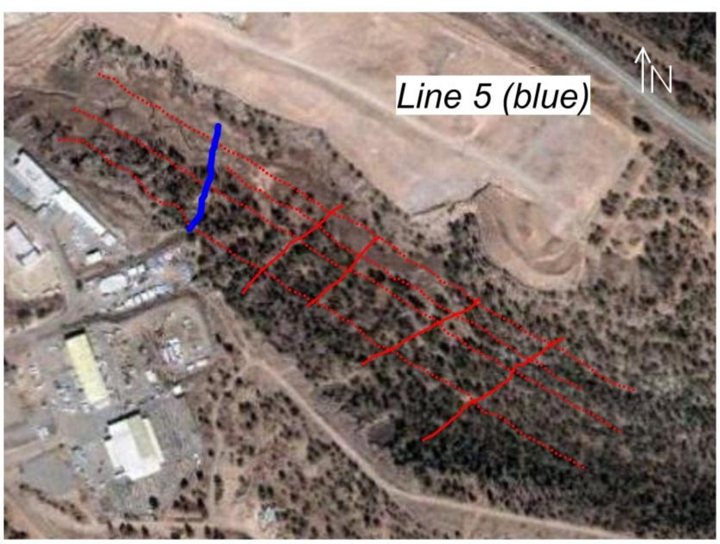
◇ Monocline
Geologic information digitized from Lewis et al., 2009 - Fig. 4



LANL Resistivity Survey	
Line:	Line 5
Date:	09/2011

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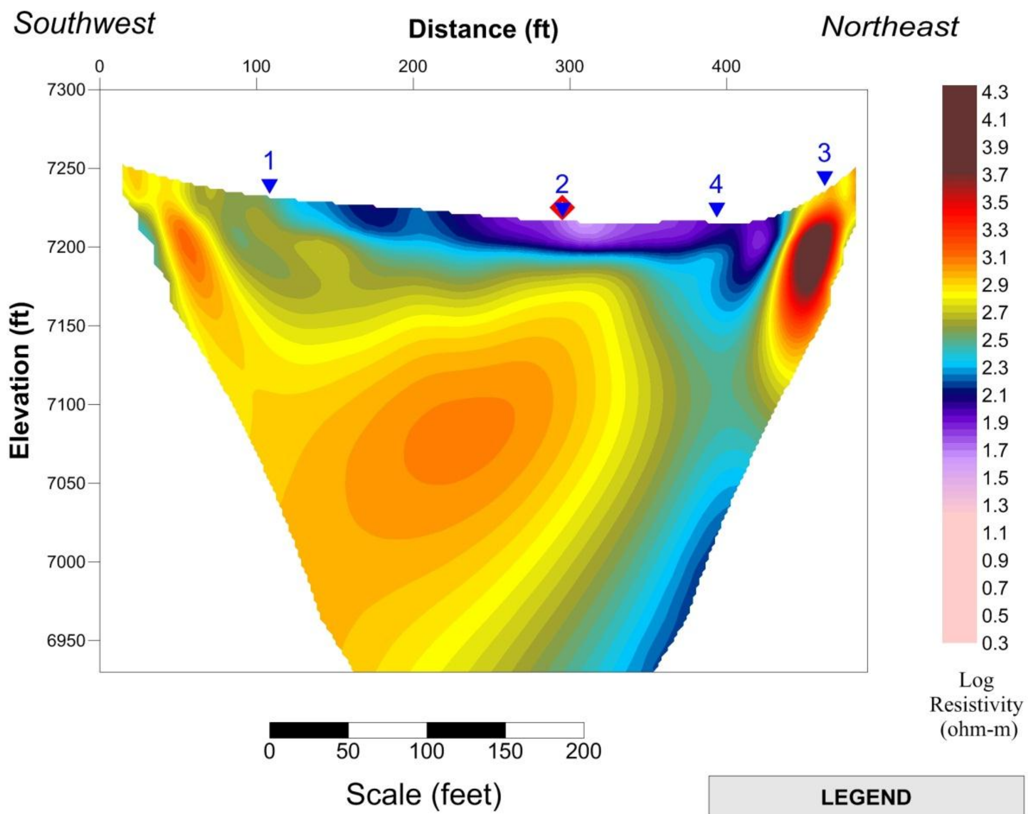
Plate 7 Profile 6 - Two-dimensional Model Resistivity Results

Los Alamos National Laboratory 2D Inversion Sections - Line 6



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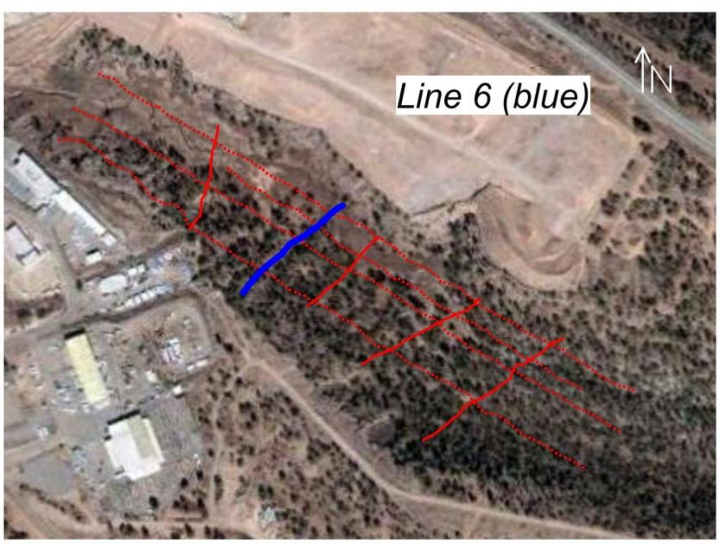

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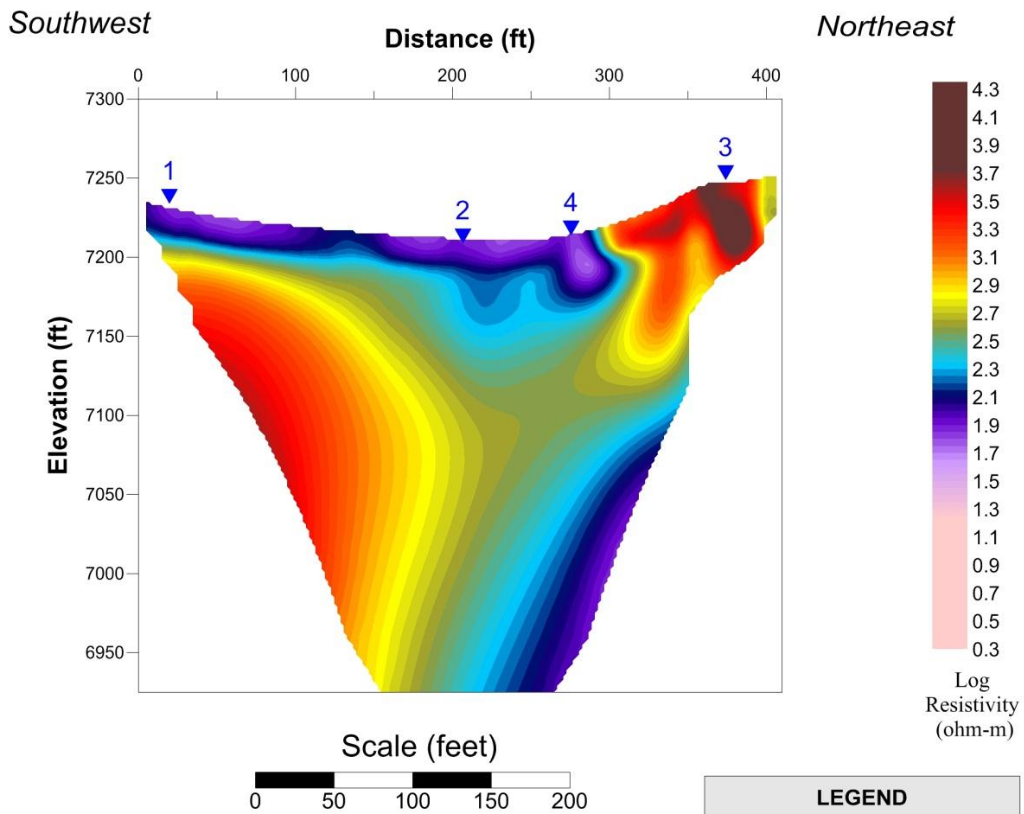
Plate 8 Profile 7 - Two-dimensional Model Resistivity Results

Los Alamos National Laboratory 2D Inversion Sections - Line 7



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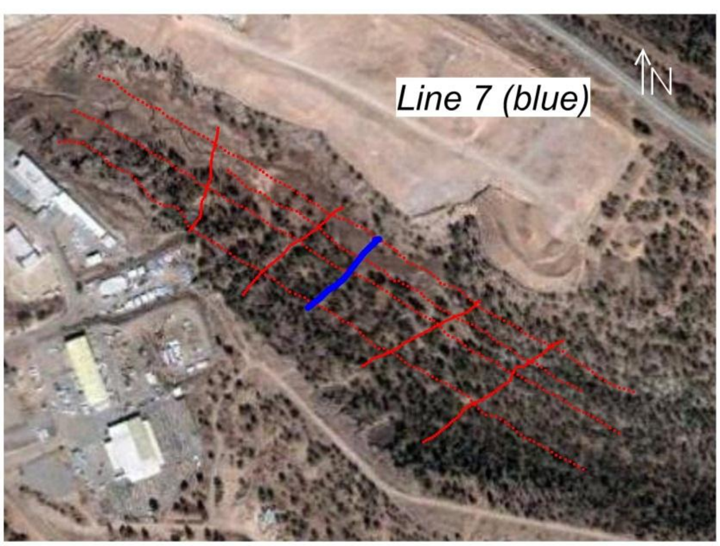

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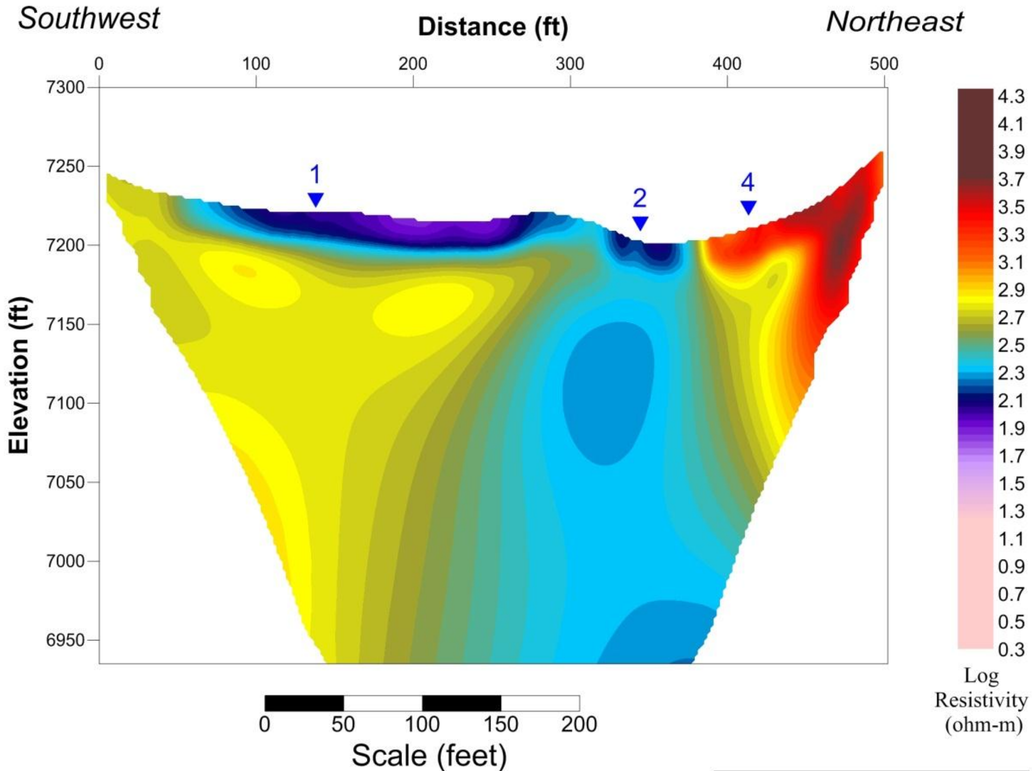
Plate 9 Profile 8 - Two-dimensional Model Resistivity Results

Los Alamos National Laboratory 2D Inversion Sections - Line 8



LEGEND

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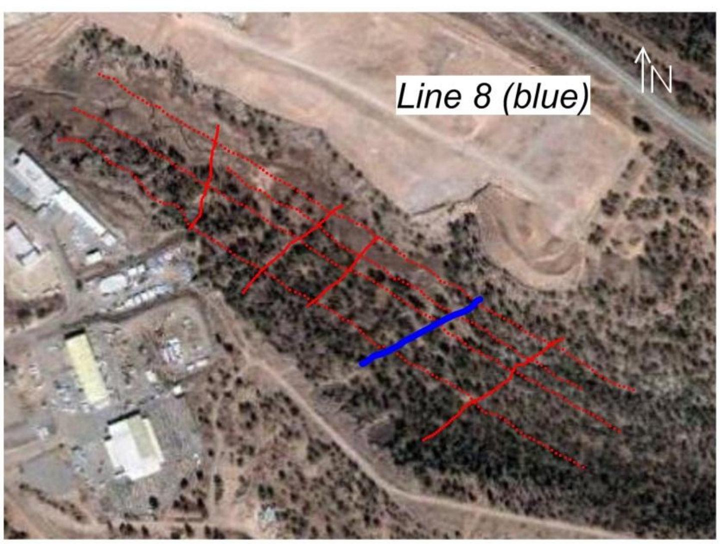

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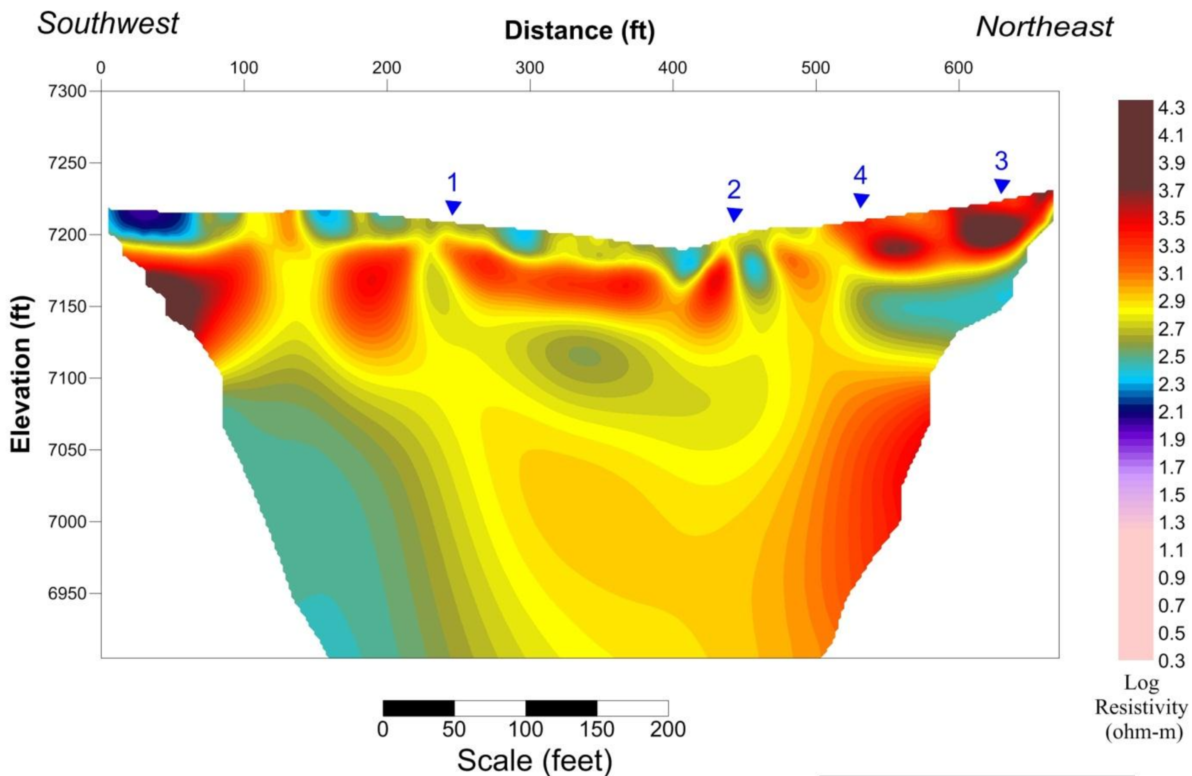
Plate 10 Profile 9 - Two-dimensional Model Resistivity Results

Los Alamos National Laboratory 2D Inversion Sections - Line 9



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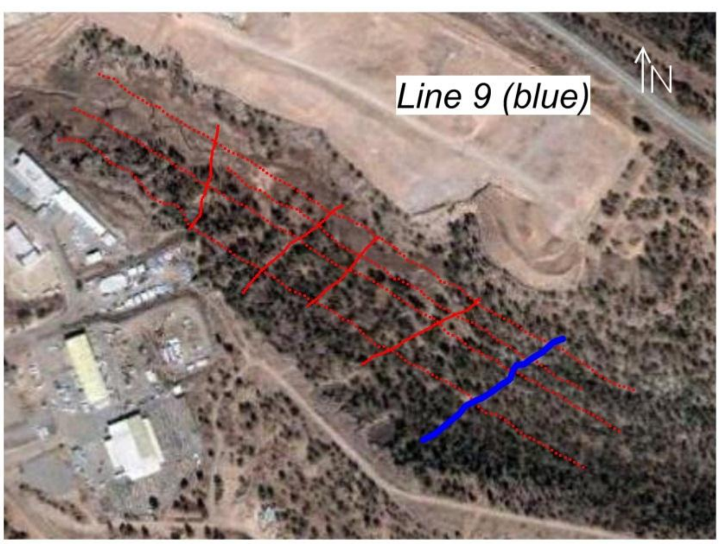
◇ Monocline
Geologic information digitized from Lewis et al., 2009 - Fig. 4



LANL Resistivity Survey	
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Plate 11 Profiles 5 through 9 Fence Plot - Two-dimensional Model Resistivity Results