Appendix H

Geophysical Investigations

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HARPER LAKE BASIN
GEOPHYSICAL SURVEYS
HINKLEY, CALIFORNIA

Prepared for:

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23 May 2009

LGS Project No. 27-1643

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HARPER LAKE BASIN
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HINKLEY, CALIFORNIA

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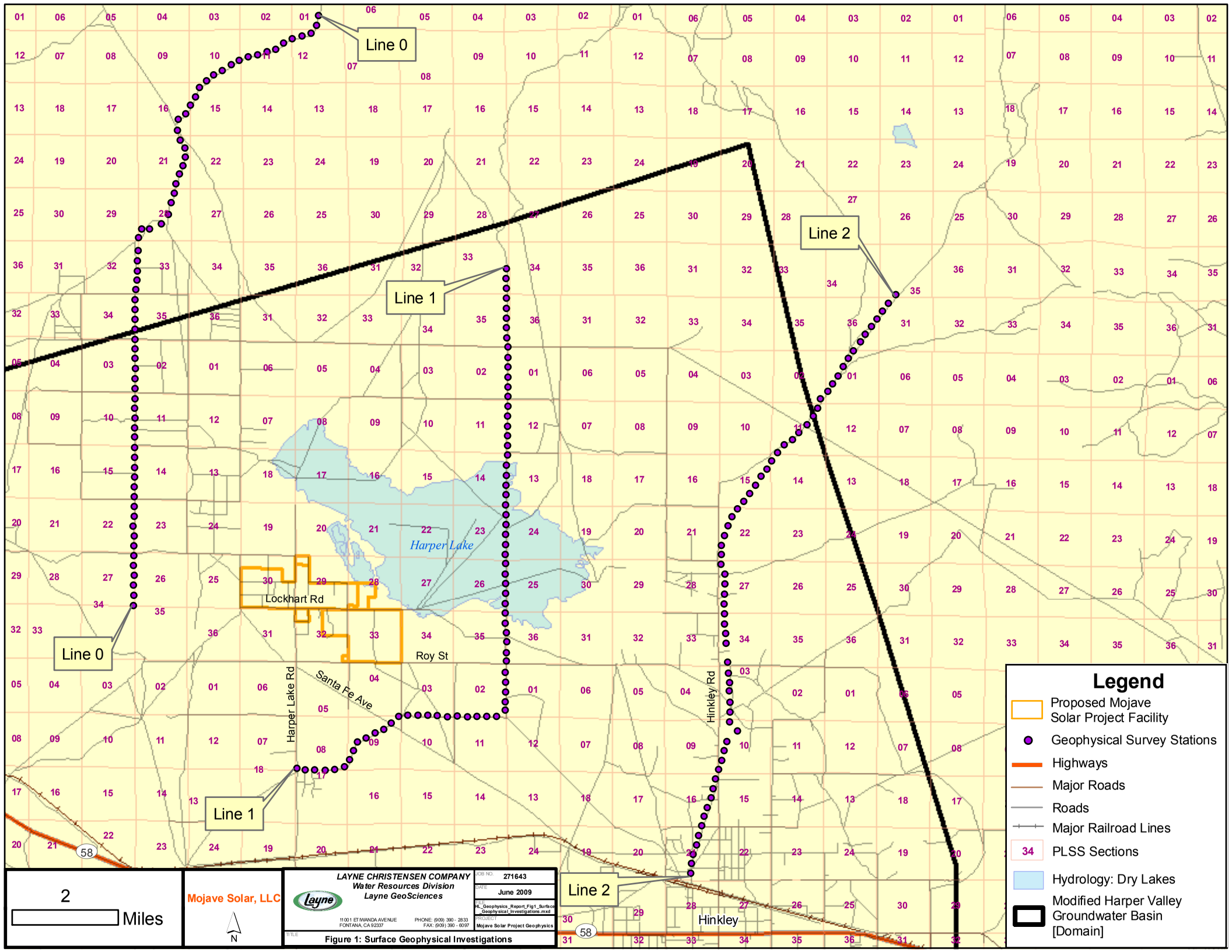
1. INTRODUCTION

This report presents the results of geophysical surveys conducted from June 2008 to February 2009 by Layne GeoSciences (LGS) in the Harper Lake groundwater basin in the vicinity of Hinkley, California. The purpose of the survey was to identify the overall configuration of the basin and to reveal intra-basin structures (e.g., basalt flows) which might impact groundwater flow. We used magnetotellurics (MT) and gravimetry to infer variations in subsurface resistivity and density, respectively, which can be interpreted in terms of subsurface lithology and weathering. The original survey design comprised profiles trending southwest-northeast, perpendicular to regional strike, for optimal imaging of the expected structure. Biological concerns necessitated a reorientation of the survey to eliminate most off-road access; as a result, many features were imaged obliquely, with more ambiguous results than would otherwise have been the case. The general site location and survey configuration are shown in Figure 1.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PROJECT Mojave Solar Project Geophysics
TITLE Figure 1: Surface Geophysical Investigations

2. BACKGROUND

2.1 PROJECT AND GOALS

The Harper Lake groundwater basin is northwest of Barstow, California in the vicinity of the dry Harper Lake bed north of Hinkley, California. The objective of geophysical surveys is to quantitatively describe the aquifer associated with the basins and to ascertain its continuity with respect to faults and basalt flows which may be present. We used MT to estimate depth to bedrock beneath the study area and to identify probable areas of basalt accumulation which impact groundwater flow. The MT system used in this investigation will often, but not always, provide a reliable image to depths as great as those expected for Harper Lake bedrock. Gravity data collected concurrently with the MT data provide an independent estimate of depth to bedrock to corroborate the information provided by the MT survey.

2.2 GEOLOGY AND HYDROGEOLOGY

The Harper Lake basin is within the Mojave Desert and encompasses portions of San Bernardino and Kern counties. Surficial and subsurface sediments include alluvium derived from the surrounding mountains, lacustrine deposits associated with Harper Lake, and fluvial deposits associated with the ancestral Mojave River. Pleistocene basalt flows are intermittently present within the sedimentary sequence. Bedrock has been encountered by only a few wells and may be very deep (hundreds of meters) at some locations (California DWR, 2003).

The Mojave River is 18 km (11 miles) to the southeast and does not typically provide recharge to the basin. Surface drainage is internal, toward Harper Lake; recharge is primarily via precipitation and runoff from the surrounding mountains. The Lockhart and Harper Lake faults may provide a barrier to groundwater flow at some locations.

3. GEOPHYSICAL APPROACH

The principal advantage of using geophysical methods is that good subsurface information can be obtained over large areas at low cost, usually without significantly disturbing the ground surface. The principal limitation of any geophysical method is that the results are an interpretation of an indirect measurement, not a direct physical observation of geological materials at depth. Geophysical surveys are useful in developing a subsurface model, but the model is much more reliable when the results can be confirmed by drilling at selected locations.

The MT method involves indirectly measuring the electrical and magnetic properties of the subsurface to infer the subsurface stratigraphy. Unfractured crystalline rocks, such as the granitic basement and shallower basalt flows expected at Harper Lake, tends to have high resistivity. Sedimentary material, on the other hand, is typically lower in resistivity, depending upon water saturation and grain size: saturated sediments are less resistive than unsaturated sediments, and clays are less resistive than sand and gravel. These types of comparisons can be useful to delineate areas of permeable formation in the subsurface.

MT is a geophysical method used to determine subsurface resistivity from measurements of Earth's natural electric and magnetic fields. In some applications these fields are augmented by electromagnetic fields generated by a transmitter placed some distance from the survey area. The ratios of these measured fields and their variation as a function of frequency can be related to the resistivity distribution in the subsurface. Tensor MT involves collecting electrical and magnetic data along perpendicular *x* and *y* directions. This allows the inference of information about two-dimensional structure and orientation which is not as easily retrievable via other electrical or electromagnetic methods. Nearby conductors, such as railroad lines, metal pipelines, and chain-link fences, and power sources, such as transmission lines or antennas, may cause noise or interference which adversely affect data quality.

The apparent resistivities which are measured by MT investigation are a weighted average of true formation resistivity over a range of depth and lateral position. In general, high frequencies correspond to shallow investigation and low frequencies correspond to deeper investigations. True formation resistivities are estimated by iterative computer modeling and inversion of multiple MT soundings.

Gravimetry involves measuring gravitational acceleration at points on Earth's surface and using the information to infer the density of subsurface materials. The acceleration due to Earth's gravitational field changes in time and space due to many known and predictable factors, such as elevation and tides. Measured gravity will also vary as a result of instrument drift. The gravitational changes of interest are due to lateral variations in the densities and depths of subsurface materials. Specifically, crystalline bedrock tends to have higher density, and therefore a stronger gravitational pull, than the sedimentary material presumed to overlie it. Where this higher-density material is near the surface, the result will be an increase in the measured gravity. By taking very careful measurements of gravitational acceleration at Earth's surface and then removing the predictable effects, we can reconstruct an image of subsurface density distribution, which is directly related to bedrock configuration and the distribution of basalt flows. Because the relative influences of shallower basalt and deeper bedrock can be indistinguishable, our interpretation of the gravity data is constrained by the MT survey, available well data, and geologic reasonableness.

The gravitational acceleration typically measured at Earth's surface is on the order of 980,000 milliGals (mGal), and variations in bedrock topography typically result in changes of 1 mGal or less. Gravimetry is therefore more concerned with relative changes in gravity than with the absolute value of the gravitational acceleration. Accounting for elevation is crucial for proper interpretation of gravity data. The gravitational field becomes much stronger with decreasing distance; i.e., lower elevations will exhibit a greater gravitational acceleration than higher elevations. This effect is so pronounced that a map of uncorrected gravity data might be indistinguishable in appearance from an elevation map. The so-called "free-air correction" transforms a gravity measurement into that which would have been made at a surface elevation of sea level (Dobrin and Savit, 1988). At 0.03086 mGal/m, the magnitude of the free-air correction is typically much greater than that of any other tidal correction, and precise measurement of elevation is important for proper calibration of the gravity measurements.

The free-air correction is so named because it assumes that the vertical span between the measurement point and sea level is filled with air. This assumption, while mathematically simple, is obviously incomplete; an additional correction is necessary to account for the materials which occupy the subsurface between sea level and the measurement point. Some judgement must be exercised in applying this Bouguer

correction because its magnitude depends upon the density of the materials beneath the measurement point; for example, unconsolidated sediments would imply a smaller Bouguer correction than would crystalline rock (Dobrin and Savit, 1988).

The Bouguer correction assumes that the space between sea level and the measurement point is occupied by a horizontally infinite slab of uniform density (i.e., Earth is flat). The terrain correction is an attempt to make this assumption more realistic by accounting for local topography. Hills reduce the observed gravity because they pull the meter's sensor upward, and valleys also reduce the observed gravity because they fail to pull the meter's sensor downward, so the terrain correction is always positive. Terrain very close to the meter has a large effect on the measured gravity; this effect decreases with the square of the distance to the meter. Topographic variations near the meter are therefore documented in the field. Corrections for more distant topography can be made with the help of a sufficiently precise digital elevation model.

The tidal correction is the factor applied to the gravity reading that compensates for the gravitational attraction of both the sun and moon. The tidal correction is a complex function with approximately twelve hours between peaks. The waveform is complex because the tides themselves are complex, with variations due to changes in Earth--Moon and Earth-Sun distance, inclination and precession of the lunar orbit, and seasonal changes in Earth's axial tilt with respect to the sun. The maximum tidal correction for these data is on the order of 0.2 mGal.

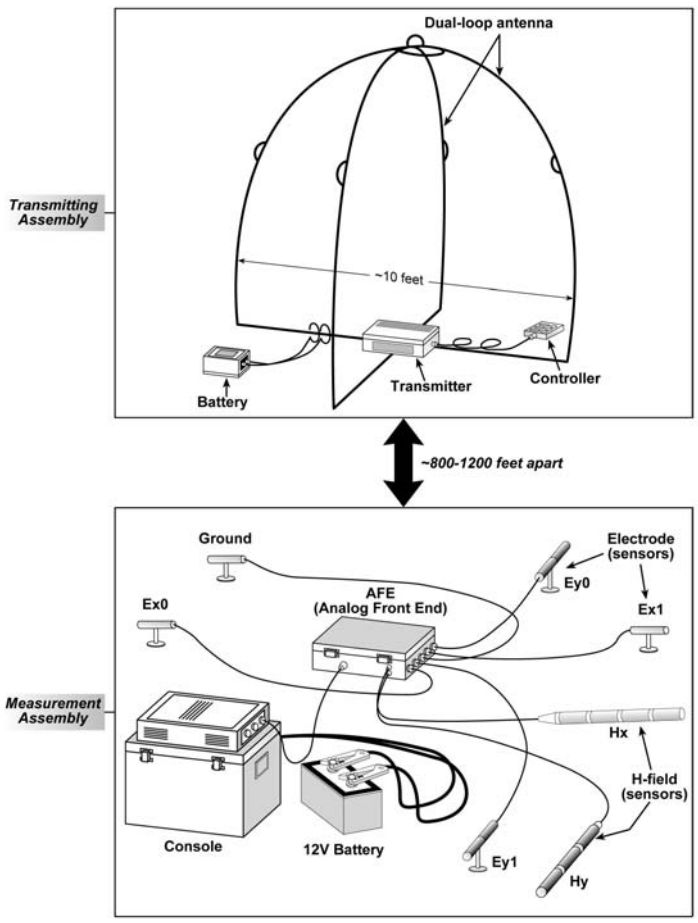
A drift correction is required because, over time, components within a gravity meter change their basic configuration slightly. The quartz spring which is at the heart of many relative gravimeters will slowly, and for the most part predictably, stretch, or relax, throughout the gravimeter's lifetime. Although these effects are very small, they should be removed whenever possible by re-measuring the gravity value at the same location at different times. Meter drift is assumed to occur in a linear or nearly linear manner over time, and it is usually recommended that repeat base-station readings be made at least twice daily.

4. DATA ACQUISITION

4.1 MT

LGS uses a Geometrics Stratagem EH4 tensor MT unit, which employs a transmitter for energy in the high-frequency band (approximately 750-92,000 Hz) where natural signals are weak. The Stratagem uses four metal electrodes inserted into the ground at the endpoints of two perpendicular lines as the *x* and *y* electric dipoles and two cylindrical magnetic dipoles, carefully leveled and precisely oriented along the same directions, as the *x* and *y* magnetic dipoles.

Typical CSAMT/MT Equipment Setup



The survey utilized electric dipoles up to 50 m in length in order to register a strong signal. In areas near power lines or other obvious interference, a smaller dipole (typically 25 m) was used to reduce the amount of noise recorded from these sources.

Dipole orientation was typically north-south and east-west, but in the presence of significant interference from power-line noise parallel to one of the dipoles we rotated the apparatus by 45° to minimize this noise source. Nominal station spacing was 200 m along the survey lines indicated in Figure 1. Actual survey locations were adjusted in the field based on access, topography, and obvious sources of interference.

4.2 GRAVIMETRY

LGS uses a Scintrex Ltd. CG-5 gravity meter. This system uses a thermally isolated quartz spring to measure relative gravity to within 0.001 mGal over a range of 8000 mGal. Because the spring must be aligned with the gravitational field to accurately measure it, the instrument is manually leveled in the field; a built-in tilt correction can accommodate up to 200 arc-seconds of error in this process. The spring is maintained at a constant temperature of 50 °C to avoid errors due to thermal expansion or contraction. The system reads at 6 Hz, and readings were taken continuously for 60 seconds for an average over 360 independent measurements. We took five such readings at each measurement station to ensure statistically repeatable data and discarded the highest and lowest after review of all data. Inconsistent and unreliable data might be acquired due, for example, to soft ground, traffic, or inadvertent impacts to the meter. During the data review, these suspect stations could be flagged and the data reacquired as necessary.

Standard field procedures were to begin each day of field work with a base-station gravity reading. After this initial measurement, the operator would navigate to the preselected stations using a hand-held GPS. During or after MT data acquisition, the operator would level the instrument to within the manufacturer's specifications, then take the five readings and record estimates of local topography (within 15 meters of the station) on field logs for later near-field terrain correction. A technician would then make precise measurements of latitude, longitude, and elevation using a survey-quality GPS (typical accuracy of 10 cm for position and 20 cm for elevation). An additional base-station reading was made at approximately noon, and a final base-station reading was taken at the end of each day of field work.

5. DATA PROCESSING

5.1 MT

Field data were downloaded for processing by Geosystem's WinGLink system. The software mathematically rotated the data to a principal axis upon input, meaning that the orthogonal *x* and *y* data were rotated to approximate data collected along dip and strike. The two measurements are expressed as apparent resistivity and phase. We edited the data to remove obviously noisy measurements which would otherwise corrupt the remaining data and fit each component with a smooth, geologically realistic curve based on the best mutual fit for apparent resistivity and phase in a laterally invariant earth.

As a first step in verifying the legitimacy of the data, we performed a one-dimensional inversion of each MT sounding assuming a laterally invariant earth. In many cases this process revealed additional editing needed to make the inversion stable. We then employed a constrained two-dimensional inversion using a finite-element model on a grid with roughly uniform cell size in the horizontal dimension and approximately logarithmically increasing cell size with depth. Within each cell, the resistivity is constant; therefore the chosen mesh size is related to the size of features which can be resolved. A finer grid results in a model that fits the data more closely and therefore reveals more detail, but at the expense of increased CPU time and, if the grid is too fine, incorporation of noise into the model. A coarser grid is quicker to model but will not fit the data as closely and may sacrifice detail. We used a very fine (on the order of a few meters) grid in the near surface increasing to several tens of meters with depth.

A uniform earth resistivity was used as a starting model on this grid. Apparent-resistivity data were computed for this model and compared to the actual apparent-resistivity data, and a damped least-squares method was used to calculate updates to the model. The updated model was then used to produce a new set of predicted data. This process was repeated up to 50 times. The inversion procedure was stable (e.g., not fitting noise) and the results converged to a reasonable solution.

5.2 GRAVIMETRY

Field data were downloaded for processing by Geosystem's WinGLink software. Positioning information was reformatted and entered first into the WinGLink database to establish each station location. Gravity data were broken down into manageable units

of one field day (typically two loops tied by three base-station measurements). We reviewed the data for consistency; the highest and lowest values at each station were discarded and the remaining three readings were averaged. Tidal corrections and adjustments for known instrument drift are made automatically by the CG-5 meter. Repeat base-station measurements were used to correct the data for residual instrument drift (a procedure known as “tying the loop” in gravity exploration).

Once the GPS and gravity data were merged, we made topographic corrections. Because it was not practical to locate and incorporate a calibrated base station, the data could not be assigned a calibrated value; however, previous regional gravity surveys were calibrated, and we used an interpolated value at the base-station location from these earlier surveys to constrain the present dataset. We applied a free-air correction to the data based on the measured elevations. Bouguer and terrain corrections were based on field estimates of topography in the near field and a 10-m digital elevation model for the far field; we assumed a density of 2.67 g/cm^3 for the near surface for consistency with the earlier surveys.

6. INTERPRETATION

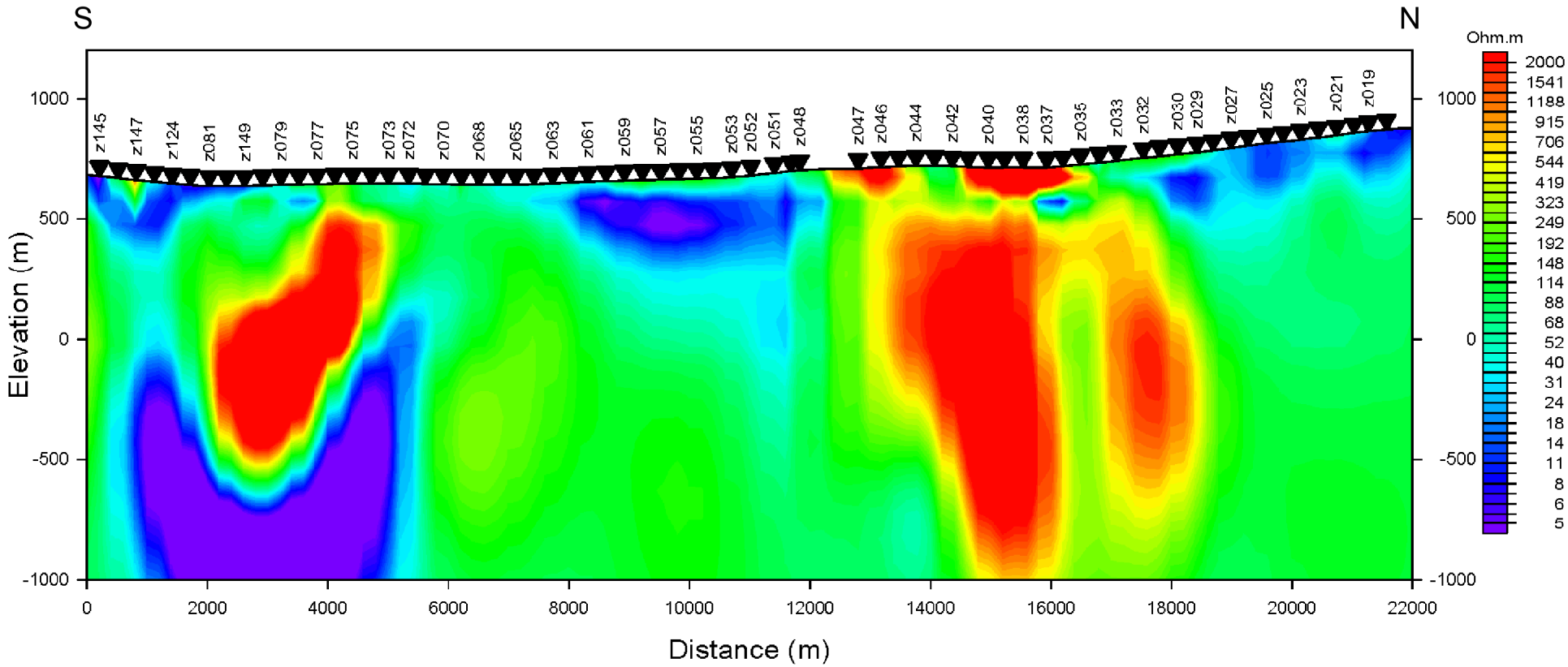
6.1 MT

The relationship between calculated resistivity and lithology is complex. Water saturation, water quality, and variations in lithology and mineralogy all affect the resistivity at any point in the subsurface, and various sources of background noise or limitations in electrode coupling to the ground may mask these values. In addition, the MT technique cannot measure point resistivity; rather, the measured resistivity is a weighted average over a larger volume of earth determined by the electrode configuration and distribution of earth resistivity. We can, however, infer relative changes in lithology or hydrogeology from measured resistivity. In this geologic environment, we expect generally high resistivity in the bedrock and in any basalt present, lower resistivity in the overlying sediments, and the lowest resistivities in clays and sediments saturated with conductive (poor-quality) water. When we incorporate the gravity data as well, it will be possible to further constrain the geophysical interpretation.

Profile 0 (Figure 2) contains two prominent resistive features at distances of approximately 4000 and 1500 m. These are likely due to bedrock highs. Although the plot extends down to an elevation of -1000 m, it is unlikely that useful information corresponding to depths significantly below sea level has been recovered from these data. Given their morphology, both the very resistive units near the surface at 12000-17000 m and the low resistivities at both 8000-12000 m and the southern end may indicate basalt; in the latter case weathered to a conductive clay.

Profile 1 (Figure 3) displays what appears to be a pronounced bedrock high which abruptly drops off at either end. It should be noted that the 2D algorithm used will by definition not account for any crossline structure. Since this profile departs from the straight line assumed by the algorithm, one should view abrupt changes along the line with suspicion; in fact, the southern (western) edge of the bedrock feature corresponds to a noticeable bend in the survey line. Shallower tabular resistive features atop the bedrock high and on the northern end of the profile may indicate basalt.

Profile 2 (Figure 4) also displays the apparent bedrock ridge and overlying basalt seen in profile 2. The bedrock appears to drop abruptly on the northern edge of the high; the basalt extends further north but likewise is not visible across the entire basin.



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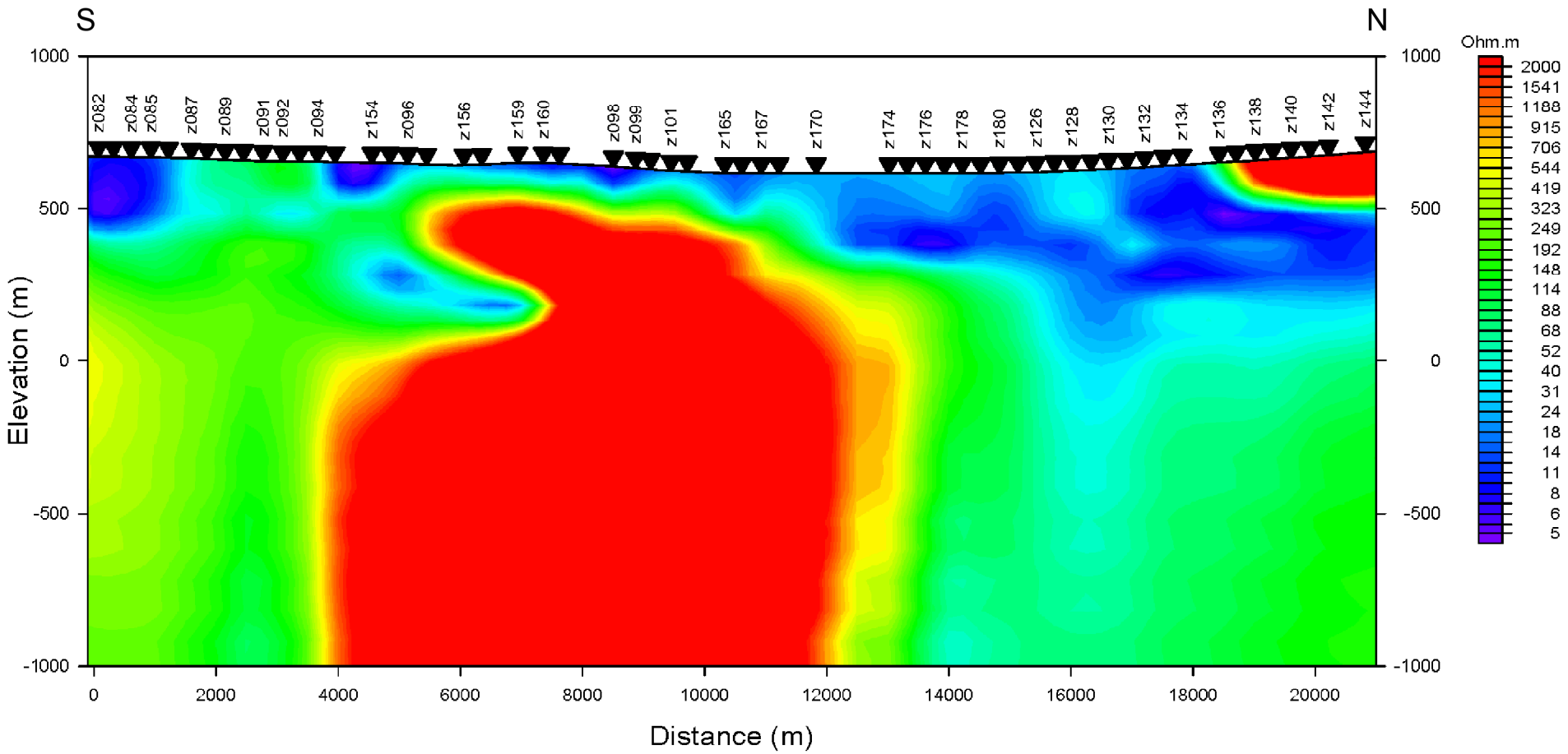
DATE: June 2009

FILE: HL_Geophysics_Report_Fig2_MT_Profile_Line0.mxd

PROJECT: Mojave Solar Project Geophysics

TITLE: Figure 2: MT Profile - Line 0



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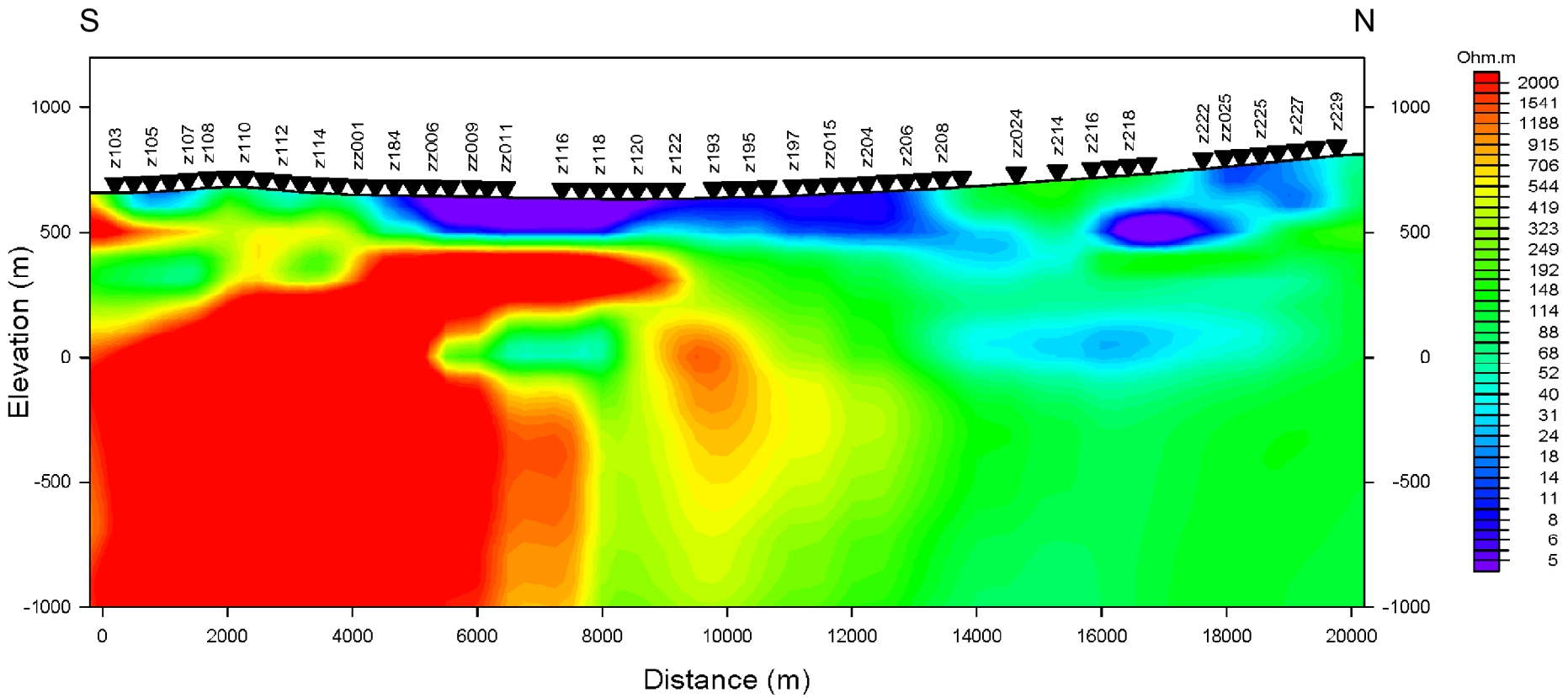
TITLE: Figure 3: MT Profile - Line 1



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FILE: HL_Geophysics_Report_Fig4_MT_Profile_Line2.mxd
PROJECT: Mojave Solar Project Geophysics

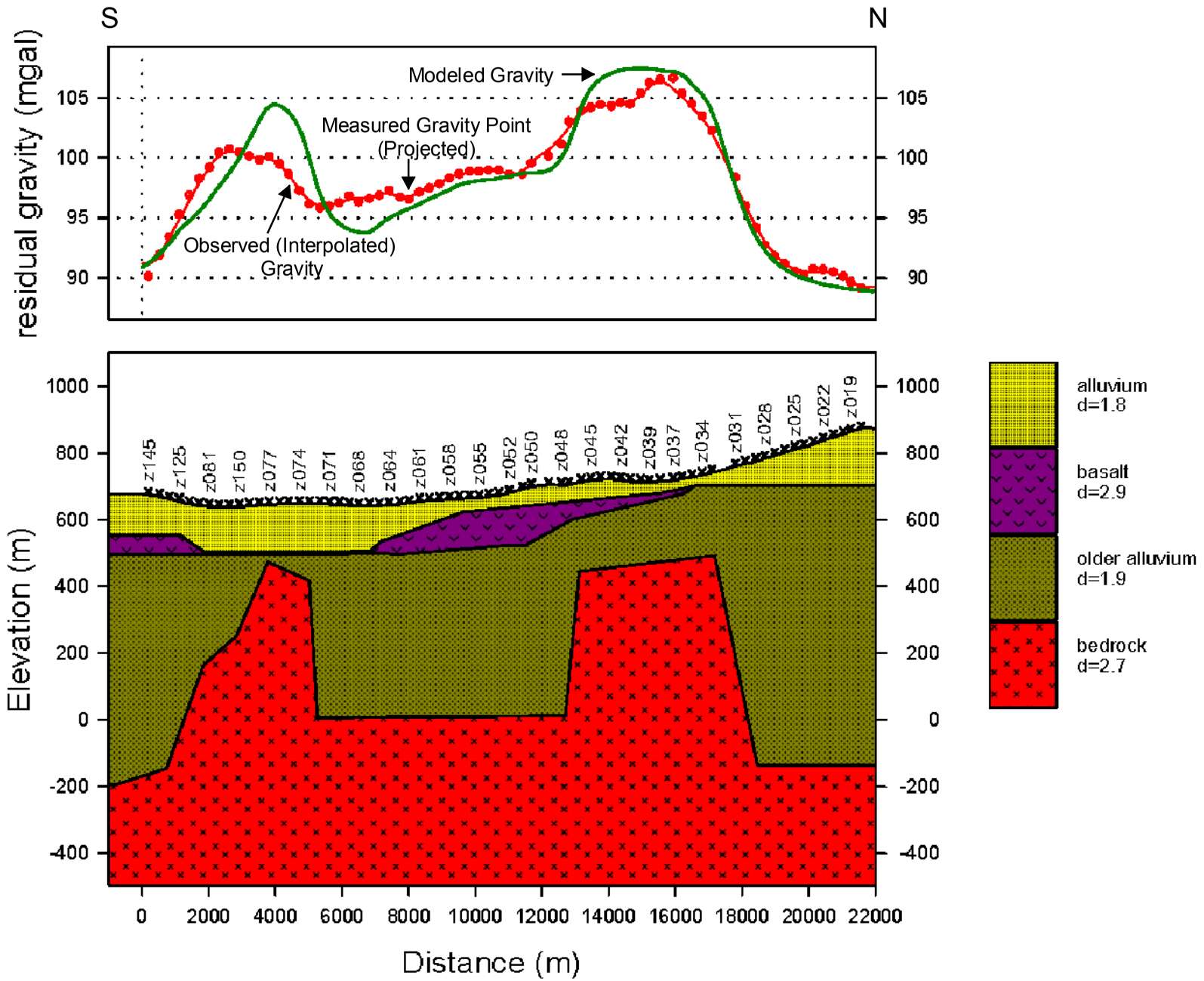
TITLE: Figure 4: MT Profile - Line 2

6.2 GRAVIMETRY

The gravity anomaly at any point is due to the distribution of bedrock and/or basalt, not just the depth to bedrock at that point. Estimating depth to bedrock, especially given the presence of an intermittent basalt layer, is therefore not as straightforward as it might first appear. Fortunately, limited well data are available and can be used to constrain the basin model. Although few boreholes penetrate basalt and extend to bedrock, enough information was available to indicate that the basin could be described by a four-layer subsurface comprising surficial alluvium (1.8 g/cm^3), basalt (2.9 g/cm^3), sub-basalt alluvium (1.9 g/cm^3), and bedrock (2.7 g/cm^3). These values are within the range of accepted values (Dobrin and Savit, 1988), and changing them by reasonable amounts would not appreciably affect our results. We produced two-dimensional forward models, constrained by available borehole data and the most reliable MT data, along each of the three profiles, calculated the expected gravity anomaly due to the models, and adjusted those models until a reasonable fit was obtained between the calculated gravity anomalies and those interpolated from the measured data points. The geological models shown here do not represent the best fit that can be made to the gravity data, but rather a reasonable fit to the gravity data that also honors the borehole and MT data.

Profile 0 (Figure 5) is not well constrained by borehole data; only a few wells are present 2 km or more from the southern portion of the line. They indicate that the bedrock is typically deep (300 m or more) at those locations, and that the basalt is typically but perhaps not always present. The two bedrock highs indicated by the gravity data, however, are consistent with those interpreted from the inverse-modeled MT data, and the basalt / clay can also be accommodated in the gravity model.

Gravity data from Profile 1 (Figure 6) contain little evidence of the bedrock high imaged in the inverted MT data. If we assume that the bedrock high is a ridge trending northwest-southeast (a reasonable assumption since it also appears in Profile 2 to the southeast), then this is precisely what we should expect: the measured gravity along the east-west portion of the profile will be influenced by the bedrock high immediately to the north, and the 2-D modeling algorithm will not account for this. Based on the inverted MT data, the basalt is competent above the bedrock high and at the far north end of the profile; elsewhere it is weathered or absent.



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DATE: June 2009
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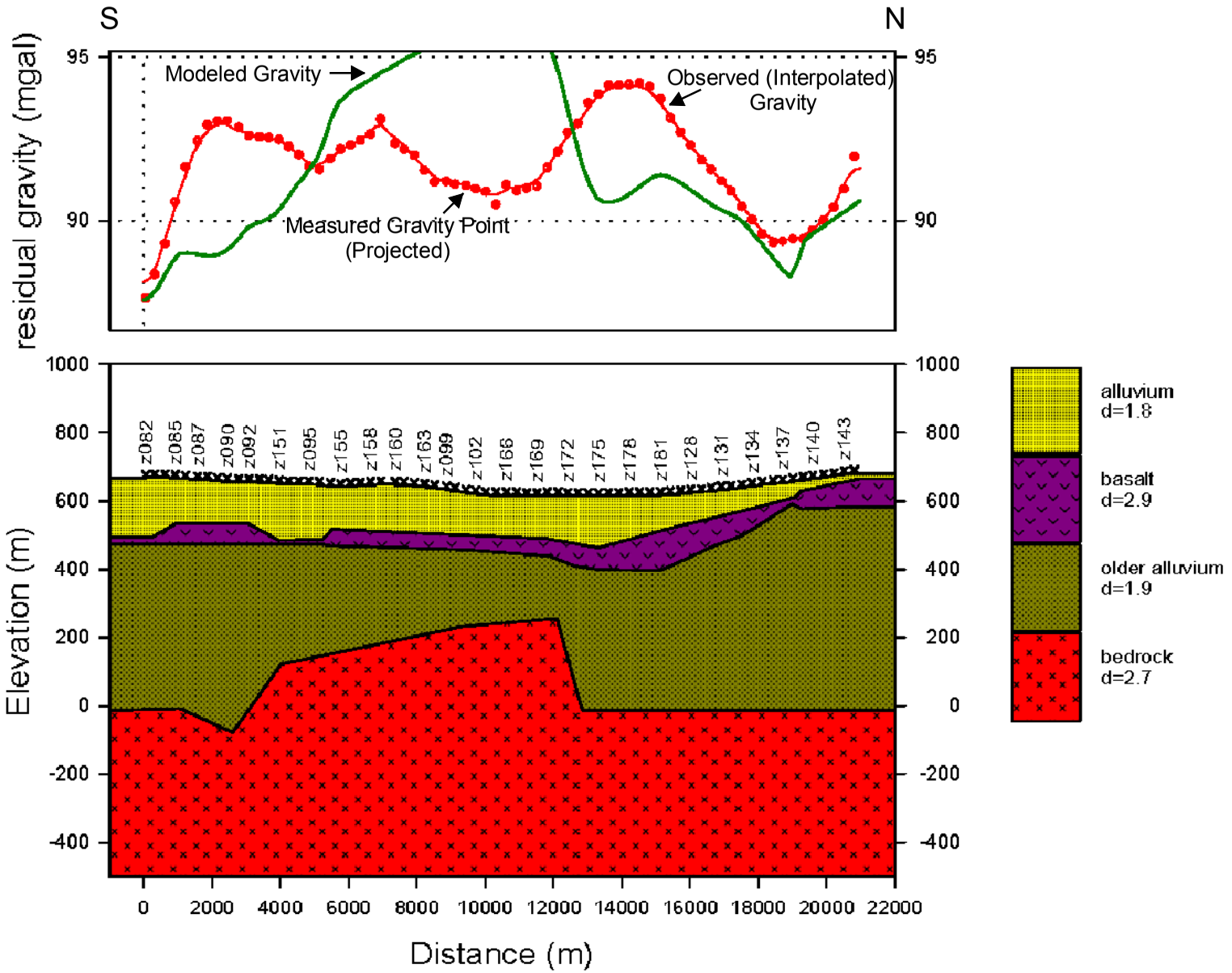
PROJECT: Mojave Solar Project Geophysics

TITLE: Figure 5: Line 0 Cross Section



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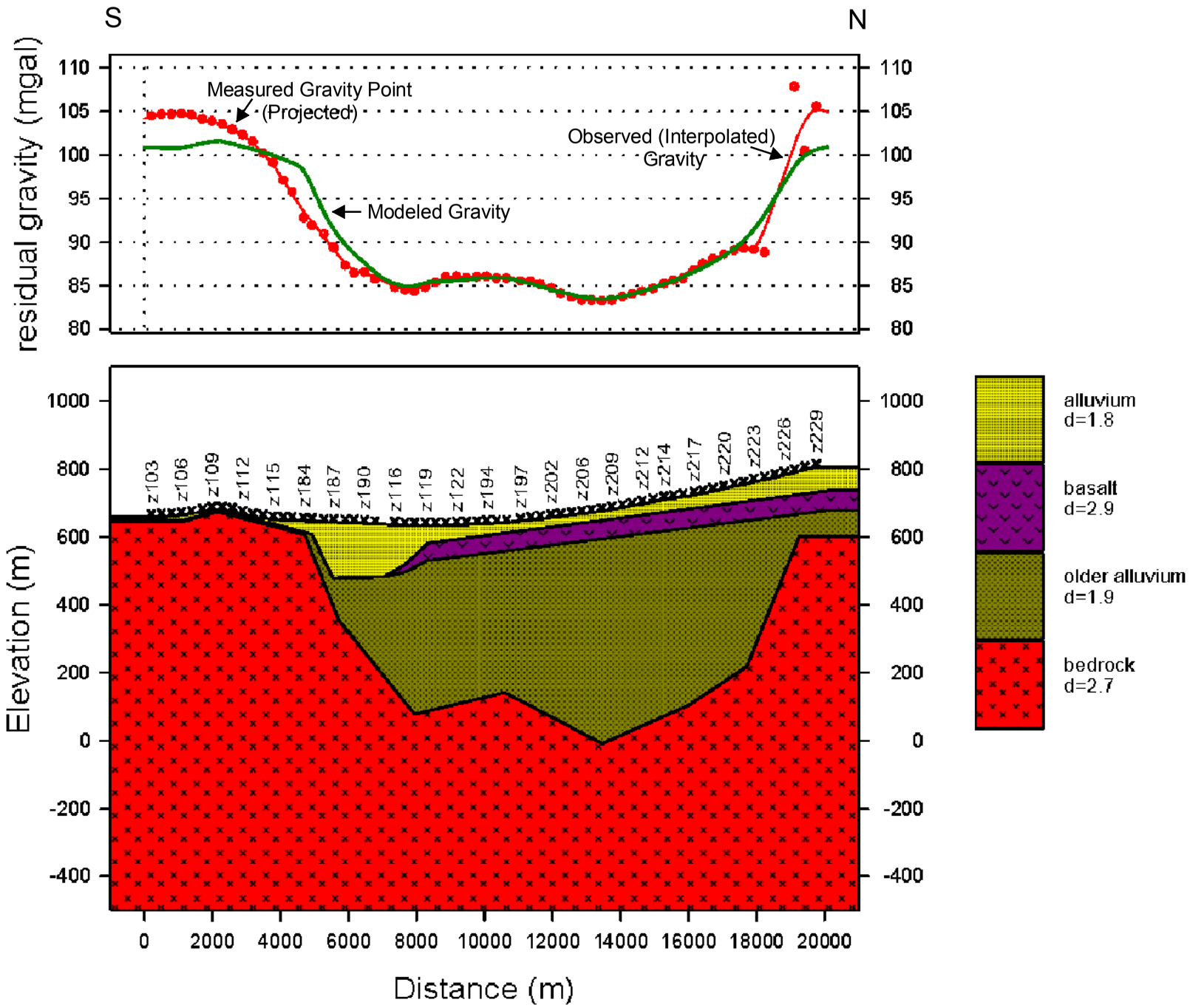
JOB NO.: 271643
DATE: June 2009
FILE: HL_Geophysics_Report_Fig6_Line1_X_Section_Gravity.mxd
PROJECT: Mojave Solar Project Geophysics

TITLE: Figure 6: Line 1 Cross Section

Profile 2 (Figure 7) is fairly well constrained by borehole in its southern portion; six wells are within 2 km of the line. They indicate shallow bedrock and no basalt in the far southern portion of the section typically deep (300 m or more) at those locations, and an abrupt increase in depth to bedrock corresponding closely to the edge of the basalt. The abruptness of both of these features suggests that they may be fault-controlled. This interpretation is severely constrained by the borehole and MT information, but the agreement with the gravity data is very good.



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JOB NO.: 271643
DATE: June 2009
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PROJECT: Mojave Solar Project Geophysics

TITLE: Figure 7: Line 2 Cross Section

7. CONCLUSIONS AND RECOMMENDATIONS

LGS provides the following conclusions and recommendations based on the geophysical data gathered and analyzed for this project.

LGS performed the gravity and MT surveys to delineate variations in density and electrical resistivity which may be indicative of structural changes in the bedrock underlying the Harper Lake basin. Actual locations of survey stations were limited to existing roads due to biological concerns, which impacted the reliability of the resulting data, but the primary objectives of the project were achieved. The bedrock and intra-alluvial basalt were imaged along the survey lines; this information will be incorporated into the numerical groundwater model which will be used to ascertain the impacts of pumping on the hydrogeology of the basin.

Based upon the geophysical investigations, we conclude the following.

- The deepest part of the basin is north of the present Harper Lake playa. The location of Harper Lake does not appear to be controlled by deeper bedrock structure.
- Southeast of Harper Lake, Profile 2 indicates an abrupt vertical displacement of the top of the bedrock and termination of the basalt, suggesting the presence of a fault. Bedrock south of the purported fault is near the ground surface.
- Because the field crews were required to stay on existing roads due to biological concerns, Profile 1 included a significant east-west portion, perpendicular to the remainder of the profile. The data in this area are difficult to model correctly, most likely due to the inconsistent effects of out-of-plane structures relative to the rest of the line. A bedrock ridge oriented subparallel to this portion of the profile and likely related to the vertical displacement of bedrock discussed for Profile 2 is our best interpretation of these data.

Recommendations for improving upon the foundation provided by this study include the acquisition of additional data in the vicinity of the hypothesized bedrock ridge to further define its extent. An extensive southwest-northeast profile, as originally proposed, would aid greatly in illuminating the effect of offline structures on our recovered model of subsurface geology. Ground control in the form of reliable borehole information is primarily limited to the south and east; additional deep boreholes in the north and/or west would allow us to clarify our picture of bedrock and basalt in these areas.

8. LIMITATIONS

This investigation was performed using the degree of care and skill ordinarily exercised, under similar circumstances, by experienced geophysicists and hydrogeologists practicing in this or similar locations. No warranty, expressed or implied, is made as to the conclusions and professional advice included within this report.

The findings of this report are valid as of the present date. However, changes in the conditions of a property can and do occur with the passage of time, whether they be due to natural processes or the work of people on this or adjacent properties. Accordingly, the findings of this report may be invalidated wholly or partially by changes outside of our control. Therefore, this report is subject to review and revision as changed conditions are identified.

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