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ELECTRICAL RESISTIVITY STUDIES OF FORTYMILE WASH, NYE COUNTY, NEVADA

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ABSTRACT

This report provides a summary of recent D.C. electrical resistivity, induced polarization and electromagnetic studies performed in southern Fortymile Wash and northern Amargosa Valley, Nevada, in 1998 to 1999 by the Center for Nuclear Waste Regulatory Analyses staff. These studies were conducted to support a better understanding of the geology and hydrogeology of these regions. In particular, the results from these studies will support an improved understanding of the hydrostratigraphy of the regions. The report shows that when good constraints are available through either multiple data sets or good geologic data, the simultaneous inversion of induced polarization D.C. electrical resistivity and transient electromagnetic resistivity data provides a reasonable approach for imaging the broad structure of the water table. Unfortunately, for the level of accuracy required for hydrogeologic models in the Yucca Mountain region and given the shallow groundwater gradients that exist, it is unlikely this approach will yield adequate data to support detailed hydrogeologic assessments that include groundwater modeling. As shown in the report, however, the approach may be suitable for constraining the hydrostratigraphy of the wash.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

QUALITY OF DATA: Several sets of data have been developed for this project. Data associated with the 1999 geophysics field survey are contained in scientific notebook 317E. Additional support data are contained on the computer Medusa (Room 212A) in directory d:\emproj\1999-survey-data. Field and processed data for the 1998 field survey described in this report and Sandberg (1998a) are contained in d:\emproj\1998-survey-data. Nye County Early Warning Drilling Program well data used in the report were obtained from http: www.nyecounty.com/ewdpmain.htm. The source of the Nye County Early Warning Drilling Program data should be consulted to determine the level of quality of the data. Data used to support this project are also stored at the CNWRA on a CD associated with this report in the CNWRA quality assurance (QA) system.

ANALYSES AND CODES: The suite of codes (ZONGE, READZONG, T47INPUT, READ, SLUMBER, RAMPRES3, AND EINVRT6) described in Sandberg (1998b) was used to process the field geophysical data collected. This suite of codes is controlled following the procedures described in the CNWRA Technical Operating Procedure (TOP)–TOP–18, which implements the QA guidance contained in the CNWRA QA manual. One-time use only scripts used to reorganize the Nye County Early Warning Drilling Program well data are stored at CNWRA on the computer Medusa (Room 212A) in directories d:\emproj\1999-survey-data-ncewdp-10S, d:\emproj\1999-survey-data-ncewdp-2DB, d:\emproj\1999-survey-data-ncewdp-23p, and d:\emproj\1999-survey-data-ncewdp-4p. These data are also stored on a CD associated with this report in the CNWRA QA system.

References

Sandberg, S.K. "Draft Report on Modeling TEM Data from Nevada." Albuquerque, New Mexico: Geophysical Solutions. 1998a.

———. "Inverse Modeling Software for Resistivity, Induced Polarization (IP), and Transient Electromagnetic (TEM, TDEM) Soundings: Manual for Computer Programs, ZONGE, READZONG, T47INPUT, READ, SLUMBER, RAMPRES3, EINVRT6 (MS-DOS Version 6.0)." Albuquerque, New Mexico: Geophysical Solutions. 1998b.

1 INTRODUCTION

Yucca Mountain, Nye County, Nevada, is being characterized by the U.S. Department of Energy (DOE) as a potential location for an underground high-level waste repository. The proposed repository site is adjacent to the Nevada Test Site and approximately 105 km [65 mi] northwest of Las Vegas, Nevada. The repository design currently being proposed by DOE requires the high-level waste to be placed in engineered containers prior to emplacement in engineered drifts excavated approximately 300 m [984 ft] below ground surface in low-permeability, unsaturated tuff formations.

DOE is expected to submit a license application to construct the repository facility to the U.S. Nuclear Regulatory Commission (NRC) in the near future. An important consideration in the licensing decision is whether the repository and surrounding environment will provide a regulated level of protection to the accessible environment from the stored waste during a regulated timeframe of 10,000 years. Should the engineered barriers at the repository fail, one likely scenario is that radionuclides will be transported through the unsaturated zone by percolating groundwater and subsequently transported through the saturated zone before entering the biosphere through groundwater extraction or discharge.

Current groundwater flow and mass transport models proposed for the site (Winterle, et al. 2002; Winterle, 2003; CRWMS M&O, 2000) indicate that, should radionuclides enter the saturated zone below the proposed repository location, transport would be initially toward the southeast prior to taking a more southerly route through southern Fortymile Wash and northern Amargosa Valley (Figure 1-1) prior to extraction at a pumping well at the location of the reasonably maximally exposed individual approximately 18 km [11.2 mi] away (see 10 CFR Parts 63.1, 63.302, 63.311, and 63.312). In southern Fortymile Wash, it is currently postulated that radionuclies will flow from a fractured tuff aquifer system to a valley-fill aquifer system. The transition from fractured tuff to valley-fill is significant for repository performance because of contrasting hydrologic and geochemical properties of the two media. It is currently estimated that groundwater velocities through the valley-fill system will be significantly lower than those in the fractured tuff system (Winterle, et al., 2002). Hence, depending on the ratio of the radionuclide travel path in the fractured tuff to that in the valley-fill, significant residence times within the valley-fill are possible. Longer radionuclide residence times in the valley-fill coupled with the greater number of radionuclide sorptive sites of this medium compared to the fractured tuff could delay and reduce radionuclide concentrations at the location of the reasonably maximally exposed individual (10 CFR Parts 63.1, 63.302, 63.311, and 63.312) thereby enhancing repository safety performance.

Although the potential importance of southern Fortymile Wash and northern Amargosa Valley to repository safety performance is recognized, the geologic and hydrogeologic structure of the region is not well constrained. Prior to the start of the Nye County Early Warning Drilling Program in 1999, insufficient data were available to constrain the geologic structure and hydrogeology of the Fortymile Wash region. Because of the limited hydrogeologic and geologic data available for the wash, there is considerable uncertainty in (i) the location of the tuff and valley-fill interface, (ii) hydraulic gradients to the south of the repository, and (iii) general geologic structure of the region. These uncertainties need to be better constrained to better assess repository safety performance.

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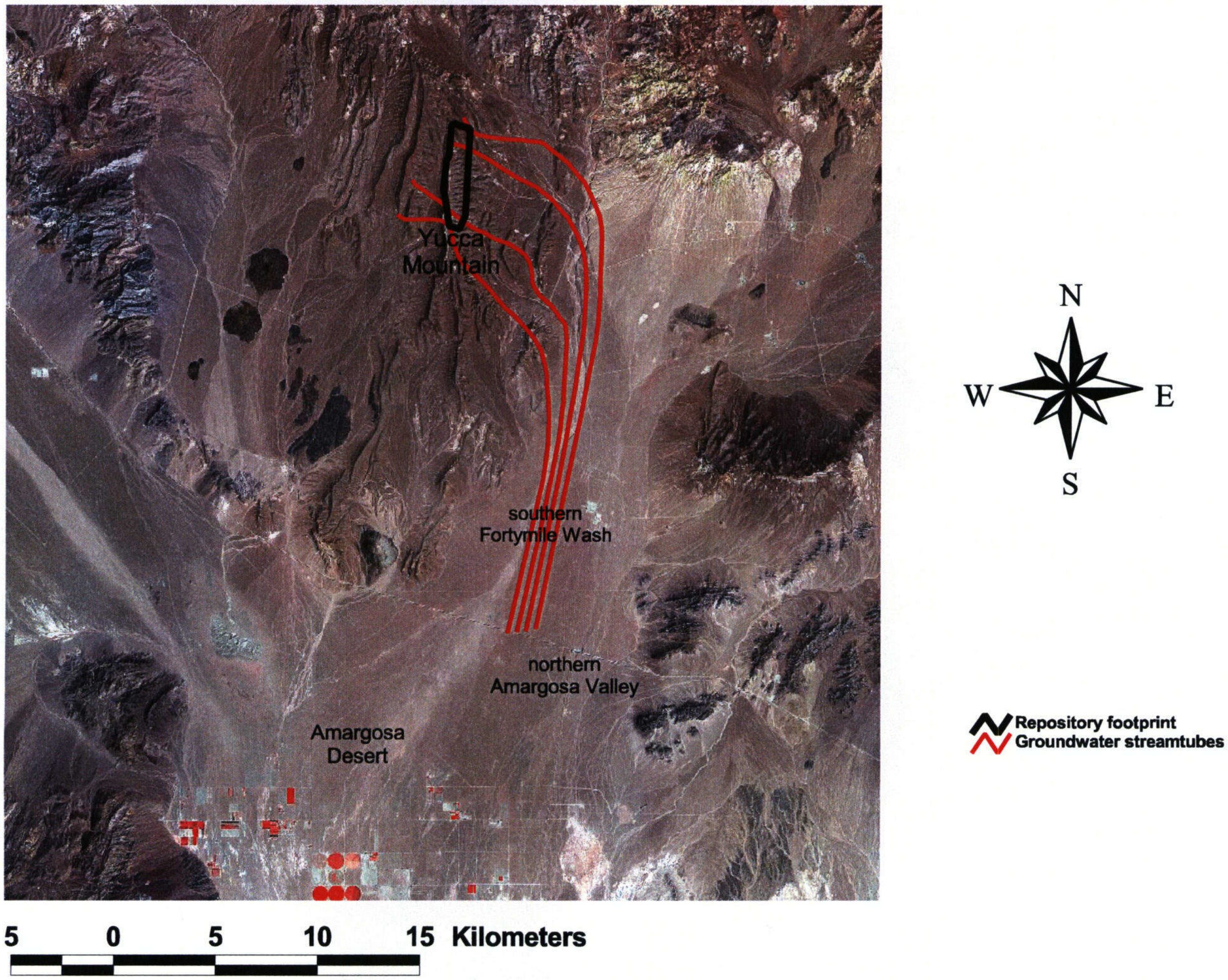

Figure 1-1. Satellite Image of Southern Fortymile Wash and Northern Amargosa Valley. Also Shown Are the Locations of Nye County Early Warning Drilling Program Wells and Groundwater Flow Tubes Used in Total-system Performance Assessment, Version 4.0 Code (Mohanty, et al., 2000).
NOTE: Scale information provided in kilometers; for conversion use 1 km = 0.621 m.

Attempts to constrain the geology of southern Fortymile Wash and neighboring northern Amargosa Valley using noninvasive geophysical surveys have been conducted for the past 30 years. Only a few of these studies, however, have been designed to address the hydrogeologic features of southern Fortymile Wash and northern Amargosa Valley. Beginning in 1998, and prior to the Nye County Early Warning Drilling Program, NRC funded several geophysical surveys to verify and better constrain the structural geology and hydrogeologic structure of the southern Fortymile Wash and northern Amargosa Valley in an effort to independently evaluate repository performance. This report summarizes these studies and the results. Where appropriate, the report also discusses research findings from other groups. Results from the Nye County Early Warning Drilling Program are used to provide constraints on models inferred from geophysical data.

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Chapter 2 of this report summarizes the geological setting of southern Fortymile Wash and neighboring northern Amargosa Valley. Chapter 3 summarizes electrical and electromagnetic resistivity studies performed across the Fortymile Wash. Chapter 4 summarizes the results of this work and suggests possible paths forward.

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2 OVERVIEW OF THE GEOLOGY AND HYDROGEOLOGY OF SOUTHERN FORTYMILE WASH AND NORTHERN AMARGOSA VALLEY

Southern Fortymile Wash and northern Amargosa Valley are located east and south of the proposed high-level waste repository at Yucca Mountain (Figure 1-1). As discussed in the previous chapter, one likely scenario, should the engineered containment system at the proposed repository fail, is for radionuclides to be transported through the saturated zone to discharge points or extraction locations to the south. This predominantly southerly migration path crosses southern Fortymile Wash and northern Amargosa Valley. In southern Fortymile Wash, it is currently assumed that radionuclides will flow from a tuff hydrostratigraphy into valley-fill hydrostratigraphy. As discussed in Chapter 1, this transition is expected to result in a significant decrease in radionuclide transport velocities and increased sorption. Both these factors can result in reduced and delay concentrations at the location of the reasonably maximally exposed individual 18 km [11.2 mi] away in the valley-fill deposits south of the proposed repository. Therefore, an understanding of the geologic structure and hydrostratigraphy of this region is important. This chapter summarizes the current understanding of the structural geology and hydrostratigraphy of this region.

2.1 Geologic Setting of Fortymile Wash and Northern Amargosa Valley

Fortymile Wash is an important discharge and transitional geomorphic feature between Fortymile Canyon to the north and northern Amargosa Valley to the south. Young, et al. (1992) describe the general concave to the west curvilinear trend of the wash as concordant with the curved fault fabric characteristic of Yucca Mountain. They assert it is reasonable to suggest the underlying geologic structures, genetically related to the fault system through Yucca Mountain, exert significant control on the trend and position of the wash. The lack of discernible fault scarps within southern Fortymile Wash is attributed to the fact that the wash is active and flood events are likely to have masked or destroyed traces of Quaternary fault displacement (Young, et al., 1992).

Interpretation of a block-bounding, west-dipping, normal fault beneath Fortymile Wash by Young, et al. (1992) is based primarily on

- The presence of the top of the Topopah Spring Member of the Paintbrush Tuff (Tptw) in borehole Well J–13 (in Fortymile Wash) at an elevation of 800 m [2,625 ft] and the projected top of the Tptw at elevations between 1,190 and 1,780 m [3,904 and 5,840 ft] in the Calico Hills and Little Skull Mountain to the east of Fortymile Wash.

- The western end of the AV–1 seismic reflection and gravity line (Brocher, et al., 1990), which shows clear evidence of a west-dipping fault system that marks the eastern edge of a sediment-filled trough.

In addition, a north-south trending, west-dipping normal fault system beneath southern Fortymile Wash is consistent with the regional pattern of faulting and with faults in the Calico Hills that border Fortymile Wash to the north (Frizzell and Shulters, 1990).

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Data acquired from the Nye County Early Warning Drilling Program and other available geological and geophysical data for the region were used to construct three geological cross sections: Nye–1, Nye–2, and Nye–3 (Spengler and Chornack, 2002). Nye–1 and Nye–3 (Spengler and Chornack, 2002) are east-west trending cross sections that span southern Fortymile Wash. Nye–2 (Spengler and Chornack, 2002) is a north-south trending cross section coincident with the trace of the flow channel in the wash. All three sections were designed to be coincident with selected Nye County Early Warning Drilling Program wells.

The Nye–1 and Nye–3 (Spengler and Chornack, 2002) cross sections depict southern Fortymile Wash as part of a half-graben defined at its eastern margin by the west-dipping Gravity fault system. Most of these faults along the cross sections have no surface expression and were identified using interpretation of geophysical data. The southern portion of Fortymile Wash, as illustrated by Nye–1 (Spengler and Chornack, 2002), appears to be bounded to the west by the dip slopes of fault blocks east of the Windy Wash fault and to the east by the normal, west-dipping Gravity fault system. In the hanging wall of the Gravity fault is an east-dipping (antithetic to the Gravity fault) normal fault coincident with the trace of the primary drainage feature of the wash. Along Nye–1 (Spengler and Chornack, 2002), the valley-fill attains its maximum thickness of approximately 500 m [1,640 ft] at this fault.

Nye–3 (Spengler and Chornack, 2002) provides an interpretation of the geologic structure of the northern portion of Fortymile Wash. Along this cross section, the wash appears to be bounded to the west by a series of unnamed faults in the footwall of the Paintbrush Canyon fault (which is east of the Windy Wash fault) and to the east by the normal, west-dipping Gravity fault system. Between these fault systems and beneath southern Fortymile Wash, several faults contribute to the geometry of the wash. The most significant of these faults is an east-dipping (antithetic to the Gravity fault) normal fault that coincides with the greatest thickness {approximately 200 m [656 ft]} of the valley-fill. This significant fault is in close proximity to the main drainage channel in Fortymile Wash and is an along-strike continuation of the antithetic fault system interpreted along Nye–1 (Spengler and Chornack, 2002).

Nye–2 (Spengler and Chornack, 2002) is a north-south trending transect coincident with the primary drainage channel in southern Fortymile Wash. The southern portion of this transect is coincident with the groundwater flow pathway from the proposed repository location and includes the tuff valley-fill transition zone important to repository performance. The structural framework along Nye–2 (Spengler and Chornack, 2002) includes several faults that have no surface expression and are inferred from geophysical data interpretation. The near-surface geologic structure along the northern portion of the transect is constrained by several wells drilled prior to the Nye County Early Warning Drilling Program. The geologic structure is inferred in the area south of the last of these wells, JF–3, and north of Nye County Early Warning Drilling Program Well 19D. Within this zone is a normal west-dipping fault that appears as south-dipping on Nye–2 (Spengler and Chornack, 2002). The approximate location of this fault corresponds to a similar feature reported by Farrell, et al. (2000). This normal fault and a series of east-west trending, northward dipping normal faults located to the south (the Highway 95 fault system), essentially bound a local basin beneath the southern portion of Fortymile Wash and northern Amargosa Valley. Within this basin, valley-fill thicknesses increase from approximately 250 m [820 ft] in the north to approximately 500 m [1,640 ft] in the south.

2.2 Stratigraphy of Southern Fortymile Wash and Northern Amargosa Valley

A comprehensive understanding of the stratigraphy of southern Fortymile Wash and northern Amargosa Valley is not currently available, however, several recent studies of sedimentary sequences along the southern Fortymile Wash drainage system, coupled with existing boreholes and wells being completed as part of the Nye County Early Warning Drilling Program, are expected to lead to a better understanding of the stratigraphy and hydrostratigraphy of the southern Fortymile Wash and northern Amargosa Valley region.

Winterle and Farrell (2002) provided a summary of the hydrogeologic properties of the southern Fortymile Wash and northern Amargosa Valley that includes discussions of the stratigraphy and hydrostratigraphy of the region. In particular, Winterle and Farrell (2002, Table 2-1) provided summaries of the geologic information for wells that penetrated the valley-fill and underlying volcanic units. Winterle and Farrell (2002, Table 2-1), along with the comprehensive well-log descriptions provided by the Nye County Early Warning Drilling Program, demonstrated the complex spatial distribution of geologic units within southern Fortymile Wash and northern Amargosa Valley. In addition to the information provided by the Nye County Early Warning Drilling Program logs, Ressler, et al. (2000) and Ressler (2001) [see also Winterle and Farrell (2002)] provided detailed discussions of the valley-fill stratigraphy based on field studies in southern Fortymile Wash. These studies demonstrated the complex range of sedimentary facies present in the exposed portions of the wash that could affect groundwater flow at depth, as well as the spatial distribution of geophysical properties within the wash.

These sources and associated interpretations will be used to constrain the interpretation of the geophysical data discussed in subsequent chapters.

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3 ELECTRICAL AND ELECTROMAGNETIC GEOPHYSICAL RESISTIVITY SURVEYS IN SOUTHERN FORTYMILE WASH AND NORTHERN AMARGOSA VALLEY

Southern Fortymile Wash and northern Amargosa Valley are poorly characterized with regard to geology and hydrogeology. In recent years, data from the Nye County Early Warning Drilling Program have increased the level of characterization in this region. The low density of wells being installed for this program, however, even when combined with other existing wells, does not support a comprehensive characterization of the region.

Prior to initiation of the Nye County Early Warning Drilling Program, large spatial gaps existed in the hydrogeologic and geologic data sets for southern Fortymile Wash and northern Amargosa Valley and the Amargosa Desert. In some locations, separations as large as 10 km [6.2 mi] existed between adjacent water level measurements in areas viewed as critical to evaluating the safety performance of the proposed repository. To reduce the uncertainty in the hydrogeologic and geologic structures of the region and to verify current and future U.S. Department of Energy models for this region unsaturated and saturated flow under isothermal conditions (USFIC) agreement USFIC.5.04 and radionuclide transport (RT) agreements RT.3.03 and RT.2.08],[1,2] a suite of noninvasive field geophysical surveys was planned and executed during 1998–1999 by the U.S. Nuclear Regulatory Commission (NRC) and the Center for Nuclear Waste Regulatory Analyses (CNWRA) staff. These surveys coincided with initiation of the Nye County Early Warning Drilling Program.

Included in the suite of surveys were induced polarization, electromagnetic, and D.C. electrical resistivity studies designed to delineate the electrical resistivity structure of the region. This structure is expected to reflect the near-surface geology and hydrogeology and the transition from the unsaturated to the saturated zone.

This chapter summarizes the results from the suite of surveys and discusses the associated interpretations. In addition to presenting the NRC and CNWRA work, this chapter summarizes related electrical resistivity studies performed by other research teams in the study region.

3.1 Previous Electrical and Electromagnetic Resistivity Studies in Fortymile Wash and Northern Amargosa Valley

Farrell, et al. (1999) included a summary of several electrical resistivity studies conducted in the general Yucca Mountain region, including southern Fortymile Wash and northern Amargosa Valley. These studies included telluric surveys and Schlumberger D.C. electrical resistivity soundings. This section summarizes the important findings of these studies.

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[1]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Unsatured and Saturated Flow Under Isothermal Conditions (October 31–November 2, 2000)." Letter (November 17) to S.J. Brocoum, DOE. Washington, DC: NRC. 2000.

[2]Reamer, C.W. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Radionuclide Transport (December 5–7, 2000)." Letter (December 12) to S.J. Brocoum, DOE. Washington, DC: NRC. 2000.

3.1.1 Telluric Studies

Telluric methods map electrical potential differences in the subsurface that result from subsurface current flows induced by varying ionospheric current flows. Higher frequency current fluctuations caused by electrical storms may be superimposed on the natural long-wavelength telluric currents.

Telluric studies conducted in the Yucca Mountain region and, more specifically, southern Fortymile Wash and northern Amargosa Valley by Hoover, et al. (1982) consisted of four east-west trending lines: two lines that extend from the area of Yucca Mountain, across Fortymile Wash and into Jackass Flats, and two additional lines located in northern Amargosa Valley [see Hoover, et al. (1982)].

Line 1 of the survey (Hoover, et al., 1982) was located 0.6 km [0.4 mi] north of Well J–13 and approximately 3 km [1.8 mi] south of Line 2. Within southern Fortymile Wash, data collected along these two transects identified four north-south trending lineaments (two on either side of the wash) of low telluric voltages indicative of low earth electrical resistivity. Hoover, et al. (1982) described these lineaments as possible fault zones and asserted that the lower electrical resistivity along these features may result from increased porosity associated with fracturing. If this is indeed the case, the enhanced porosities along these faults may explain enhanced transmissivities observed in Fortymile Wash. Hoover, et al. (1982) further suggested that if the assertion that Fortymile Wash is fault controlled [Lipman and Mackay (1965)] is correct, and Well J–13 is assumed to lie within a graben, the inner lineations interpreted in the telluric profiles could define the Fortymile Wash graben. Farrell, at al. (1999) noted the westernmost of the four faults correlates reasonably well with the general location of Paintbrush fault.

The telluric transect (L-N), north of the town of Amargosa Valley (Lathrop Wells), identified several contrasting responses (Hoover, et al., 1982). West of point 6E on this line, low telluric voltages occur; whereas, immediately east of this location, higher voltages occur. This gradient was interpreted by Hoover, et al. (1982) to represent carbonate rocks to the east juxtaposed with alluvium (valley-fill), and possible volcanics, to the west. This contact appears to be coincident with the known location of the Gravity fault (Farrell, et al., 1999). Possible faulting between 1W and 3E along line L-N also may be inferred from the data (Farrell, et al., 1999).

Telluric transect L-S, located south of the town of Amargosa Valley, is almost coincident with the joint seismic and gravity line AV-1 (Brocher, et al., 1990). Along this line, the voltage gradient observed near point 12 appears to correlate to the general location of the Gravity fault.

3.1.2 Schlumberger D.C. Electrical Resistivity Depth Sounding Studies

From 1978 through 1980, the U.S. Geological Survey performed 136 Schlumberger D.C. electrical resistivity depth soundings across Amargosa Desert, Ash Meadows, southern Fortymile Wash, and northern Amargosa Valley. These soundings were performed as part of the initial site characterization for the proposed repository at Yucca Mountain. The objectives of the soundings were to define the basement structure and basin characteristics that may influence hydrological systems in the region (Greenhaus and Zablocki, 1982). Because of the anticipated deep basement, maximum current electrode spacings at each sounding location ranged from 1,219 to 2,438 m [4,000 to 8,000 ft]. Additional data collection strategies included

(i) using crossed pairs of soundings at several locations to identify anisotropy and
(ii) reoccupying some sounding locations with an extended array to support deeper penetration.

The depth to electrical basement modeled in this work may differ from the true geologic basement. As noted by Greenhaus and Zablocki (1982), depths to the electrical and geologic basements will generally be consistent if there is no alteration of the bedrock contact surface. However, if the uppermost part of the geologic basement has been extensively fractured, such that the secondary porosity produced may become either filled with clay-rich sediments or water, the reduced electrical resistivity in this zone may preclude it being modeled as part of the electrical basement. That is, the top of the electrical basement will be interpreted to be below this layer of high fracturing.

Greenhaus and Zablocki (1982) made the following observations based on their analyses of the electrical resistivity soundings. They observed that a significant electrical resistivity gradient existed east of Fortymile Wash and south of the town of Amargosa Valley (Lathrop Wells). They concluded this feature represented a north-south trending normal fault, with an 800 m [2,625 ft] down-throw to the west. The location of this fault is consistent with the location of the Gravity fault.

The second observation of Greenhaus and Zablocki (1982) relates to the sources of the observed electrical resistivity anomalies. On the basis of existing borehole logs, the authors assumed the valley-fill was composed of heterogeneous distributions of clay, sand, gravel, and boulders. Near-surface high resistivities on the order of 10–100 ohm-m were assumed to represent dry surficial sands and gravels. North of Highway 95, the thickness of the high electrical resistivity zone was observed to be on the order of 100 m [328 ft]. This thickness is in reasonable agreement with recent data obtained from Nye County Early Warning Drilling Project wells for southern Fortymile Wash. Beneath this zone, electrical resistivities on the order of 10 to 100 ohm-m were assumed to represent sands and clay-rich sediments, and electrical resistivities less than 10 ohm-m were assumed to represent saturated clays or saline groundwater.

The third observation of Greenhaus and Zablocki (1982) concerns the thick low electrical resistivity zone located on the down-thrown side of the Gravity fault. Electrical resistivities beneath the near-surface high electrical resistivity zone represent some of the lowest electrical resistivities in the surveyed area (estimated at approximately 10 ohm-m). Greenhaus and Zablocki (1982) concluded this zone may represent several hundred feet of either clay-rich sediments or saline groundwater above the electrical basement. The presence of a thick sequence of clay-rich sediment in this general area appears to have been confirmed by geologic logs from Nye County Early Warning Drilling Program Wells 5S and 5SB.

The findings of Greenhaus and Zablocki (1982) have been used in subsequent synthesis reports that attempt to describe the depth to basement in the Amargosa Desert and Fortymile Wash regions (e.g., Oatfield and Czarnecki, 1989). The work of Oatfield and Czarnecki (1989) is interesting because it attempts to infer hydrologic relations from geophysical and grain-size analysis data. The following summarizes the findings of Oatfield and Czarnecki (1989) with respect to electrical resistivity.

In their analysis, Oatfield and Czarnecki (1989) assumed the electrical resistivity of the valley-fill is controlled by three factors: (i) salinity of the groundwater, (ii) degree of saturation, and

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(iii) electrical conductivity of the mineral grains. It was also assumed the electrical resistivity of the electrical basement is significantly larger than that of the overlying sediment. This assumption is consistent with the findings of Greenhaus and Zablocki (1982).

As part of their analysis, Oatfield and Czarnecki (1989) also computed an average transverse electrical resistivity, R, for the valley-fill at each of the vertical electrical resistivity profiles produced by Greenhaus and Zablocki (1982) using the following formulation

$$R = \frac{\sum_{i=1}^{n} r_i t_i}{\sum_{i=1}^{n} t_i} \tag{3-1}$$

where

r_i and t_i	—	represents the electrical resistivity and thickness of layer i
n	—	represents the number of layers

It is important to note that a representative value of R for the alluvium (valley-fill) is only valid provided the profile extends across the entire thickness of the alluvium (valley-fill). If this is not the case, the thickness of layer n cannot be defined. Hence, this approach cannot be applied to the profiles computed in the CNWRA analyses described later in this chapter.

The estimate of R for southern Fortymile Wash, northern Amargosa Valley, and central Amargosa Desert represented some of the lowest values calculated. This result was described by Oatfield and Czarnecki (1989) as unexpected because it was counter to the trend in grain size measurements and sodium concentrations observed. As an additional analysis, Oatfield and Czarnecki (1989) computed R for the upper 75 m [246 ft] of valley-fill. The depth of 75 m [246 ft] was chosen to be consistent with the depth of water wells used for grain-size analyses (Oatfield and Czarnecki, 1989). Contours of the re-computed values of R using this approach were described as more consistent with the spatial distribution of sodium. Results from the re-computed values of R were interpreted as indicating fresher waters, hence, higher average transverse electrical resistivities, beneath southern Fortymile Wash, northern Amargosa Valley, and the central Amargosa Desert.

In reality, the average transverse electrical resistivity computed by Oatfield and Czarnecki (1989) is difficult to interpret in the manner proposed. As mentioned earlier, the parameter is influenced to varying degrees by saturation, mineral conductivity, and salinity. The relative importance of each of these factors is masked in the value of R. As a result, it is not surprising that some of the trends and correlations noted by Oatfield and Czarnecki (1989) are not readily apparent. For example, Oatfield and Czarnecki (1989) expressed surprise that some of the lowest R values were observed in southern Fortymile Wash, northern Amargosa Valley, and central Amargosa Desert. In their opinion, this observation is contrary to the observed grain-size distributions and sodium concentrations. This is not surprising, however, given the shallowest groundwater depths occur in these regions, and small values of t_i significantly increase R. An alternate approach that could yield improved correlations and minimize the

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impact of the unsaturated zone on the calculated value is to compute *R* for the region below the water table.

3.2 NRC and CNWRA Electrical and Electromagnetic Resistivity Studies in Fortymile Wash and Northern Amargosa Valley

During 1998 and1999, CNWRA and its contractors performed a suite of D.C. electrical and electromagnetic resistivity surveys in southern Fortymile Wash and northern Amargosa Valley to discern the electrical resistivity structure of the region. The earliest of these later surveys was planned prior to development and initiation of the Nye County Early Warning Drilling Program. The goal of this early survey was to evaluate the applicability of these techniques to support delineation of the major hydrogeologic and geologic features of the region in a noninvasive and cost effective manner. Following preliminary assessments from this initial survey (Sandberg, 1998a), several other surveys were planned and subsequently executed. Where possible, the locations of these surveys were designed to coincide with well placements proposed by the Nye County Early Warning Drilling Program. This section summarizes these methods, their deployment in southern Fortymile Wash and northern Amargosa Valley, and subsurface models of the geology and hydrogeology developed based on the data collected.

3.2.1 Summary of the Methods Applied

Schlumberger D.C. electrical resistivity, induced polarization, and time-domain electromagnetic resistivity depth sounding methods constituted the suite of measurements performed. This suite of methods has been shown in the past to provide constraints for subsurface models when used in a simultaneous inversion modeling framework. Although the application of this suite of measurements at each sounding station is ideal for characterization, time constraints dictated this suite only be applied at selected locations. Hence, at some sounding stations, only one method, time-domain electromagnetic resistivity depth sounding was employed. This choice was dictated by the greater depth of penetration compared with the other survey methods in the suite and increased speed of data acquisition.

3.2.1.1 Schlumberger D.C. Electrical Resistivity Depth Sounding Method

The Schlumberger D.C. electrical resistivity depth sounding array (Figure 3-1) consists of two electrodes (A and B) for injecting electrical current into the ground and two additional electrodes (M and N) for recording the resulting electrical potential differences between two points at the ground surface. These measurements are often reduced to apparent electrical resistivities (ρ_a) using

$$\rho_a = \frac{\pi \Delta V}{2L\,l}(L^2 - l^2) \qquad (3\text{-}2)$$

where

L	—	represents half the distance between the current electrodes A and B
l	—	represents half the distance between electrodes M and N
I	—	represents the magnitude of the injected electrical current, at A and B
ΔV	—	represents the measured potential difference between M and N

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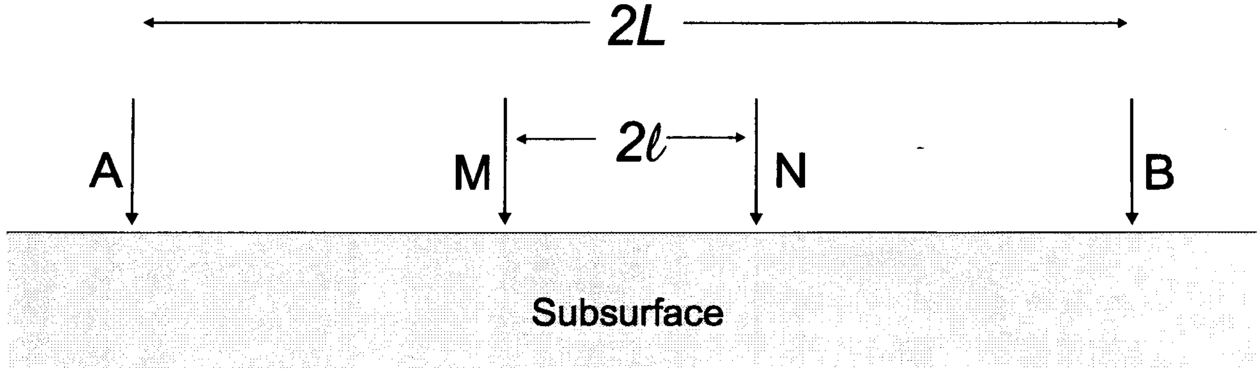

Figure 3-1. Schematic of Schlumberger Electrical Resistivity Depth Sounding Array

The apparent resistivity is generally not a correct estimate of the subsurface electrical resistivity distribution. Rather, it represents the electrical resistivity of a uniform homogeneous medium that would produce the observed potential difference given the injected current and the geometric configuration of the electrodes. Hence, the apparent electrical resistivity only reflects the true electrical resistivity of the subsurface for mildly heterogeneous conditions. For the Schlumberger depth sounding data, one-dimensional heterogeneous models of the subsurface electrical resistivity may be constructed using geophysical inversion techniques. These techniques will be discussed later in this report.

3.2.1.2 Induced Polarization Method

Induced polarization describes the electrical potential decay phenomenon observed after a direct current injected into the surface is instantaneously turned off. After the injected current is discontinued, the measured potential difference is observed to gradually decay to zero. The voltage decay, measured as a function of time, is referred to as time-domain induced polarization.

There are two mechanisms identified as the source for induced polarization membrane polarization and electrode polarization. Membrane polarization results from a nonequilibrium distribution of ions in pore fluids in an applied voltage and is enhanced by the presence of charged mineral and soil grains, including clay particles. After current flow is induced through a system in which ions are uniformly distributed, the motion of negatively charged ions may be inhibited by the presence of negatively charged minerals and soil grains. This inhibition results in localized regions of negative ion accumulation. Discontinuing the induced current flow produces a measurable voltage decay as ions diffuse away from zones of accumulation to reestablish a uniform distribution.

Electrode polarization is caused by the presence of conductive minerals in the subsurface. When these minerals are present, electrical current flow is by electronic conduction. This leads to an accumulation of ions at the interface between the mineral and solution, resulting in an increase in the electrochemical voltage at the metallic grain surfaces. After the applied external voltage is discontinued, the electrochemical voltage decays with time. The rate of voltage decay is proportional to the concentration of metallic minerals in the rock.

Clay-rich units are known to exist within the valley-fill deposits in Fortymile Wash and northern Amargosa Valley as demonstrated by geologic logs recorded at several Nye County Early Warning Drilling Program Wells (e.g., 5S). These clay-rich units can be expected to contribute to membrane polarization and, hence, induced polarization. Also present in Fortymile Wash and northern Amargosa Valley are geologic units that represent intact and weathered volcanic units. These units may support the induced polarization effect. The significance of this contribution, however, is not clear because of uncertainties related to the size and spatial continuity of these volcanic units.

The physical property often estimated in induced polarization surveys is chargeability. This property provides an indication of the electrical capacitance of the subsurface and reflects the time required for the polarization effect to decay to background conditions. Several approaches exist for estimating chargeability, however, the expression commonly used and integrated into most commercial time-domain induced polarization equipment is

$$M = \frac{1}{V_0}\int_{t_1}^{t_2} V(t)dt \qquad (3\text{-}3)$$

where

M	—	represents the chargeability
V_0	—	represents the voltage at cut-off
V(t)	—	represents the voltage as a function of time during the decay cycle
t	—	represents time

3.2.1.3 Time-Domain Electromagnetic Method

The time-domain electromagnetic resistivity depth sounding method is a broadband electromagnetic technique (Sandberg, 2000) in which current is rapidly turned off in a surface transmitter wire loop after a steady-state magnetic field has been created. In accordance with Faraday's Law, the changing magnetic field associated with the decaying current induces a current flow in subsurface conductors. The decay of the secondary magnetic field associated with the current flow induced in the subsurface can be recorded at the surface using a wire coil. By analyzing the primary and secondary magnetic fields, a model of the subsurface can be developed.

Several time-domain electromagnetic measurement configurations are possible. The most often used configuration, and the simplest to apply, is the central loop depth sounding configuration. This configuration consists of a large square transmitter loop laid out at the ground surface. At the center of the transmitter loop is a much smaller receiver coil. Data from this configuration are commonly interpreted using a one-dimensional model. Assumptions inherent in this model are that electrical resistivity layers are horizontal and laterally continuous, layer electrical resistivities are homogeneous, and the electrical resistivity within each layer is isotropic.

Although time-domain electromagnetic resistivity depth sounding data can be inverted on their own, they are insensitive to near-surface changes and to highly resistive layers, even when the

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latter are quite thick (Sharma, 1997). To overcome this limitation, joint inversion of time-domain electromagnetic and Schlumberger D.C. resistivity depth sounding data is sometimes used, with the latter providing strong constraints on the near-surface interpretation. From a hydrogeologic perspective, however, none of these methods is well suited to differentiating high electrical conductivity clay layers in the subsurface from water saturated formations. For this reason, inclusion of induced polarization data within the joint inversion framework is compelling.

As with most electrical resistivity methods, apparent resistivity is readily computed by the measuring instrument. For time-domain electromagnetic resistivity sounding instruments, the field-based apparent resistivity is often expressed as a function of time, either early time or late time. Here, the measured response at early time is largely from the near-surface layers, whereas, the late-time response is predominantly from lower layers. Because characterization of the deeper structures is important for this work, greater emphasis is placed on modeling the late-time data.

In the analyses of the field data collected in this work, apparent resistivities were calculated using two methods. The first analysis approach is based on the late-time asymptotic relationship

$$\rho_a = \frac{a^{1/3} A_R^{2/3} \mu_0^{5/3}}{20^{2/3} \pi^{1/3} t^{5/3} Z^{2/3}} \tag{3-4}$$

where

a	—	represents the radius of an equivalent circular transmitter loop
A_R	—	represents the area of the receiver coil
$\mu_0 = 4\pi \times 10^{-7}$	—	represents the magnetic permeability of free space
t	—	represents the sample time
Z	—	represents the receiver voltage divided by the transmitter current

The first approach assumes a step function transmitter turn-off and is only accurate at late times. The second method used a ramp-correction that accounts for the finite transmitter turn-off ramp (Sandberg, 1998b). This approach is reasonably accurate for determining the near-surface, or early-time, resistivity structure.

Ramp-corrected, time-based apparent resistivities were converted to depth-based approximate resistivities using Meju (1998, Equation 2)

$$\delta_{eff} = \sqrt{\frac{3.9\rho_a t}{2\pi\mu_0}} \tag{3-5}$$

where δ_{eff} represents effective depth.

3.2.2 Data Modeling

Recognizing the limitations inherent in modeling geophysical data, simultaneous-inverse modeling of collected data was applied when multiple data sets were available. As noted earlier, the inclusion of multiple geophysical data sets in the simultaneous-inversion framework minimizes model nonuniqueness through the implicit inclusion of additional model constraints.

Two approaches to one-dimensional modeling exist: approximate analysis, often referred to as imaging, and discrete-layer modeling. In the latter, the zones of discrete electrical resistivity are assumed independent. This assumption can produce significant discontinuities in the electrical resistivity field and is appropriate for modeling environments in which sharp electrical resistivity transitions occur. In the imaging process, the electrical resistivity is modeled as a continuous function. Where sharp electrical resistivity discontinuities exist, this approach can smear the interface. EINVRT6 (Sandberg, 1998b), the computer code used to perform the single and simultaneous-inversions documented in this work, is based on the discrete layer modeling framework.

EINVRT6 (Sandberg, 1998b) supports inversion of D.C. electrical resistivity, induced polarization, and time-domain electromagnetic data sets either separately or jointly: (i) D.C. electrical resistivity and induced polarization data, (ii) D.C. electrical resistivity and time-domain electromagnetic data, and (iii) D.C. electrical resistivity, induced polarization, and electromagnetic data. Parameter values derived from the inversion include layer electrical resistivity and thickness. The conceptual and mathematical approximations used in this software are summarized in Sandberg (1998b) and are not reproduced in this report.

3.2.3 Field Surveys and Modeling Results

The locations of the 1998 and 1999 geophysical surveys in southern Fortymile Wash and northern Amargosa Valley surveys are shown in Figure 3-2. Preliminary modeling and interpretation of the 1998 data are summarized in Sandberg (1998a). Descriptions of the equipment used to perform the surveys are contained in CNWRA Scientific Notebook 317E and are not reproduced here. This section summarizes the surveys performed and resulting electrical resistivity cross-sectional models produced by combining the one-dimensional models developed for the various sounding stations.

3.2.3.1 1998 Time-Domain Electromagnetic Resistivity Depth Sounding Field Survey

The suite of time-domain electromagnetic resistivity soundings that constitute this cross section were performed to investigate the adequacy of the method to characterize the hydrogeology of southern Fortymile Wash and northern Amargosa Valley. In particular, the survey was aimed at filling the approximately 10-km [6.2-m] hydrogeologic data gap that extends from Well JF–3 in the north to the community of Amargosa Farms in the south.

The transect is composed of 10 sounding locations (Figure 3-2 and Table 3-1) occupied during the spring of 1998. To effectively image the anticipated depth of the water table, a 200-m [656 ft] transmitter loop was used with applied signal frequencies below 32 Hz. Data collected at each sounding station were modeled using EINVRT6 (Sandberg, 1998b) to produce a series of discrete electrical resistivity layers and associated thicknesses (Figure 3-3).

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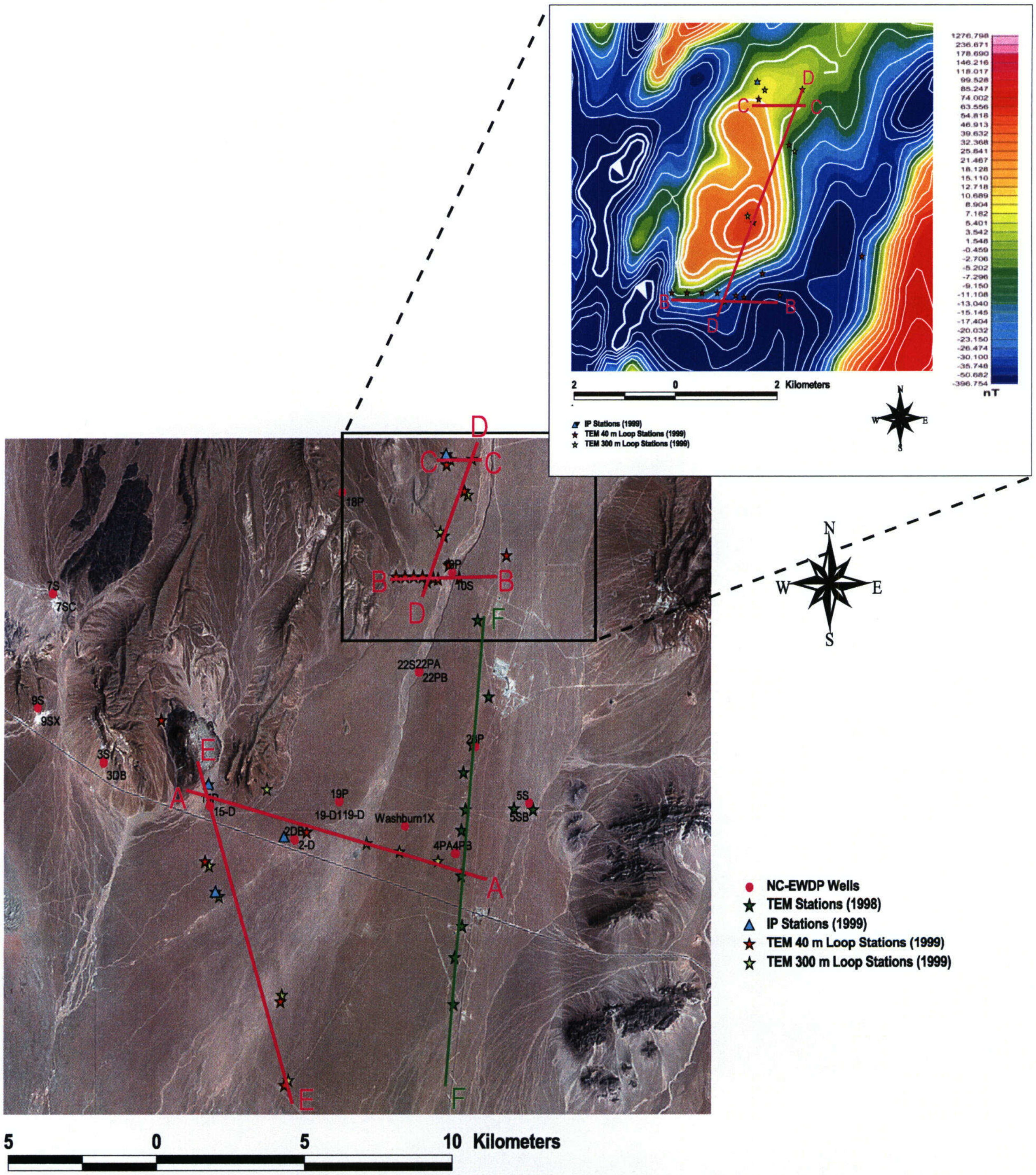

Figure 3-2. Locations of Schlumberger D.C. Electrical Resistivity Depth Soundings, Time-Domain Electromagnetic (TEM) Resistivity Depth Soundings, and Induced Polarization (IP) Depth Soundings. NC-EWDP Represents Nye County Early Warning Drilling Program. Inset Figure Shows the Transects B-B', C-C', and D-D' Superimposed on a Portion of an Aeromagnetic Map Based on Blakely, et al., 2000.
NOTE: Scale information provided in kilometers; for conversion use 1 km = 0.621 m.

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Table 3-1. Station Locations for Electrical Resistivity Transect F-F’			
Station	**UTM-Easting (m)**	**UTM-Northing (m)**	**Estimated Elevation (m)***
A	550,680	4,045,799	784.9
B	553,039	4,052,576	786.4
C	553,070	4,053,930	797.1
E	553,280	4,056,330	819.0
F	553,301	4,057,646	831.2
G	553,429	4,058,250	837.3
H	553,370	4,059,330	846.7
I	553,670	4,060,130	854.7
J	554,220	4,061,530	865.6
K	553,845	4,063,735	892.8

*Elevations are estimated from the Geologic Map of the Specter Range SW Quadrangle, Nye County, Nevada. U.S. Geological Survey Quadrangle Map, Topographic 7.5 Minute Series. Scale 1:24,000. 1984.

NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

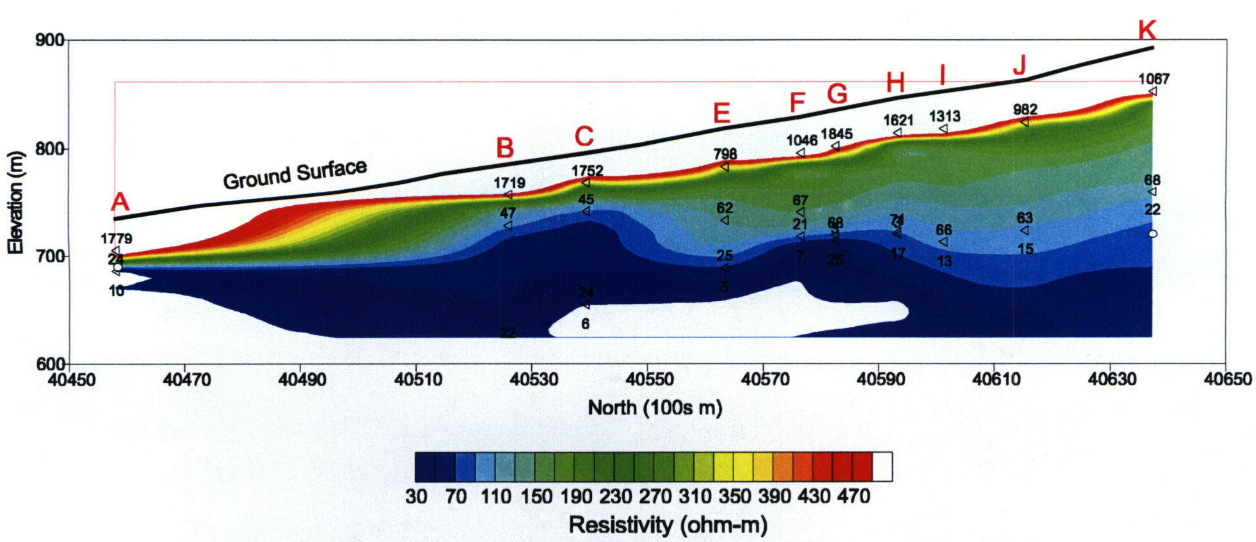

Figure 3-3. Electrical Resistivity Cross Section for 1998 Survey Transect F-F’ (see Figure 3-2). Numbers on the Figure Represent Electrical Resistivities in Ohm-m. NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

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The upper layer of each model is 25 to 40-m [82 to 131 ft] thick and is characterized by a high electrical resistivity that commonly exceeds 1,000 ohm-m. These electrical resistivities are consistent with those reported by Greenhaus and Zablocki (1982) based on their modeling effort and are significantly greater than those of the underlying layer. These high electrical resistivities more than likely reflect hydrologic and lithologic variations within the near surface. The modeled magnitude and thickness of the layer, however, may be affected by modeling nonuniqueness.

The transition from the upper layer to the underlying lower electrical resistivity layer is abrupt. Modeled electrical resistivities in the underlying layer range from 45 to 75 ohm-m. As mentioned before, the modeled transition may result from a combination of lithologic and hydrologic factors. The lithologic logs from Nye County Early Warning Drilling Program wells 4PA and 4PB, which are in close proximity to sounding station E (Figure 3-4), do not show the modeled transition. Soil moisture logs recorded at these Nye County Early Warning Drilling Program wells also do not support the modeled transition. It should be noted, however, the soil moisture logs reported for the Nye County Early Warning Drilling Program wells were recorded several years after the geophysical surveys were completed, and because of the transient nature of soil moisture may not represent previous field conditions at the time of the surveys. Unfortunately, few geophysical logs are available for the Nye County Early Warning Drilling Wells 4PA and 4PB at the current time.

Available well logs for Nye County Early Warning Drilling Program well 23P (which is in close proximity to sound station I) were reviewed in an effort to further explore the cause of the first transition. Unfortunately, no lithologic logs are currently available for this well, and available electrical resistivity logs do not cover the depth of interest. A comparison of the modeled electrical resistivity profile at the depth of the transition with the magnetic logs shows a

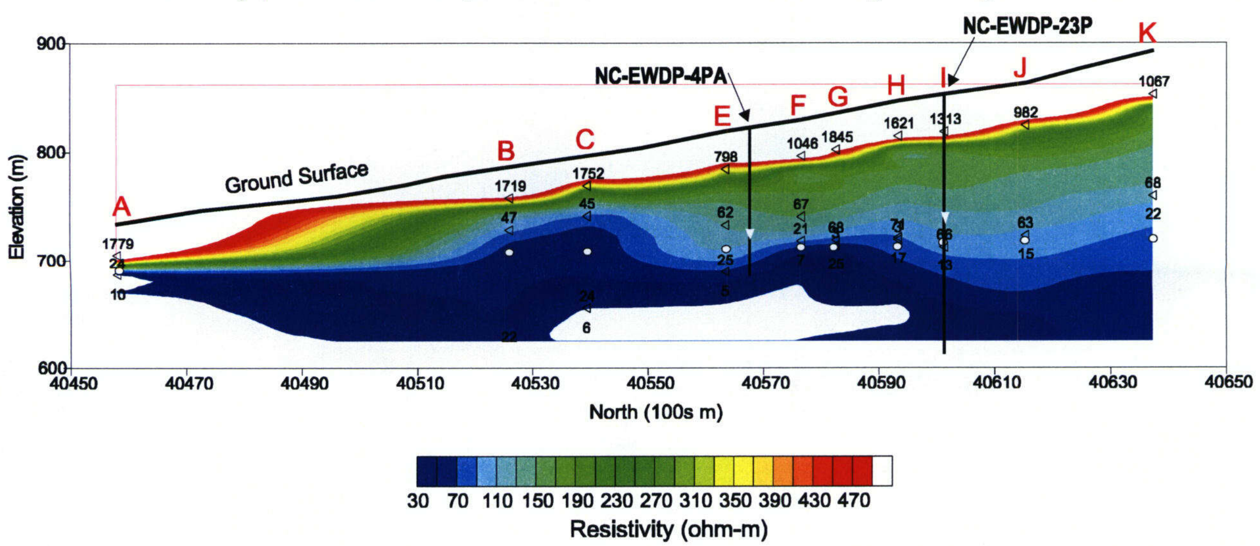

Figure 3-4. Comparison of Data from Nye County Early Warning Drilling Program Wells 4PA and 23P and Hill, et al. (2002) to the Electrical Resistivity Cross Section for 1998 Survey Transect F-F'. White Dots Represent Water Table Elevation Estimates from Hill, et al. (2002), and White Triangles Represent Water Table Elevation Estimates from Nye County Early Warning Drilling Program Wells.
NOTE: Information provided in meters; for conversion use 1 m = 3.281 ft.

reasonable correlation (Figure 3-5). Note that within the high resistivity zone, the recorded magnetization is generally different from the underlying zone, suggesting the transition may represent a lithologic contact. This possibility will be examined in a followup report once a comprehensive set of lithologic and geophysical logs becomes available for Nye County Early Warning Drilling Program Wells 4PA, 4PB, and 23P.

The second transition modeled separates electrical resistivities of 45–70 ohm-m from underlying electrical resistivities of 7–25 ohm-m. The electrical resistivities in the underlying zone are interpreted to reflect the regional aquifer system. To investigate this assumption, the measured depths to the water table at the Nye County Early Warning Drilling Program Wells 4PA and 23P were superimposed on the electrical resistivity section (see Figure 3-4). The comparison shows the depth to the measured water table is generally within 10–20 m [33 to 66 ft] of the modeled interface and, therefore, supports the assumption. The assumption is further supported by the general agreement between the depth to the interface and the depth to the water table estimated from the contour map of Hill, et al. (2002). The area of poor agreement between the modeled transition and the map of Hill, et al. (2002) occurs at sounding stations B and C where a low electrical resistivity mound is modeled. These soundings appear to coincide with the location of the buried volcanic cone Magnetic Anomaly B (Figure 3-6). Depths to the second interface compare favorably to the observed depths to the tuff/valley-fill interface {61–73 m [200–240 ft]} reported for the Felderhoff wells by Carr, et al. (1995). Figure 3-6 also

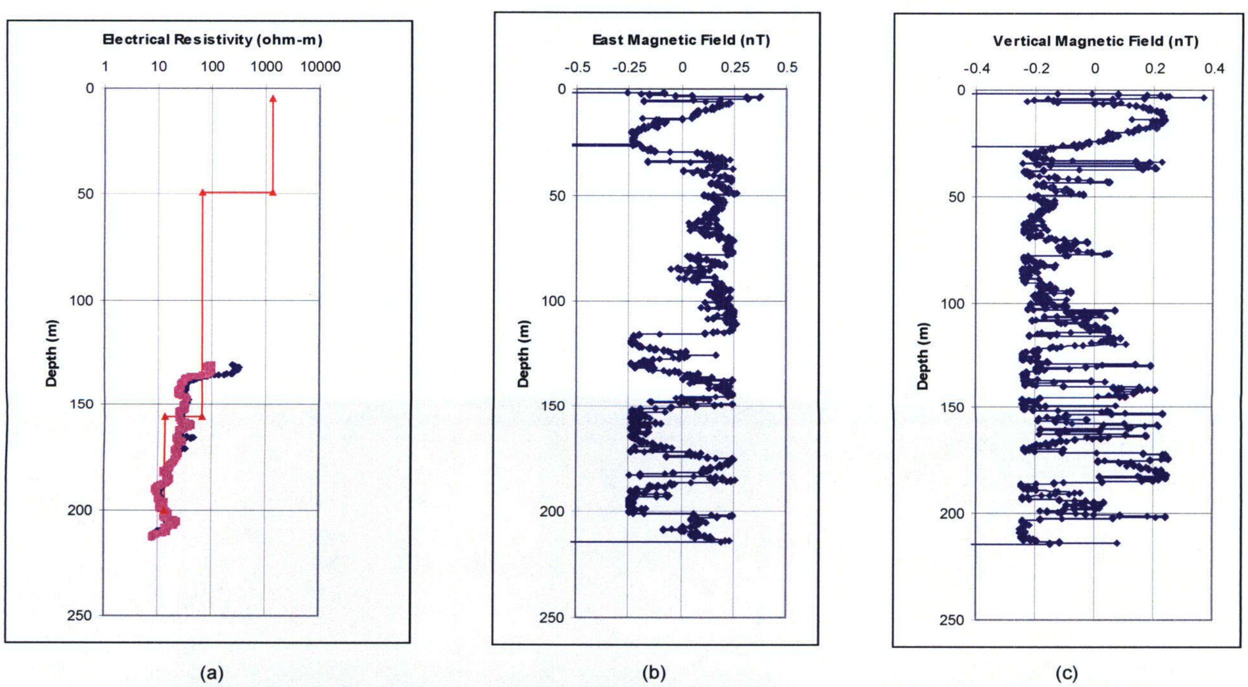

Figure 3-5. Comparison of Modeled Electrical Resistivities at Sounding Station I (Transect F-F') to Geophysical Logs from Nye County Early Warning Drilling Program Well 23P: (a) Modeled Electrical Resistivities Versus Recorded (Orange), R16 Resistivity Log (Pink), and R64 Resistivity Log (Navy Blue); (b) East Component of Magnetic Log; and (c) Vertical Component of Magnetic Log
NOTE: Information provided in meters; for conversion use 1 m = 3.281 ft.

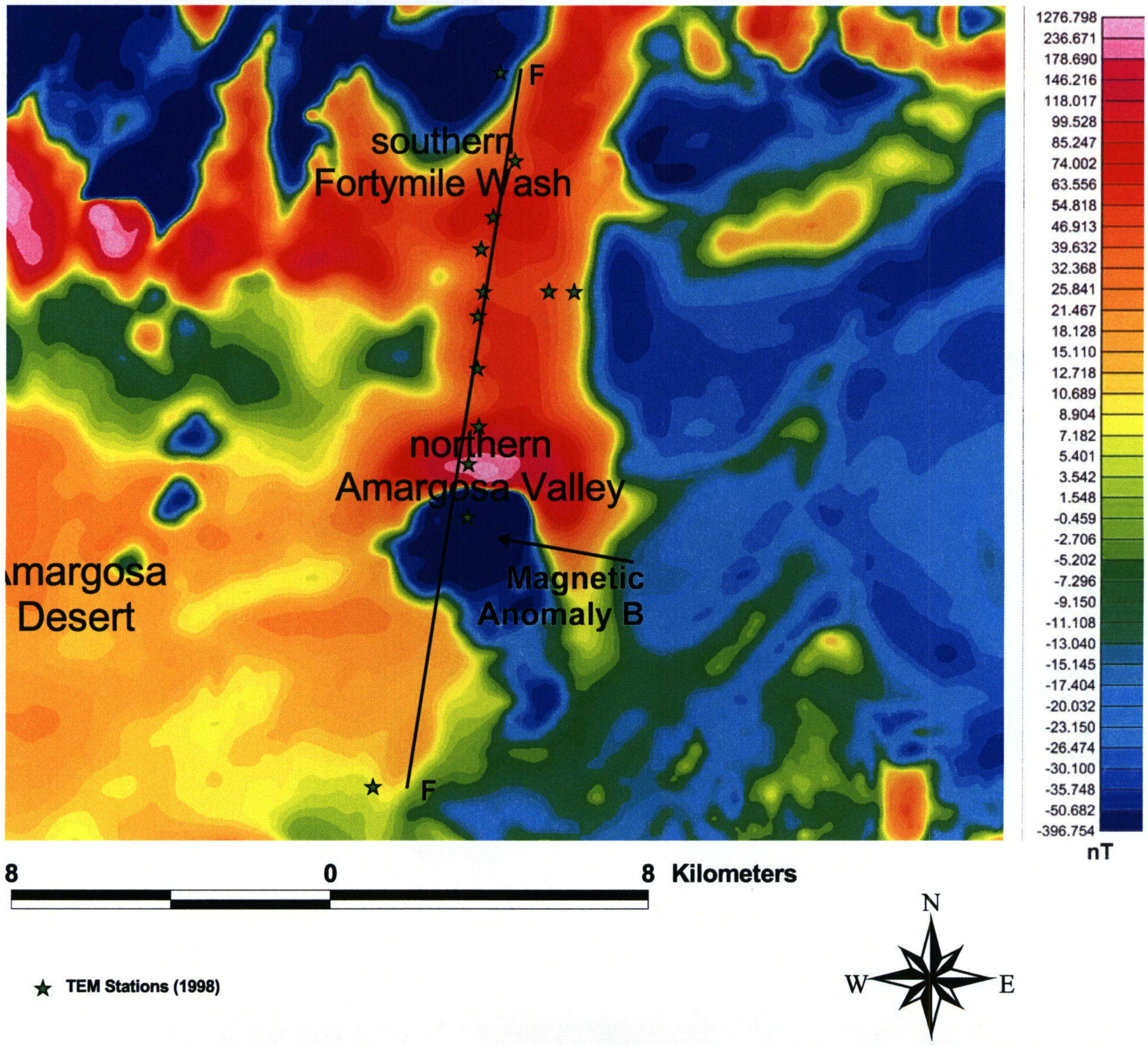

Figure 3-6. Distribution of Aeromagnetic Magnetic Features (Based on Blakely et al., 2000) Relative to Transect F-F'. TEM Represents Time-Domain Electromagnetic. NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

shows the magnetic anomalies that result from the complicated distribution of tuff and basalt rocks along the transect. The potential impact of these units on the electrical resistivity models developed along the transect will be investigated in a followup report.

3.2.3.2 1999 Resistivity Field Surveys

In 1999, a suite of time-domain electromagnetic and Schlumberger D.C. electrical resistivity depth soundings, as well as induced polarization soundings, was designed and executed to address the hydrologic data gaps that existed in the region prior to the development of the Nye County Early Warning Drilling Program. Although the Nye County Early Warning Drilling Program wells have increased the amount of data available for this region, and further constrained the geology of the area, the geophysical soundings performed in 1999 remain important because they provide a means through which hydrostratigraphies and the water table may be spatially mapped in inter-well regions, thereby, further reducing uncertainty.

The 1999 field survey consisted of 35 time-domain electromagnetic resistivity depth soundings, 4 time-domain induced polarization depth soundings, and 4 Schlumberger D.C. electrical resistivity depth soundings (Figure 3-2). For the time-domain electromagnetic resistivity depth soundings, two rectangular transmitter loop sizes {300- × 300-m, and 40- × 40-m [984 × 984 ft and 131 × 131 ft]} and several transmitter frequencies were used to map both near-surface and deeper resistivity features. As the time-domain induced polarization and Schlumberger D.C. electrical resistivity depth soundings were much more timeconsuming than the time-domain electromagnetic soundings and only constrained the near-surface environment, only four of these soundings were performed (Figure 3-2).

Five transects (resistivity depth sections) were constructed from the suite of measurements, A-A', B-B', C-C', D-D', and E-E' as shown in Figure 3-2. Line A-A' extends across southern Fortymile Wash and is constrained by data at Nye County Early Warning Drilling Program Wells 15P, 2D, Washburn 1X, and 4PB (see Figure 3-2). Note that prior to the development of Nye County Early Warning Drilling Program Well 15P, Farrell, et al. (2000) used data from a well located at the Lathrop Wells cinder cone to constrain models of the western portion of Line A-A'. Lines B-B', D-D', and C-C' intersect each other and are located on the Nevada Test Site, west of the Fortymile Wash channel. Few data exist to constrain the models along these lines. For these lines, an attempt has been made to constrain the interpretation with data from Wells JF–3, J–13, J–12, and Nye County Early Warning Drilling Program Well 10S. Line E-E' extends from the Lathrop Wells cinder cone toward Amargosa Farms and, as a result, crosses the central portion of the Amargosa Desert. This line is constrained by data from Nye County Early Warning Drilling Program Well 15P and the Amargosa Farms Town C Well.

3.2.3.3 Transect A-A'

Electrical resistivity and chargeability models determined from the single and simultaneous inversions of data sets recorded at stations along transect A-A' were used to construct the cross section shown in Figure 3-7. Along this line, models based on simultaneous inversion of multiple data sets were considered to be the most reliable. The computed one-dimensional models and resulting cross section show the subsurface electrical resistivity structure to be vertically layered and laterally correlated.

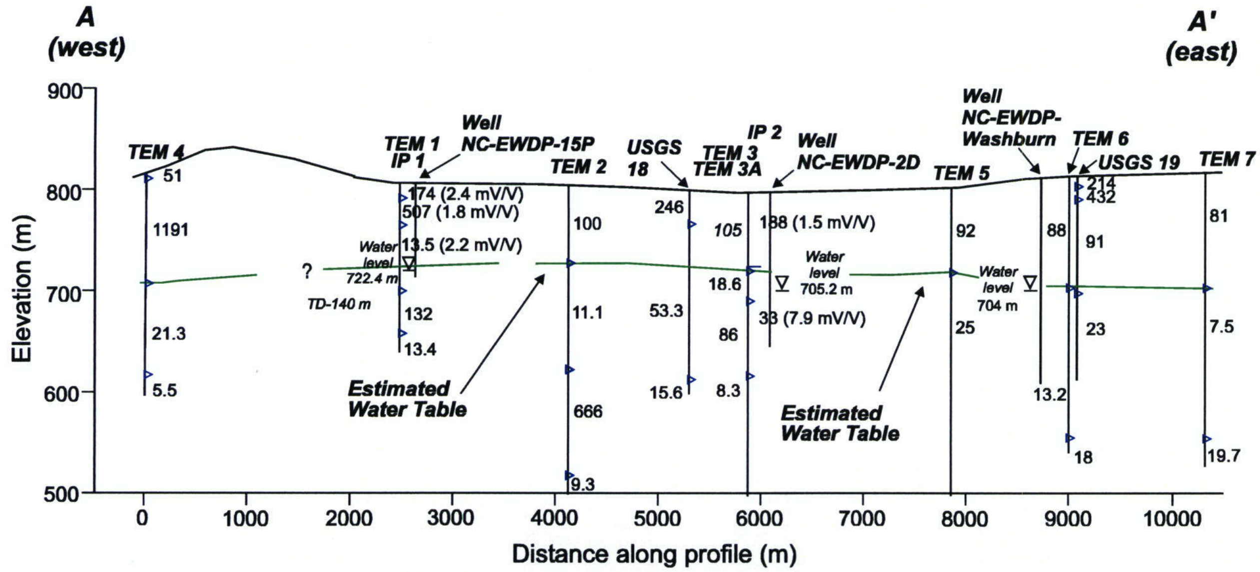

Figure 3-7. Electrical Resistivity Cross Section for Transect A-A' (See Figure 3-2). Numbers in Parenthesis on the Figure Represent Chargeabilities in mV/V and Numbers Without Parenthesis Represent Electrical Resistivities in Ohm-m. NOTE: Information provided in meters; for conversion use 1 m = 3.281 ft.

The electrical resistivity cross section is made up of two major layers, an upper layer of relatively high electrical resistivity and an underlying layer of lower electrical resistivity. Additional electrical resistivity layering can be inferred within these primary layers. The general distribution of electrical resistivities is similar to that shown in Figure 3-3. Electrical resistivities in the upper layer generally exceed 80 ohm-m and at shallow depth may locally exceed 500 ohm-m. In contrast, electrical resistivities in the lower layer are generally less than 25 ohm-m, with exceptions occurring at sounding locations TEM2 and TEM1. The greater than 600 ohm-m electrical resistivity modeled at TEM2 is suspect. This large magnitude reflects model nonuniqueness associated with limited modeling constraints. This assertion is supported by a similarly modeled feature at TEM1 where the inversion is based solely on time-domain electromagnetic resistivity data (Table 3-2). When Schlumberger D.C. electrical resistivity and induced polarization data are simultaneously included in the inversion at TEM1 (Figure 3-7; see also Table 3-3), the magnitude of this feature is significantly reduced. Note although the magnitude of the electrical resistivity of the zone is significantly reduced, the zone is electrically resistive relative to adjacent zones.

In an effort to validate the modeling results, models developed for the region that includes TEM3, TEM3A, and IP2 were compared with gamma and electrical resistivity logs recorded at Nye County Early Warning Drilling Program Well 2DB (Figure 3-8), which is in close proximity to Nye County Early Warning Drilling Program Well 2D. The inverted electrical resistivity models correlate reasonably well with the electrical resistivity log with deviations occurring at depth. These deviations are because of the combined decreasing resolution of the surveying methods with depth as well as the number of layers and associated constraints specified in the models.

Table 3-2. Electrical Resistivity Model for Station TEM1 Based on Inversion of Time-Domain Electromagnetic Resistivity Depth Sounding Data		
Layer	**Electrical Resistivity (ohm-m)**	**Thickness (m)**
1	434.0	41.8 [137.1 ft]
2	13.4	67.3 220.8 ft]
3	656.6	38.0 [124.8 ft]
4	13.4	—

Table 3-3. Electrical Resistivity Model for Station IP2 Based on Simultaneous Inversion of Induced Polarization and Schlumberger D.C. Depth Sounding Data				
Layer	**Electrical Resistivity (ohm-m)**	**Chargeability (mV/V)**	**Thickness (m)**	**Normalized Chargeability (μS/m) × 100**
1	832.7	3.0	1.73 [5.6 ft]	0.4
2	156.5	4.9	3.09 [10.2 ft]	3.1
3	188.2	1.5	67.81 [222.4 ft]	0.8
4	33.0	7.9	—	23.8

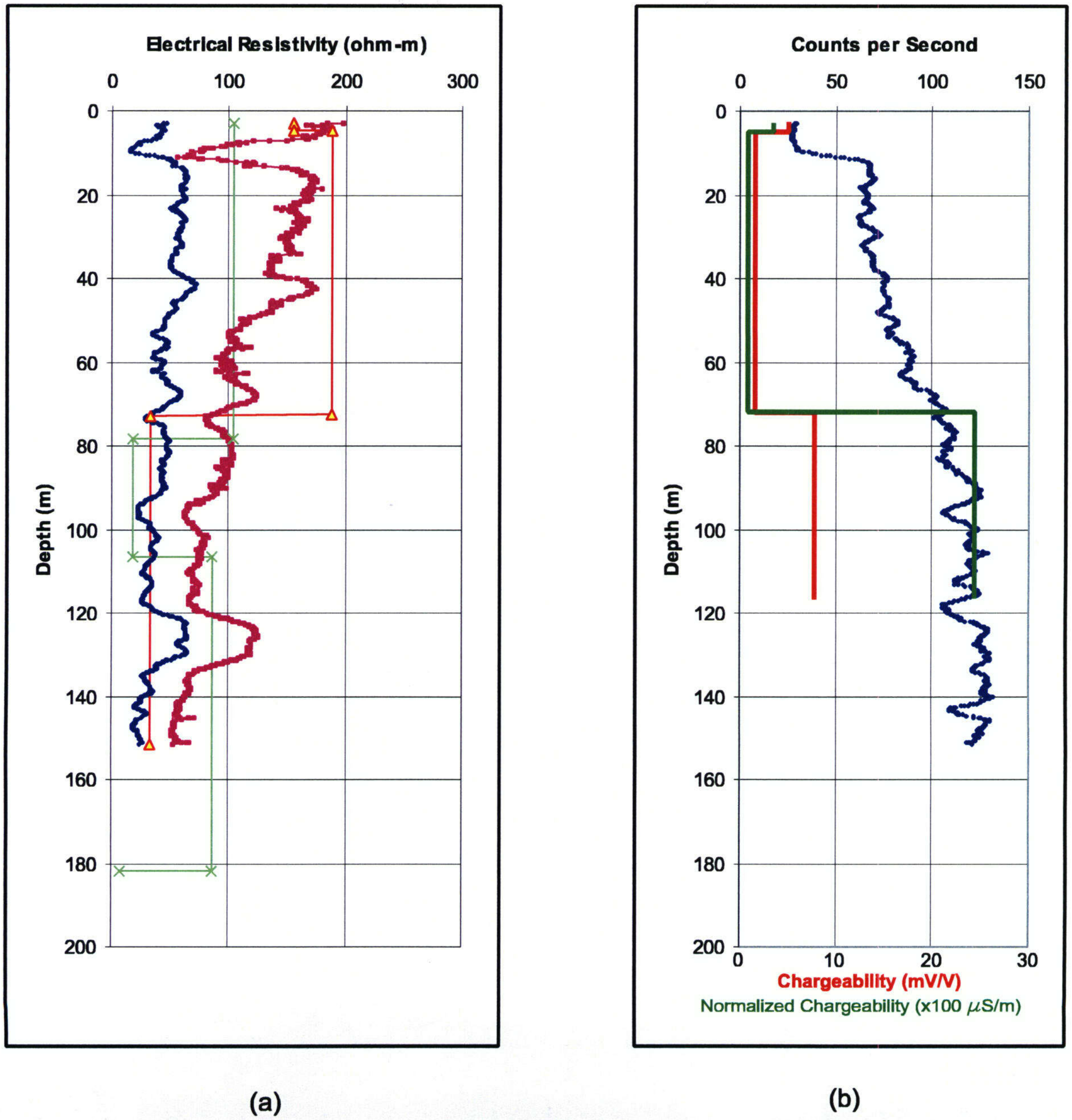

Figure 3-8. Comparison of Electrical Resistivities Modeled at TEM3/TEM3A and IP2 with Logs for Nye County Early Warning Drilling Program Well 2DB: R64 Resistivity Log (Pink), R16 Resistivity Log (Navy Blue), IP2/Schlumberger Simultaneous Inversion Model (Orange), Gamma Log (Navy Blue), Modeled Chargeability (Red), Normalized Chargeability (Green)

NOTE: Information provided in meters; for conversion use 1 m = 3.281 ft.

Chargeabilities inverted from the induced polarization data also show good correlation to the gamma log. This correlation is currently assumed to reflect the increased clay content with depth described in the geologic log. Note the correlation of the induced polarization model with clay content can be improved using the normalized chargeability (Slater and Lesmes, 2002) (chargeability/electrical resistivity)×100 (Table 3-3) where the larger values indicate higher clay content.

Water table elevations recorded at Nye County Early Warning Drilling Program Wells 2D and Washburn 1X show good correlation to the primary transition from high to low electrical resistivity modeled at TEM2, TEM3/TEM3A/Schlumberger/IP2, TEM5, TEM6, and TEM7 (Figure 3-5). Also modeled in this work were Schlumberger D.C. electrical resistivity depth sounding data from two U.S. Geological Survey stations, USGS 18 and 19 (Greenhaus and Zablocki, 1982). The modeled transition from high to low electrical resistivity at USGS 19 correlates well with the interpolated water table (Figure 3-7). At USGS 18, the correlation between the modeled transition from high to low electrical resistivity is rather poor.

The water level at Nye County Early Warning Drilling Program Well 15P allows the water table to be interpolated and extrapolated west of Nye County Early Warning Drilling Program 2D. Using water level data from these two wells, the correlation with the transition from high to low electrical resistivity at TEM4 is reasonable. At TEM2, the correlation from high to low electrical resistivity occurs at a higher elevation than at the interpolated water table elevation. At TEM1/IP1, the correlation is poor. This poor correlation is believed to be because of lateral discontinuities in the geologic structure in the vicinity of TEM1/IP1 that violate the modeling assumption of minimal lateral variability of the electrical resistivity structure. The lateral variability may reflect the nearby contact between basalt deposits and valley-fill sediments.

The water table elevations estimated from the interpretation of the geophysical soundings were further compared to water table elevations estimated from a water table contour map developed by Hill, et al. (2002). The map of Hill, et al. (2002) considers water table data from various sources including the Nye County Early Warning Drilling Program, U.S. Geological Survey, and municipal sources. In most cases, the water table elevations estimated from the geophysical surveys correlate reasonably well with water table elevations inferred from the contour map (Figure 3-9).

Note some of the differences between the measured water table elevation and the interpreted elevation may be because of approximate elevation estimates at some sounding stations along the transect.

3.2.3.4 Transect B-B'

Transect B-B' is an east-west trending profile located several kilometers north of transect A-A' (Figure 3-2). The transect is composed of several soundings including TEM24, TEM23, TEM22, TEM21, TEM20, TEM25, TEM26, TEM11, TEM10, TEM9, and TEM8. These soundings were based on 40 × 40-m [131 × 131-ft] transmitter loop sizes, with the exception of TEM9 and TEM20, which were based on 300 × 300-m [984 × 984-ft] transmitter loop sizes. The primary objective of this survey was to map the tuff/valley-fill contact in the region. Because the depth to the water table in this region is greater than 100 m [328 ft] (based on data from Wells J–12 and JF–3), it is unlikely that, with the exception of TEM9 and TEM20, these soundings support mapping the regional water table.

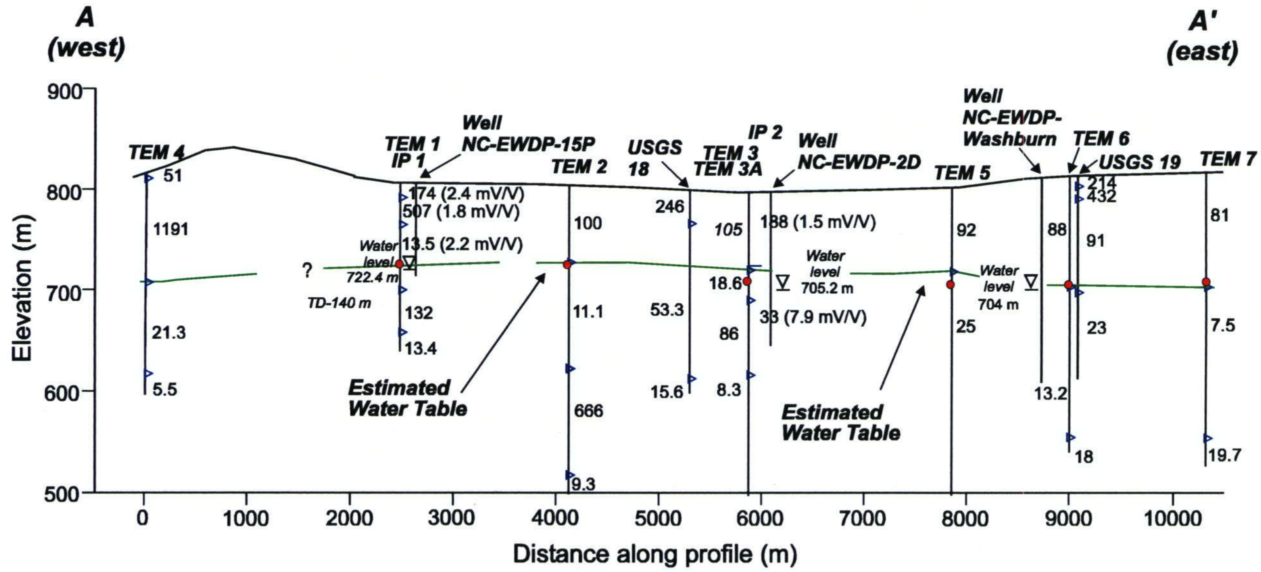

Figure 3-9. Comparison of Estimated Water Table Elevations for Transect A-A' with Estimated Water Table Elevations from Hill, et al. (2002) Represented by Red Dots. Numbers With Parenthesis on the Figure Represent Chargeabilities in mV/V and Numbers Without Parenthesis Represent Electrical Resistivities in Ohm-m. NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

The electrical resistivity cross section developed for this transect by combining the individual one-dimensional models for the various stations is presented in Figure 3-10. Of the transects modeled, B-B' is considered the least constrained, due, in part, to its sole dependence on time-domain electromagnetic resistivity soundings and the limited constraining data available from Nye County Early Warning Drilling Program Well 10S. Because of the possible presence of a north-trending fault beneath the Fortymile Wash channel (Spengler and Chornack, 2002), Nye–2 cross section, Nye County Early Warning Drilling Program Well 10S, located east of the fault, may provide weak constraints on geologic models constructed west of the channel.

The western edge of the B-B' transect is located just east of an eastward slipping tuff outcrop. This outcrop provides a geologic constraint on the individual one-dimensional models, particularly the westernmost one-dimensional models for sounding stations TEM24 and TEM23. Because of the proximity of these soundings to the east dipping tuff outcrop, there is the possibility that the assumption of lateral continuity of geologic units inherent in the modeling may be violated. As a result, there are concerns regarding the accuracy of one-dimensional electrical resistivity models developed for these two sounding stations. The electrical resistivity models developed for these two stations included in electrical resistivity cross section B-B' are less certain than the models generated without this caveat.

Transect B-B' displays several shallow layers. The shallowest layer is thin and relatively conductive, with modeled electrical resistivities generally less than 50 ohm-m and modeled thicknesses on the order of a few meters. The low electrical resistivities in this zone may reflect either temporal phenomena, such as shallow infiltration following periodic rain events, or a thin conductive clay layer. This surficial layer is underlain by a more electrically resistive unit with

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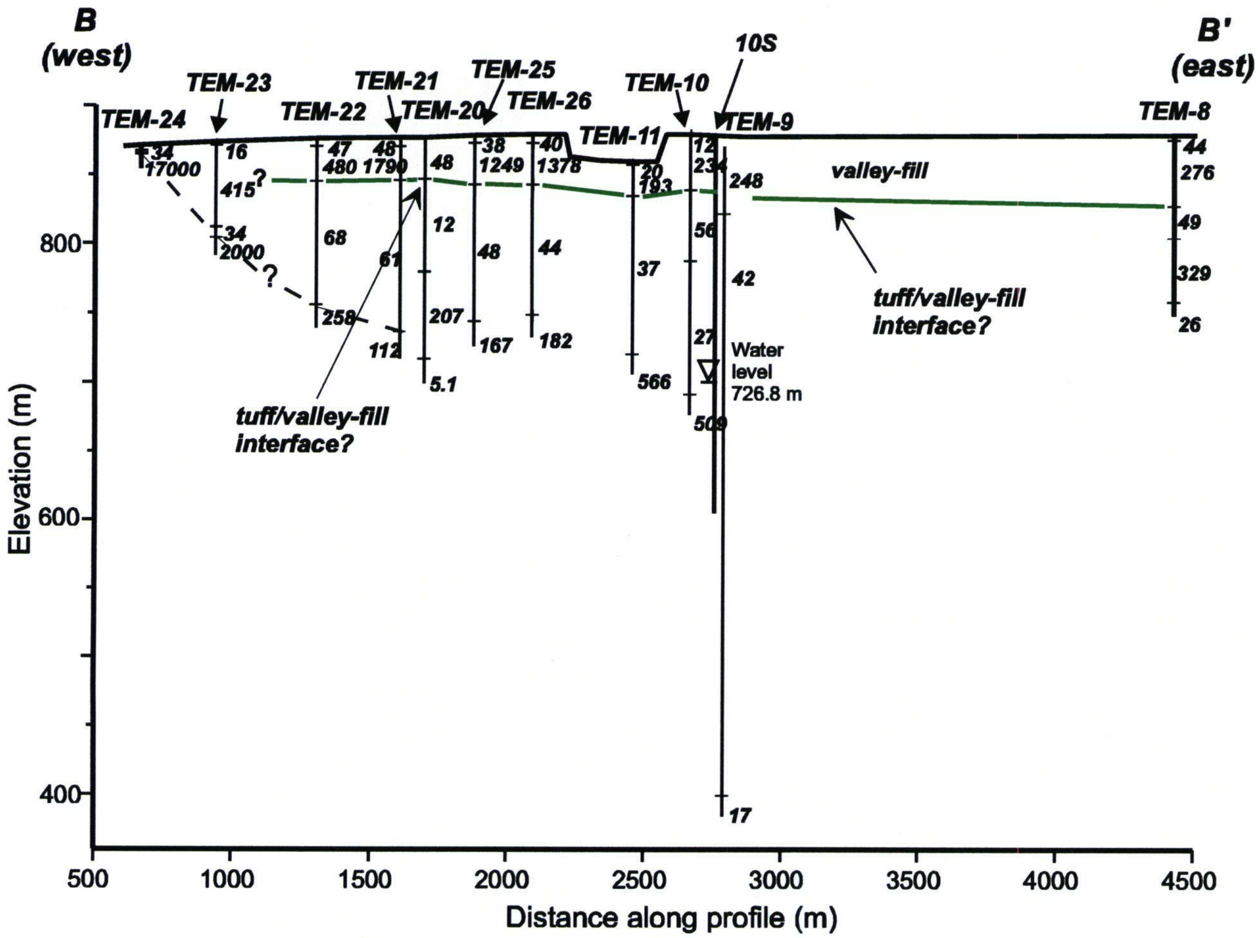

Figure 3-10. Electrical Resistivity Cross Section For Transect B-B' (see Figure 3-2). Bracketed Numbers on the Figure Represent Chargeabilities in mV/V and Numbers Without Parenthesis Represent Electrical Resistivities in Ohm-m. NC-EWDP on the Figure Represents the Nye County Early Warning Drilling Program. NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

modeled electrical resistivities on the order of hundreds to thousands of ohm-m and thickness of tens of meters. This unit is, in turn, underlain by a unit of significantly lower electrical resistivity. This transition from high to low electrical resistivity is significantly shallower than the regional water table and more than likely reflects either a change in lithology or a significant increase in the water content in the valley-fill. The base of the model appears to be controlled to the west by a dipping high electrical resistivity unit with a trend that correlates with the tuff unit that crops out just west of the western end of the transect. This electrically resistive unit can be traced across most of the soundings. Whether this contact represents the tuff/valley-fill contact or whether it represents an upper modeled transition, will be further investigated in a followup report that includes models of magnetic data collected near the transect.

The models developed for TEM9 and TEM10 are compared with electrical resistivity logs recorded at Nye County Early Warning Drilling Program Well 10S (Figure 3-11) to gauge their plausibility. The comparison shows the model developed for TEM10 reproduces many of the features observed in the well log, including the increased electrical resistivity at the base of the log. Note that because the electrical resistivity log reflects conditions near the well and may also reflect near-borehole effects, it is not expected that the log will correlate perfectly with the developed models. The resolution of the model for TEM9 is less than that for TEM10 and, as a result, does not reproduce some of the salient features observed in TEM10. Given the uncertainties in the model parameters, the models, in particular TEM10, reproduce the electrical resistivity structure observed in the log. Finally, the resolution of neither model is sufficient to resolve the water table at the Nye County Early Warning Drilling Program Well 10S.

3.2.3.5 Transect C-C'

Transect C-C' trends east-west and is located north of B-B' (Figure 3-2). The transect consists of four time-domain electromagnetic resistivity soundings. TEM14 and TEM13 have 40 × 40-m [131 × 131-ft] transmitter loops and are separated by 260 m [853 ft] along the western side of TEM12. TEM12 and TEM15 have 300 × 300-m [984 × 984-ft] transmitter loops. Coincident with TEM13 is IP3. This transect is the shortest of the transects surveyed. Data collected at sounding stations TEM13 and TEM14 appeared to be either contaminated by strong lateral inhomogeneities or anthropogenic conductors (e.g., electrical wire) in the near surface and were, therefore, not considered in subsequent analyses. The anomalous behavior observed at sounding stations TEM13 and TEM14 was not observed in the data for TEM12. Because of the proximity of TEM12 to IP3, data from these two soundings were combined in a simultaneous inversion. The results of this inversion appear reasonably well constrained. Single inversion of TEM15, however, yields a poorly constrained model.

The electrical resistivity cross section that results from simultaneous inversion of TEM12 and IP3 and single inversion of TEM15 is shown in Figure 3-12. Also included on the figure for correlation purposes is Well J–12. The model for TEM12 and IP3 consists of several distinct layers reflecting lithologic variations. In particular, there are two layers with noticeably high chargeabilities: layers 2 and 4 (see also normalized chargeabilities in Table 3-4). These layers may indicate the presence of clay-rich units.

Comparison with cross section C-C' to Well J–12 shows the recorded water level correlates favorably with the transition from high (218 ohm-m) to low (27.8 ohm-m) electrical resistivity at sounding TEM12/IP3.

Because of the poor quality of the model constructed for TEM15, a transition from high to low resistivity that correlates well with the measured water table at Well J–12 cannot be identified.

3.2.3.6 Transect D-D'

Transect D-D' trends north east-southwest and intersects transects B-B' and D-D' (Figure 3-2). This transect is comprised solely of time-domain electromagnetic resistivity soundings. These include four 300 × 300-m [984 × 984 ft] transmitter loop soundings (TEM20, TEM18, TEM16, and TEM15) and two 40 × 40-m [131 × 131-ft] transmitter loop soundings (TEM17 and TEM19). Apart from TEM20, inversion of the remaining soundings generally resulted in poorly resolved

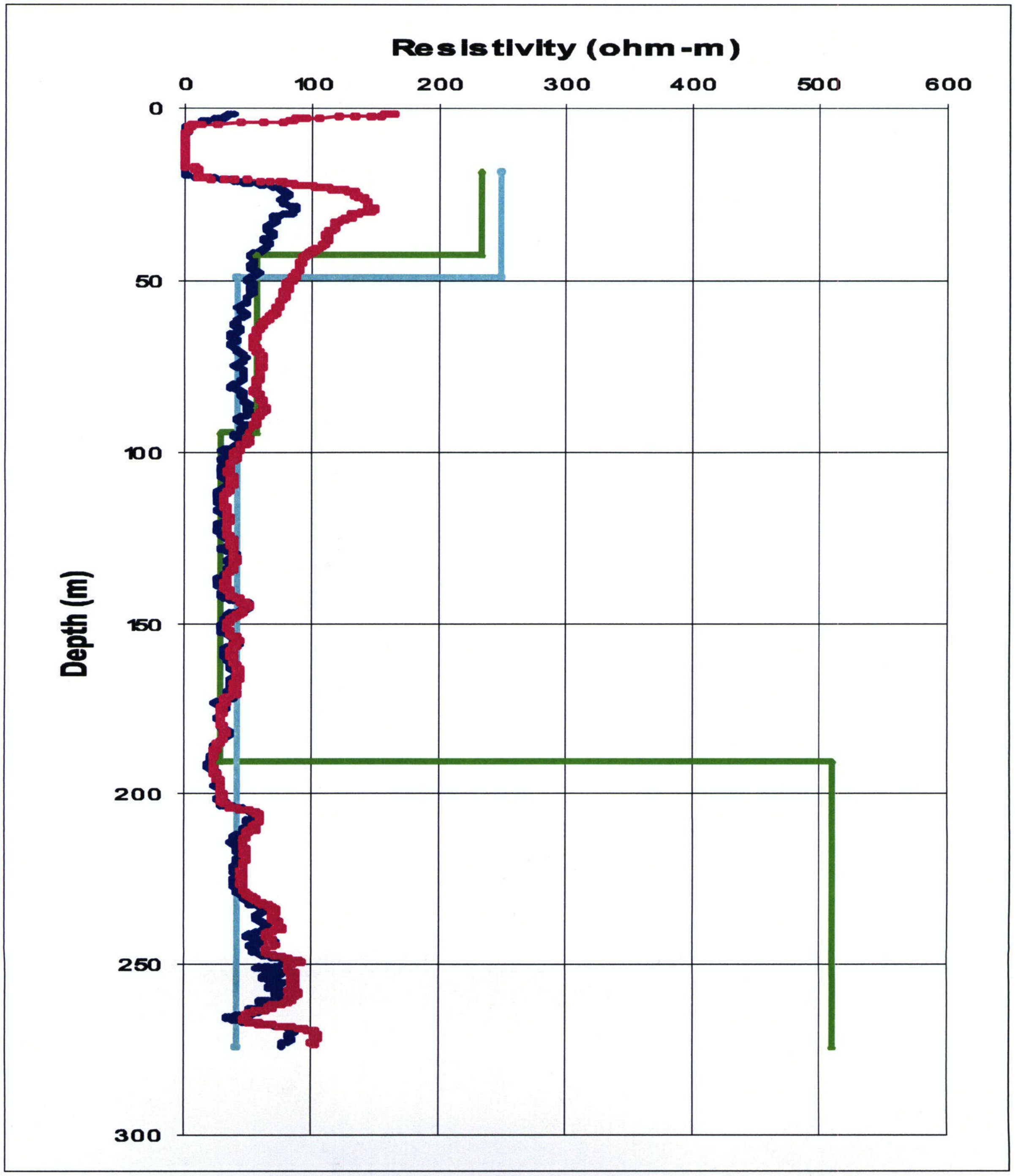

Figure 3-11. Comparison of Electrical Resistivities Modeled at TEM9 and TEM10 with Logs for Nye County Early Warning Drilling Program Well 10S (a) R64 Resistivity Log (Pink), R16 Resistivity Log (Navy Blue), IP2/Schlumberger Simultaneous Inversion Model (Orange), TEM9 Electrical Resistivity Model (Light Blue), and TEM10 Electrical Resistivity Model (Green)

NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

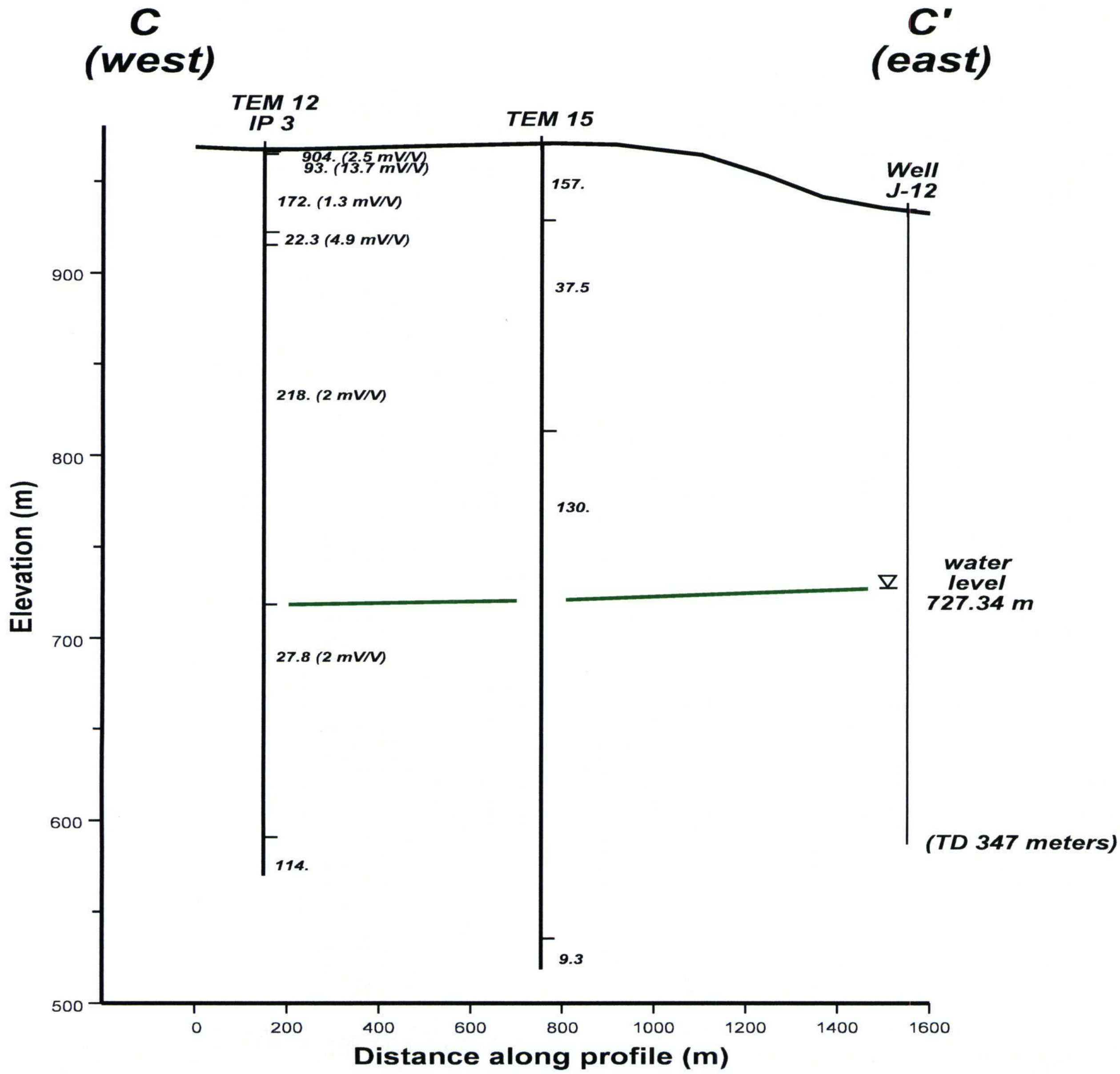

Figure 3-12. Electrical Resistivity Cross Section for Transect C-C' (see Figure 3-2). Bracketed Numbers on the Figure Represent Chargeabilities in mV/V and Numbers Without Parenthesis Represent Electrical Resistivities in Ohm-m.
NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

Table 3-4. Electrical Resistivity Model for Sounding Station TEM12/IP3 Based on Simultaneous Inversion of Time-Domain Electromagnetic Resistivity Sounding Data, Induced Polarization Data, and Schlumberger D.C. Depth Sounding Data				
Layer	**Electrical Resistivity (ohm-m)**	**Chargeability (mV/V)**	**Thickness (m)**	**Normalized Chargeability (μS/m)×100**
1	904	2.5	2.0 [6.6 ft]	0.3
2	93	13.7	0.8 [2.6 ft]	14.7
3	172	1.3	42.7 [140.6 ft]	0.8
4	22.3	4.9	6.7 [22.1 ft]	22.0
5	218	2*	197.0 [646.2 ft]	0.9
6	27.8	2*	—	7.2
*Chargeability values were fixed during the inversion procedure.				

models as determined by the 95-percent confidence limits for the model parameters (see Scientific Notebook 317E).

The electrical resistivity cross section generated by combining the individual one-dimensional models for the various cross sections is shown in Figure 3-13. Also superimposed on the cross section are geological and hydrological data from Wells J–12, JF–3, and Nye County Early Warning Drilling Program Well 10S. The figure shows a possible correlation between the low electrical resistivity layer ($\rho \leq$ 25 ohm-m where ρ_a represents the apparent electrical resistivity) modeled at stations TEM18 and TEM20 and the recorded water levels at Wells JF–3 and J–12. Similar correlations are not observed at stations TEM15 and TEM16/17, which are closer to Wells J–12 and JF–3 than TEM18 and TEM20. At these stations (TEM15 and TEM16/17), a low electrical resistivity layer is modeled at significantly greater depth. Although this may indicate a possible discontinuity in geologic structure, other possible explanations include either model nonuniqueness or the presence of anthropogenic electrically conductive features such as electrical wire in the subsurface. The impacts of nonuniqueness and anthropogenic factors on the models at stations TEM15 and TEM16/17 were reflected in the poor resolution and associated wide confidence intervals on the inverted electrical resistivity values and layer thicknesses (see Scientific Notebook 317E).

Evident in electrical resistivity cross section D-D' is a relatively high electrical resistivity unit ($\rho \geq$ 100 ohm-m) that appears to correlate to the depth of the Tiva Canyon Tuff unit reported in Wells J–12 and JF–3. Note that both Wells J–12 and JF–3 lie east of the proposed fault along the Fortymile Wash channel (Spengler and Chornack, 2002). Along transect D-D', the Tiva Canyon Tuff unit appears to attain a maximum elevation at TEM18. This inferred geometry appears consistent with aeromagnetic data (Figure 3-2) that indicate a local magnetic high in close proximity to TEM18. The aeromagnetic data, however, do not support a significant structural discontinuity between TEM18 and TEM16/17 (see Figure 3-13). Discussions of available

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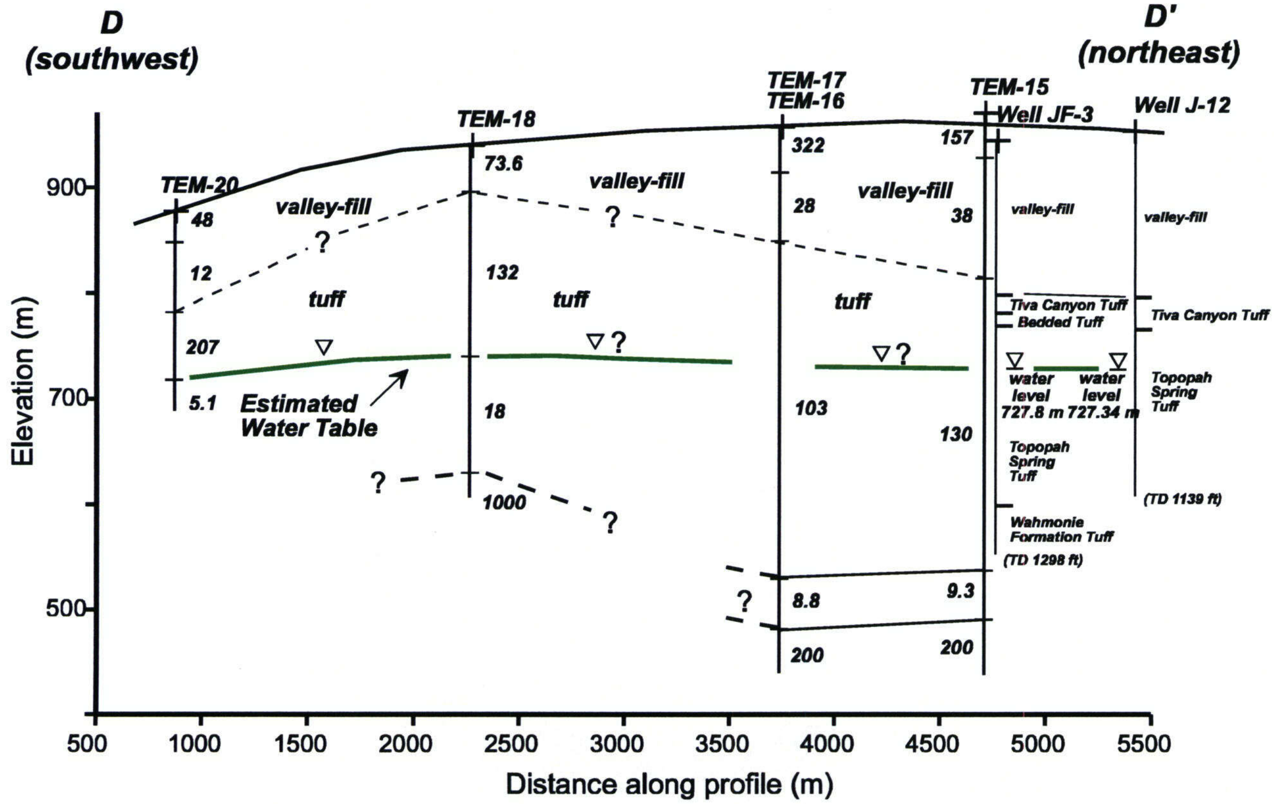

Figure 3-13. Electrical Resistivity Cross Section for Transect D-D' (see Figure 3-2). Numbers With Parenthesis on the Figure Represent Chargeabilities in mV/V and Numbers Without Parenthesis Represent Electrical Resistivities in Ohm-m. NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

magnetic data for this region are reserved for a followup report on gravity and magnetic studies in the region. Possible structural discontinuities along this transect will be further addressed in a followup report that discusses magnetic data collected in the region.

On the basis of well logs at Wells JF–3 and J–12, valley-fill deposits are assumed to overlay the Tiva Canyon Tuff across the transect. The apparent decrease in electrical resistivities modeled along the lateral flanks of the Tiva Canyon Tuff may reflect either increased saturations because of lateral drainage along the tuff valley-fill contact or increased clay content with depth. Unfortunately, no data exist to investigate these possibilities.

The estimated elevation of the water table along D-D' was also compared to the water table contour map of Hill, et al. (2002). The comparison (Figure 3-14) shows that the estimated elevations of the water table at TEM18 and TEM20 correlate well with the water table contour model of Hill, et al. (2002).

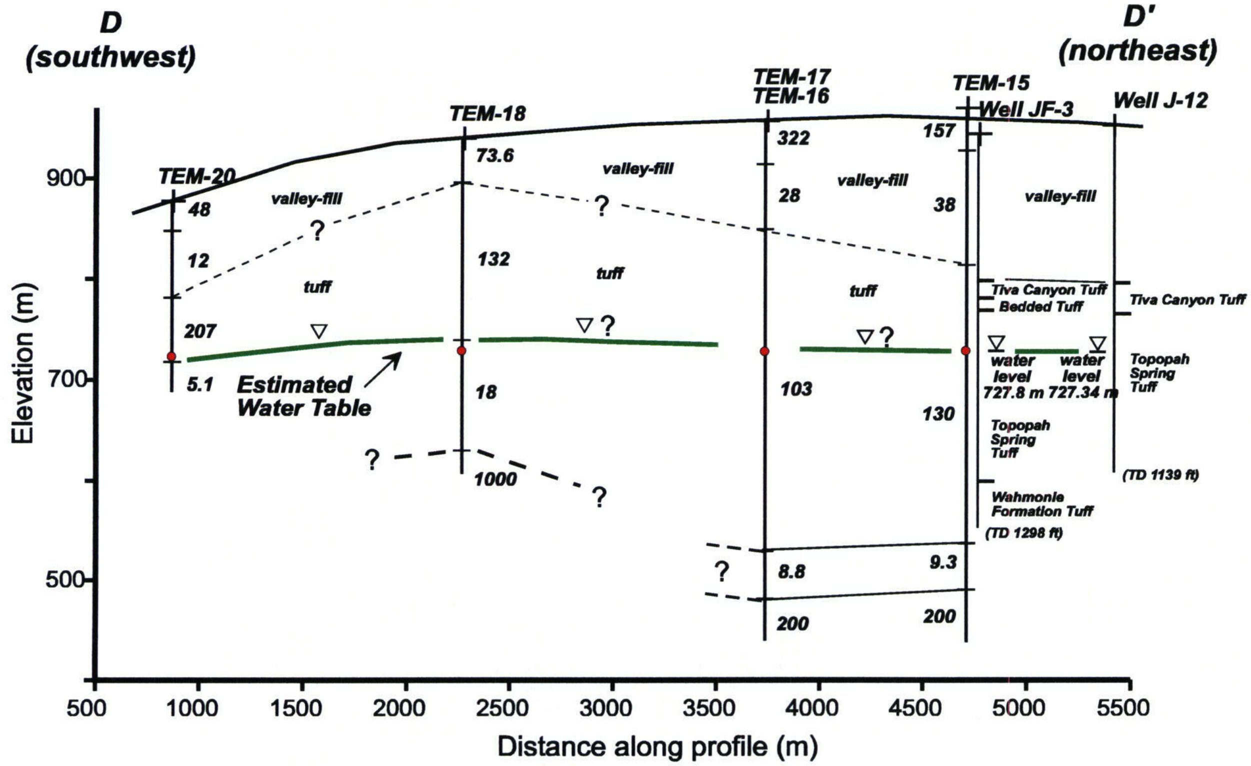

Figure 3-14. Comparison of Estimated Water Table Elevations for Transect D-D' with Estimated Water Table Elevations from Hill, et al. (2002) Represented by Red Dots. Numbers With Parenthesis on the Figure Represent Chargeabilities in mV/V and Numbers Without Parenthesis Represent Electrical Resistivities in Ohm-m. NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

3.2.3.7 Transect E-E'

Transect E-E' extends in a southeasterly direction from the Lathrop Wells cinder cone to the Amargosa Town C Well (Figure 3-2). Recorded water levels at Nye County Early Drilling Program Well 15P and the Amargosa Town C Well are used to evaluate the appropriateness of the models. Transect E-E' includes soundings TEM1/IP1, TEM27/TEM28, TEM29/TEM30/IP4, TEM31/TEM32, and TEM33/TEM34 as well as U.S. Geological Survey electrical resistivity soundings USGS-20 and USGS-110 (Greenhaus and Zablocki, 1982). TEM1/IP1 and TEM29/TEM30/IP4 facilitate simultaneous inversion of time-domain electromagnetic and induced polarization data, while the time-domain electromagnetic pairs facilitate simultaneous inversion of 300 × 300-m [984 × 984 ft] and 40 × 40-m [131 × 131 ft] time-domain electromagnetic data sets. Data from USGS 20 and USGS 110 (Greenhaus and Zablocki, 1982) are inverted in this work using a single data set inversion strategy. The electrical resistivity cross section generated for this transect is illustrated in Figure 3-15.

The confidence limits on model parameters determined using simultaneous inversion are generally narrow and therefore, are, viewed as well constrained (see CNWRA Scientific Notebook 317E). As noted earlier, TEM1/IP1 is influenced by strong lateral variations in

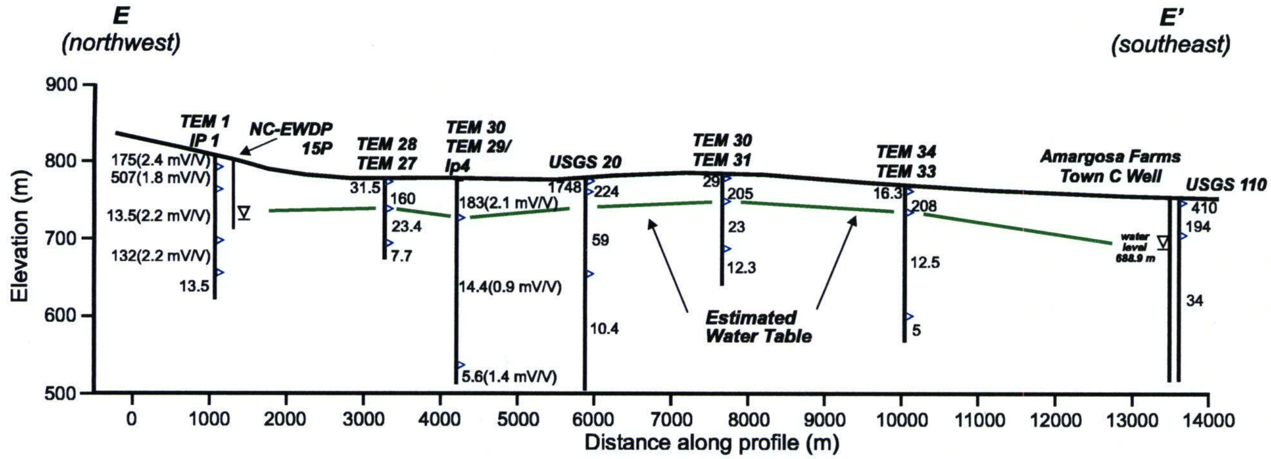

Figure 3-15. Electrical Resistivity Cross Section for Transect E-E' (see Figure 3-2). Numbers With Parenthesis on the Figure Represent Chargeabilities in mV/V and Numbers Without Parenthesis Represent Electrical Resistivities in Ohm-m. NOTE: Scale information provided in meters; for conversion use 1 m = 3.281 ft.

subsurface electrical resistivity and, therefore, does not provide a realistic model of the subsurface at the location of the sounding. Although the upper electrical resistivity layers of model USGS 110 are interpreted as reasonably well constrained, the model developed for USGS 20 displays wide confidence limits and therefore, is, viewed as poorly constrained. The models generally indicate the near-surface environment is electrically resistive. This high electrical resistivity results largely from the low moisture content of the valley-fill as well as lithologic variations. The transition from high to low electrical resistivity modeled at each sounding appears to be relatively consistent and correlates reasonably well with measured water levels. Note the difference in elevation between the estimated elevation of the water table at TEM33/TEM34 and the measured water table at Amargosa Town C well may reflect the drawdown cone at the Amargosa Town C Well. It should also be noted the possibility of clay layers at depth is indicated by the IP4 Well data (see normalized chargeability in Table 3-5). Unfortunately, there are no nearby boreholes to support this assertion.

3.3 Summary

This chapter summarized the findings of electrical and electromagnetic methods used to map the subsurface electrical resistivity structure of southern Fortymile Wash and northern Amargosa Valley. As noted in the introduction to this chapter, this work has two objectives, (i) to explore the capability of the time-domain electromagnetic resistivity depth sounding method to map hydrogeologic (including the water table) and geologic targets at depths greater than 100 m [328 ft] in the thick valley-fill and bedrock located south of Yucca Mountain and, (ii) based on successful completion of the first objective, use a suite of geophysical tools, including the time-domain electromagnetic resistivity depth sounding method, to map hydrogeologic and geologic targets important for assessing repository safety in data-sparse regions south of the proposed repository location.

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Table 3-5. Electrical Resistivity Model for Sounding Station TEM29/TEM30/IP3 Based on Simultaneous Inversion of Time-Domain Electromagnetic Resistivity Sounding Data, Induced Polarization Data, and Schlumberger D.C. Depth Sounding Data				
Layer	Electrical Resistivity (ohm-m)	Chargeability (mV/V)	Thickness (m)	Normalized Chargeability (μS/m)×100
1	183	2.1	47.6 [156.3 ft]	1.2
2	14.4	0.9	190.5 [625 ft]	6.4
3	5.6	1.4	—	25.0

To address the first objective, a time-domain electromagnetic resistivity depth sounding survey was performed between the Nevada Test Site and the community of Amargosa Farms (Figure 3-2). The results produced an electrical resistivity cross section of the subsurface that showed reasonable correlation with data obtained from several sources. Although the cross-section reproduced the large-scale geologic trends of the region, the predictive accuracy of the model suffered because of limited modeling constraints. As a result, uncertainty in the water table elevations inferred from modeling the time-domain electromagnetic data is observed to be on par with the observed range in water table elevations {~20 m [66 ft]} measured along the portion of the transect north of U.S. Highway 95 (Hill, et al., 2002).

Based on the potential of the time-domain electromagnetic resistivity depth sounding approach to map hydrologic targets south of Yucca Mountain, the method was included in a suite of geophysical techniques that included induced polarization and Schlumberger D.C. electrical resistivity depth sounding to map hydrologic and geologic targets in southern Fortymile Wash and northern Amargosa Valley. By using data from these varied sources, additional constraints can be included in the modeling process to improve subsurface characterization.

This suite of measurements was included in a series of electrical resistivity surveys performed in southern Fortymile Wash and northern Amargosa Valley (Figure 3-2) during 1999. Results from the five transects showed the hydrogeologic and geologic data generated correlated well with independent sources of data. Where this suite was not employed and where additional modeling constraints were not available, model nonuniqueness illustrated by large parameter uncertainties was generally observed (see CNWRA Scientific Notebook 317E). In several instances, models generated with these conditions correlated poorly with independent sources of data (i.e., borehole data and groundwater elevations). Although the modeling results obtained from the 1999 survey were generally more accurate compared to the 1998 survey, the accuracy of water table estimates are still found to be less than that required to support detailed groundwater flow and transport modeling in support of regulatory decision making at Yucca Mountain.

In addition to supporting water table mapping, the integrate modeling strategy also supported delineating hydrostratigraphic units. In particular, the presence of clay units beneath the transects appear to be confirmed by induced polarization measurements. Other hydrostratigraphic delineations also appear to be delineated along the transect, in particular, the tuff/valley-fill interface. These potential interfaces will be further explored in a followup report on

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gravity and magnetic studies in the region. These results from these two reports are expected to yield an improved hydrostratigraphic characterization of the region. This improved characterization could lead to further constraints on groundwater flow paths through southern Fortymile Wash and northern Amargosa Valley.

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4 CONCLUSIONS AND FUTURE WORK

Several conclusions can be drawn from this work.

- Results from electrical resistivity mapping studies show the simultaneous inversion approach is capable of producing an electrical resistivity map of the subsurface that correlates well with data obtained from various sources. Although the map reproduced the large-scale geologic and hydrologic trends of the region, the accuracy of the models is insufficient to support water table mapping at the level of accuracy required for hydrogeologic modeling in the Yucca Mountain region. Observations indicate uncertainty in water table elevations inferred from modeling may be greater than the observed range in water table elevations measured in the region.

- Although the integrated suite of electrical measurements performed in this work may not support water table mapping at the level of precision required for hydrogeologic modeling, the integrated approach appears to support hydrostratigraphic mapping of geologic units at a level of precision suitable for incorporation in hydrogeologic models.

4.1 Future Work

Several areas of future study have been identified.

- Complete models of gravity and magnetic transects and verify all transects against geologic data from Nye County Early Warning Drilling Program

- Address nonuniqueness modeling concerns identified in this work by also considering models based on magnetic data (see previous bullet)

- Use the ground magnetic and aeromagnetic data to verify the cross sectional models proposed by Spengler and Chornack (2002)

- Update the U.S. Nuclear Regulatory Commission and the Center for Nuclear Waste Regulatory Analyses hydrostratigraphic framework model using the models based on recent electrical resistivity, magnetic and gravity surveys

- Integrate the tuff/valley-fill contact information into performance assessment calculations

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