

# Deep Resistivity Structure of Mid Valley, Nevada

## Test Site, Nevada

By Erin L. Wallin, Brian D. Rodriguez, and Jackie M. Williams

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Altitude, as used in this report, refers to distance above the vertical datum.

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#### Introduction

The U.S. Department of Energy (DOE) and the National Nuclear Security Administration (NNSA) at their Nevada Site Office (NSO) are addressing ground-water contamination resulting from historical underground nuclear testing through the Environmental Management (EM) program and, in particular, the Underground Test Area (UGTA) project.

From 1951 to 1992, 828 underground nuclear tests were conducted at the Nevada Test Site northwest of Las Vegas (DOE UGTA, 2003). Most of these tests were conducted hundreds of feet above the ground-water table; however, more than 200 of the tests were near, or within, the water table. This underground testing was limited to specific areas of the Nevada Test Site including Pahute Mesa, Rainier Mesa/Shoshone Mountain (RM-SM), Frenchman Flat, and Yucca Flat.

One issue of concern is the nature of the somewhat poorly constrained pre-Tertiary geology and its effects on ground-water flow in the area subsequent to a nuclear test. Ground-water modelers would like to know more about the hydrostratigraphy and geologic structure to support a hydrostratigraphic framework model that is under development for the Rainier Mesa/Shoshone Mountain (RM-SM) Corrective Action Unit (CAU) (National Security Technologies, 2007).

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During 2003, the U.S. Geological Survey (USGS), in cooperation with the DOE and NNSA-NSO collected and processed data at the Nevada Test Site in and near Yucca Flat (YF) to help define the character, thickness, and lateral extent of the pre-Tertiary confining units. We collected 51 magnetotelluric (MT) and audio-magnetotelluric (AMT) stations for that research (Williams and others, 2005a, 2005b, 2005c, 2005d, 2005e, and 2005f). In early 2005 we extended that research with 26 additional MT data stations (Williams and others, 2006) located on and near Rainier Mesa and Shoshone Mountain (RM-SM). The new stations extended the area of the hydrogeologic study previously conducted in Yucca Flat, further refining what is known about the pre-Tertiary confining units. In particular, a major goal was to define the extent of the upper clastic confining unit (UCCU). The UCCU is composed of late Devonian to Mississippian siliciclastic rocks assigned to the Eleana Formation and Chainman Shale (National Security Technologies, 2007). The UCCU underlies the Yucca Flat area and extends southwestward toward Shoshone Mountain, westward toward Buckboard Mesa, and northwestward toward Rainier Mesa. Late in 2005 we collected data at an additional 14 MT stations in Mid Valley, CP Hills, and northern Yucca Flat. That work was done to better determine the extent and thickness of the UCCU near the boundary between the southeastern RM-SM CAU and the southwestern YF CAU, and also in the northern YF CAU. The MT data have been released in a separate U.S. Geological Survey report (Williams and others, 2007).

The Nevada Test Site magnetotelluric data interpretation presented in this report includes the results of detailed two-dimensional (2-D) resistivity modeling for each profile and inferences on the three-dimensional (3-D) character of the geology within the region.



Figure 1a and 1b. Profiles and magnetotelluric stations in and near Mid Valley and North

Yucca Flat, Nevada Test Site, Nevada (modified from Slate and others, 1999).



Figure 1a and 1b. Profiles and magnetotelluric stations in and near Mid Valley and North

Yucca Flat, Nevada Test Site, Nevada (modified from Slate and others, 1999).

#### **Electrical Rock Properties**

Electromagnetic geophysical methods detect variations in the electrical properties of rocks, in particular, electrical resistivity, whose units are ohm-meters  $[\Omega m]$ , or its inverse, electrical conductivity with units of Siemens/meter or S/m. Electrical resistivity can be correlated with geologic units on the surface and at depth using lithologic logs to provide a three-dimensional picture of subsurface geology. In the upper crust, the resistivities of geologic units are largely dependent upon their fluid content, pore-volume porosity, interconnected fracture porosity, and conductive mineral content (Keller, 1987). Although there is not a one-to-one relationship between lithology and resistivity, there are general correlations that can be made using typical values, even though values can be found at other localities that may fall outside of the ranges presented in this section (Palacky, 1987). Fluids within the pore spaces and fracture openings, especially if saline, can reduce resistivities in what would otherwise be a resistive rock matrix. Resistivity can also be lowered by the presence of electrically conductive clay minerals, graphitic carbon, and metallic mineralization. It is common, for example, for altered volcanic rocks to contain replacement minerals that have resistivities ten times lower than those of the surrounding rocks (Nelson and Anderson, 1992). Fine-grained sediments, such as clay-rich alluvium, marine shales, and other mudstones, are normally conductive, with resistivities ranging from a few  $\Omega$ m to tens of  $\Omega$ m (Keller, 1987; Palacky, 1987). Metamorphic rocks (non-graphitic) and unaltered, unfractured igneous rocks are normally moderately to highly resistive (a few hundred to thousands of  $\Omega$ m). Carbonate rocks can have similarly high resistivities depending on their fluid content, porosity, and impurities (Keller, 1987; Palacky, 1987). Fault zones may be moderately conductive (tens of  $\Omega m$ ) when composed of rocks fractured enough to have hosted fluid transport and consequent mineralogical alteration (Eberhart-Phillips and others, 1995). At greater depths, higher subsurface temperatures cause higher ionic mobility that reduces rock resistivities (Keller, 1987; Palacky, 1987). Tables of electrical

resistivity for a variety of rocks, minerals, and geological environments may be found in Keller (1989) and Palacky (1987).

#### **Magnetotelluric Method**

The MT method is a passive surface geophysical technique that uses the Earth's natural electromagnetic fields to investigate the electrical resistivity structure of the subsurface from depths of tens of meters to tens of kilometers (Vozoff, 1991). Natural variations of the Earth's magnetic and electric fields are measured and recorded at each MT station. Worldwide lightning activity at frequencies of about 1 to 20,000 Hertz (Hz) and geomagnetic micro-pulsations at frequencies of about 0.0001 to 1 Hz provide the majority of the signal sensed by the MT method.

The orthogonal horizontal electric and magnetic field components (Ex, Ey, Hx, and Hy) and the vertical magnetic field component (Hz) are recorded. MT data are normally rotated into directions that are parallel and perpendicular to the subsurface geologic strike. These are usually the principal directions that correspond to the direction of maximum and minimum apparent resistivity. For a 2-D Earth, in which the Earth's resistivity structure varies with depth and in one lateral direction, the analysis is simplified. The MT fields can be decoupled into transverse electric (TE) and transverse-magnetic (TM) modes. In this case, 2-D resistivity modeling is generally computed to fit both modes. When the geology satisfies the 2-D assumption and the MT profile is perpendicular to the geologic strike, while the data for the TE mode represents the electric field parallel to geologic strike, while the data for the TM mode represents the electric field across strike. The MT method is well suited for studying complicated geological environments because the electric and magnetic field transfer functions are sensitive to vertical and horizontal variations in resistivity. The method is capable of establishing whether the electromagnetic fields are responding to subsurface rock bodies of effectively 1, 2, or 3

dimensions. An introduction to the MT method and references for a more advanced understanding are in Dobrin and Savit (1988), Vozoff (1991), and Kaufman and Keller (1981).

#### Magnetotelluric Data

The MT stations were grouped into four sounding profiles (fig. 1) that were named for the region and predominant trend of the profile, Mid Valley east to west (MVEW), Mid Valley north to south (MVNS), the southernmost Mid Valley to Yucca Flat profile trending east to west (YFS), and a northwest to southeast profile in the northern part of Yucca Flat (YFN). Within the text the stations are referred to by an integer name, e.g. MT station 52. In the 2-D profiles included in the discussion, the integer (e.g. 52) may be preceded by 0 or 1. For example, station 52 might be called 052 or 152 when it is shown on a 2-D profile.

During the inversion and modeling process, each station was rotated to a fixed angle determined by the given nominal profile orientation or the tipper strike direction (Williams and others, 2005c, 2005d, 2005e, and 2007) that is generally subparallel to the local geologic structure. Rotation of the impedance tensor allows for decoupling into the TE and TM modes. Table 1 lists the nominal profile azimuths and the fixed, orthogonal angles of rotation assigned for each station.

| Table 1. | MT | profile | azimuths | and | angles | of rotat | tion a | pplied | during | processing |  |
|----------|----|---------|----------|-----|--------|----------|--------|--------|--------|------------|--|
|----------|----|---------|----------|-----|--------|----------|--------|--------|--------|------------|--|

| Profile Name | MT Stations in Profile | Profile<br>Direction<br>(degrees) | Fixed Angle of Rotation<br>(degrees) |
|--------------|------------------------|-----------------------------------|--------------------------------------|
| MVEW         | 52-57,16-19            | 076                               | 76                                   |
| MVNS         | 10,58,54,2,59          | 169                               | 76                                   |
| YFS          | 52, 1-8, 60, 61        | 090                               | 90                                   |
| YFN          | 45,46, 62,64           | 129                               | 129                                  |
| YFN          | 63,64,65               | 129                               | 39                                   |

As mentioned above, the raw, field-processed MT data are presented in separate U.S. Geological Survey reports (Williams and others, 2005c, 2005d, 2005e, and 2007). Those reports included the following MT parameter plots for each station: Apparent Resistivity, Impedance Phase, Rotation Angle, Impedance Skew, Multiple Coherency, Impedance Polar Plots, Tipper Magnitude, Tipper Strike, and HzHx and HzHy Coherency.

The Mid Valley magnetotelluric impedance polar plots (Williams and others, 2005c, 2005d, 2005e, and 2007) provide a measure of MT data dimensionality (Reddy and others, 1977). For 1-D resistivity structures, the principal impedance polar diagram is a circle. For 2-D or 3-D resistivity structures, the principal impedance polar diagram elongates either parallel or perpendicular to strike direction. Over resistors, the principal impedance polar diagram elongates perpendicular to strike direction, and over conductors, it elongates parallel to strike direction. For 2-D resistivity structures, the additional impedance polar diagram attains the shape of a symmetric cloverleaf. For 3-D resistivity structures, the impedance polar diagram elongates in one direction and can be considered more strongly 3-D as its amplitude becomes comparable to that of the principal impedance polar diagram.

### **Two-Dimensional Resistivity Modeling**

Wannamaker (1983) found that MT responses in the northern Basin and Range region are fundamentally 3-D in nature. Wannamaker and others (1984) demonstrated that approximating 3-D structure beneath a centrally located profile with 2-D modeling is best achieved when fitting the TM curve even at the expense of a poor fit of the TE curve. However, because TM data are relatively insensitive to the depth extent of a subsurface body (Eberhart-Phillips and others, 1995), the depths to the base of the bodies in the model are not well constrained. Drill hole data from the NTS suggest 3-D structures (Cole and others, 1997). Asch and others (2006b) and Williams and others (2007) found that

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MT responses in Yucca Flat and Mid Valley are also fundamentally 3-D. Hence, clarifying the model limits with 3-D resistivity modeling may be necessary.

Using data from both the 2005 Mid Valley MT data set (Williams and others, 2007) and the 2003 Yucca Flat MT data set (Williams and others, 2005c, 2005d, and 2005e) 2-D resistivity models were constructed for each profile. The data stations used for each profile are indicated in figure 1. Initially, 2-D inversions of the transverse magnetic data were conducted using the computer program RLM2DI (Mackie and others, 1997, and Rodi and Mackie, 2001). This was followed by the application of the 2-D forward modeling algorithm program, PW2D, developed by Wannamaker and others (1987). The results of the RLM2DI 2-D inversion were used as the initial input model for the forward modeling, PW2D, where a sensitivity analysis was performed on the conductive structures derived from the inversion results.

RLM2DI uses a finite-difference network analog to the Maxwell's equations governing magnetotellurics to calculate the forward solution. A non-linear conjugate-gradient-optimization approach is then applied directly to the minimization of the objective function for the inverse problem (Mackie and others, 1997, and Rodi and Mackie, 2001). PW2D is a stable finite-element algorithm that simulates transverse electric and magnetic fields using a linear basis across each finite element (Wannamaker and others, 1987). The inversion algorithm, RLM2DI, was usually allowed to batch-run at least 25 iterations in order to reduce the root mean squared (RMS) error between the field data and the numerical model to a reasonable value. The number of trial-and-error forward modeling (PW2D) tests of model features generally depended on sensitivity testing of deeper conductors found in the inversion results.

Table 2 lists the number of horizontal and vertical nodes that were used in the modeling for each profile. The variability in the number of nodes from profile to profile is due to the different number of

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MT stations along each profile and the length of the profile. In all cases the number of horizontal and vertical nodes necessary for the iterative forward modeling (PW2D) algorithm to accurately model the Mid Valley subsurface resistivity distribution is greater than the number of nodes required by the inversion algorithm (RLM2DI). This is a function of fundamental differences between how finite-difference and finite-element algorithms handle the numerical boundary conditions and, subsequently, how the electric and magnetic fields are calculated across the mesh.

**Table 2.** 2-D inversion (RLM2DI) and forward (PW2D) numerical model meshes for eachprofile. Columns show the number of horizontal nodes and vertical nodes in each model mesh.Ten additional vertical nodes were used to model the overlying air layer.

| Profile | RLM2       | 2DI      | PW2D       |          |  |
|---------|------------|----------|------------|----------|--|
| No.     | Horizontal | Vertical | Horizontal | Vertical |  |
| MVEW    | 64         | 59       | 95         | 64       |  |
| MVNS    | 69         | 59       | 95         | 64       |  |
| YFS     | 71         | 59       | 101        | 62       |  |
| YFN     | 77         | 59       | 106        | 64       |  |

The edges of the model were extended beyond about 1,000 km horizontally and about 300 km vertically to assure that the necessary boundary conditions are met. The resolution of the resistivity boundaries used for each model is somewhat subjective. If different resistivities were used, then boundary positions and layer depths were adjusted to achieve similar fits to the observed data. The extreme case would be to use a model with a "continuous" resistivity gradient from low to high resistivities. The resolution of the resistivity boundaries is also, in part, a function of the model grid mesh design. We have attempted to keep each model simple. For each MT profile the model depth is relative to the Earth's surface.

## Discussion

The 2005 NTS magnetotelluric study was a continuation of the Yucca Flat investigation that was initiated in 2003. We increased the data coverage in Mid Valley and included an additional profile in northern Yucca Flat to further characterize the subsurface across Mid Valley and examine the relationship between the younger, shallow volcanic units and the older, deeper carbonate units. The area from Rainier Mesa in the northwest down through Mid Valley in the south and eastward into Yucca Flat includes many Tertiary volcanic units that overlie and, in some cases, pinch out, or abut, against the Eleana Fm. (late Devonian-Mississippian age) and Chainman Shale (Mississippian age) siliciclastic units (Laczniak and others, 1996). Two of the 2005 Mid Valley profiles crossed the southern half of Mid Valley, with one profile traversing the CP Hills into southern Yucca Flat and the other profile crossing into northern Frenchman Flat. A third, north-to south-trending profile, crossed the center of Mid Valley, and a fourth profile traversed Quartzite Ridge into northern Yucca Flat.

Yucca Flat and Mid Valley are alluvial basins that formed as a consequence of regional crustal extension that was oriented generally east-west (Cole and others, 1997). The overall geometry of the Yucca Flat basin was largely controlled by down-to-the-east displacements on the general northerly striking Carpetbag, Yucca, and Topgallant fault systems that resulted in down-dropping and westward tilting of Miocene strata. Profiles MVEW and YFS traverse the Mine Mountain Fault (Slate and others, 1999) and the CP Thrust Fault. Major faults near the YFN profile include the Tippinip, the CP Thrust, and Yucca Faults. Numerous smaller faults in the two basins also have northerly trends. These structural trends are displayed on Plate 1, *Sub-Crop Geologic Map of the Pre-Tertiary Rocks in Yucca Flat and Northern Frenchman Flat Areas, Nevada Test Site, Southern Nevada*, published by Cole and others (1997). This map was modified in Plate 1 to show the interpreted extent of UCCU Eleana Formation and Chainman Shale based on this study and Asch and others (2006b). The three Mid Valley

profiles and the northern Yucca Flat profile are also indicated on this map, along with all MT station locations from 2003 and 2005. The geology in this region is quite complicated, as demonstrated by drill holes and rock outcrops that provide ground truth. The complex Cenozoic and pre-Cenozoic stratigraphy of the Nevada Test Site have typically been combined into hydrogeologic groupings of aquifers and confining units (Winograd and Thordarson, 1975; Belcher, 2004; and National Security Technologies, 2007).

In the MT interpretations presented below, hydrogeologic groupings are used to label the inferred geologic units. Table 3 lists the abbreviated label names and the corresponding hydrologic grouping along with bulk average resistivities obtained from NTS wells: UE1L, UE14b, UE16d, UE17e, ER6-1, ER6-2, ER7-1, ER8-1, ER12-1, and ER12-2. The names are derived from Table 4-4 of the Bechtel Nevada report on the hydrostratigraphic framework of the Yucca Flat area (National Security Technologies, 2007).

**Table 3.** Hydrostratigraphic and hydrogeologic groups. Bulk average resistivities in Ωm are from wells UE1L, UE10aa, UE14b, UE16d, UE17e, ER6-1, ER6-2, ER7-1, ER8-1, ER12-1, ER12-2, ER12-3, and ER19-1. S is saturated; U is unsaturated. \*\*Well log data not available.

| Hydrogeologic grouping   | Abbreviation | Ohm-m                        |
|--|--------------|------------------------------|
| Alluvial aquifer   | А            | 50-300(U)/30(S)              |
| Volcanic aquifer (vitric tuff units and welded tuff aquifer)           | VTA          | 150-500(U)/200(S)            |
| Welded tuff aquifer (partially to densely welded ash flow tuff)        | WTA          | 20(S)                        |
| Volcanic tuff confining unit (zeolitized bedded tuffs)                 | TCU          | 30(U)/15-20(S)               |
| Mesozoic granitic confining unit (Gold Meadows and Climax plutons)     | MGCU         | 100(U)                       |
| Upper carbonate aquifer (Tippipah Limestone)                           | UCA          | **                           |
| Upper clastic confining unit-Eleana Fm,(Chert-lithic/carbonate facies) | UCCU-E       | 10-500(S)/200-1500(S)        |
| Upper clastic confining unit-Chainman Shale (Shale/overturned)         | UCCU-C       | 10-30(S)/500-5,000(S)        |
| Lower carbonate aquifer (many Paleozoic carbonate formations)          | LCA          | 100-7,000(U)/2,000-15,000(S) |
| Lower clastic confining unit (Cambrian Carrara/upper Proterozoic)      | LCCU         | 50-1,000(S)/500-10,000(S)    |

The geologic interpretations of the 2-D profile electrical resistivities and structures under Mid Valley and northern Yucca Flat are presented in this section (Figs. 2–5). The calculated response of the

resistivity models generally fit the observed TM data better than the observed TE data (see Appendix A), although fits to the TE data were satisfactory for stations where the MT data was 1-D, 2-D, or where the electrical strike was not sub-parallel to the MT profile strike. However, because of the widespread 3-D character of the survey area, as indicated by the MT parameters (Williams and others, 2005c, 2005d, 2005e and 2007), only the gross structure determined by the models is discussed. Vertical field data (the tipper strike) were also used to determine which measured component represented the TM mode and which represented the TE mode (Williams and others, 2005c, 2005d, 2005e, and 2007).

The interpretations presented reflect the diffusive nature of the MT fields and the nonuniqueness of the inverse problem. Properties of thin, conductive geologic units at great depths cannot be well determined. A magnetotelluric conductor thickness detectability rule-of-thumb is to use a 10:1 ratio of depth to thickness. For example, at 10 km depth, a conductive unit 1 km thick may be detected. If the unit is less than 1 km thick at 10 km depth, detection is unlikely. Thus, the models in this report are bulk-average representations of the subsurface geology. Although the MT data support these representations, detailed resolution of structures at depth is limited. Due to the large spacing of MT stations it is difficult for the model to resolve dips of different rock units. In some cases a model will display horizontal contacts where the surface geology indicates dipping structures. Again, due to the non-uniqueness of the inverse problem, the observed data fit both the horizontal and dipping models. When possible, personal communication with geologists familiar with the NTS area (Cole, 2007, and Cashman, 2007) were used to improve and constrain the interpretation of hydrogeologic structures.

Appendix A contains, for each profile, the final 2-D models without the interpretations shown in figures 2–5. The model is followed by figures showing the observed and calculated apparent resistivity sounding curves, and finally by figures showing the observed and calculated MT impedance phase curves. Double-ended arrows are added to the resistivity curves indicating electromagnetic response to

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3-D geology, based on polar impedance plots presented in Williams and others (2005c, 2005d, 2005e, and 2007). Indications of geologic structure sub-parallel to the MT profile direction, based on tipper strike data (Williams and others, 2005c, 2005d, 2005e, and 2007) have also been annotated.

The correlation of resistivity cross-sections based on MT data with hydrogeologic units is based on well logs and surface geology, mainly rocks cropping out in the vicinity of the MT cross-section. The upper carbonate aquifer (UCA, consisting of the Tippipah Limestone of Pennsylvanian and lower Permian age) are electrically resistive (hundreds to thousands of  $\Omega$ m). The upper part of the lower clastic confining unit (LCCU), consisting of shaley middle Cambrian lower Carrara Fm. (Laczniak and others, 1996) are moderately conductive (tens of  $\Omega$ m). The lower part of the LCCU, late Proterozoic and lower Cambrian, predominately quartzite and sandstone units (Laczniak and others, 1996; Sweetkind and others, 2004), are resistive (hundreds to thousands of  $\Omega$ m). Location names used to describe the traverse of the profiles come from Laczniak and others (1996). Where there is little resistivity contrast between adjacent lithologic units, borehole information and a priori knowledge were used to help constrain the models. The geologic interpretations of the upper clastic confining units (Chainman shale and Eleana Fm.) in the resistivity profile models are not well determined where conductive volcanic tuff confining unit (TCU) overlies conductive UCCU-c (Chainman Shale), where resistive UCCU-e (Eleana Fm.) overlies resistive lower carbonate aquifer formations (LCA) units, or where resistive vitric tuff aquifer (VTA) rock overlies resistive units of the Eleana Fm.

#### Profile MVEW (Stations 52-57, 16-19)

The western end of profile MVEW (Plate 1) is at MT station 52, located south of Shoshone Peak and the entrance to Tiva Canyon. The profile continues east-northeastward across Mid Valley over CP Hills north of The Bench, passing News Nob and ending at station 19 along the northeastern edge of Yucca Lake. Stations 53-57 and 16-18 are projected onto the profile to create a 2-D resistivity model. The hydrogeologic interpretation of the 2-D resistivity model for profile MVEW is presented in figure 2. At the western end of the resistivity model, a thick resistive (100 to 1000  $\Omega$ m) crust is interpreted to be LCA that underlies a thin moderately resistive (100  $\Omega$ m) layer (beneath station 52) interpreted to be UCCU-c (Chainman shale). On top is an inferred thrust of UCCU-e (Eleana Fm.) and LCA, and also a 600 m surficial layer of conductive (50  $\Omega$ m) rock (beneath and east of station 52) inferred to be TCU. LCA, UCCU-e (Plate 1), and TCU all crop out nearby. UCCU-c is inferred from outcrops west of station 52 (Slate and others, 1999). The station spacing was too large between stations 52 and 53 to accurately determine the western edge of UCCU-e. Between stations 53 and 54, several hundred meters of moderately resistive (100 to 200  $\Omega$ m) VTA, seen in nearby wells UE14b and UE14a, overlies inferred UCCU-c and LCA. East of station 54 there appears to be about a 1-km thick block of moderately conductive (20 to 50  $\Omega$ m) TCU that is penetrated by wells UE14b and UE14a. TCU appears to extend eastward near station 57 from 300 to 1,300 m depth, covered by about 300 m of moderately resistive (100  $\Omega$ m) WTA near station 56, inferred from exposed WTA to the east. Under station 55 through 17 from about 1,000 m to a maximum of about 5,000 m depth a 1,000-m-thick layer of interpreted UCCU-c and underlying LCA is folded and overturned, forming a large syncline dipping eastward, with the bottom of the fold near 5,000 m depth below station 17 (Cole and Cashman, 1997). The stratigraphic profile under station 57, 16 and 17 consists of several hundred meters of moderately resistive (200 to 500  $\Omega$ m) LCA underlain by about 300 m of overturned LCA that is slightly less resistive (100  $\Omega$ m). These are on top of the folded and altered moderately resistive (100 to 200  $\Omega$ m) UCCU-c (Chainman Shale). Exposures of UCCU-c and LCA between stations 56 and 16, along with these same overturned units seen in well ER6-2, support this interpretation. This structure is surrounded by moderately resistive (100 to 200  $\Omega$ m) LCA. The first 1,200 m of the overturned units, emplaced by westward thrusting of the mapped CP Thrust fault (Plate 1) are penetrated by well ER6-2 between

stations 57 and 16. Without the evidence of overturned units of LCA and UCCU-c seen in well ER6-2, the moderately resistive (100 to 200  $\Omega$ m) inferred folded and overturned UCCU-c could be interpreted as LCA (table 3). It is problematic interpreting where moderately resistive (100 to 200  $\Omega$ m) LCA ends and where moderately resistive (100 to 200  $\Omega$ m) inferred altered UCCU-c begins. Under stations 17-19 lies a thin conductive (10  $\Omega$ m) layer that corresponds to Yucca Lake, overlying 200 to 300 meters of conductive (20 to 50  $\Omega$ m) inferred TCU, with moderately resistive (100 to 200  $\Omega$ m) LCA beginning about 300 m deep under station 17 and about 1,000 m under station 19. TCU and LCA interpretations are constrained by nearby well UE-6d#3.

Almost the entire EM response for each MT station along this profile indicates 3-D geology, as it does for nearly all the MT data at NTS (Williams and others, 2005a, 2005b, 2005c, 2005d, 2005e, 2005f, 2006, and 2007). Although the method of inverting the TM mode of the MT data should give a good 2-D approximation to the 3-D geology, it is possible that some of the layer resistivities and thicknesses may actually increase or decrease in a 3-D resistivity model. Changes in confining unit thicknesses may have a profound effect on ground-water flow models. Changes in layer resistivities may affect geologic interpretations, based on table 3, again having a profound effect on ground-water flow models if thick layers of inferred confining units are re-interpreted to be aquifers. For these reasons, 3-D resistivity modeling of these MT data is recommended.



**Figure 2**. 2-D resistivity modeling results for Profile MVEW model. Refer to table 3 for key to hydrogeologic units.

#### Profile MVNS (Stations 10, 58, 54, 2, 59)

Profile MVNS begins at station 10, located near the intersection of Mine Mountain Road and Mid Valley Road. The profile heads south-southeast across the western half of Mid Valley, ending at station 59, located 1.5 miles north of Lookout Peak. The hydrogeologic interpretation of the 2-D resistivity model for profile MVNS is presented in figure 3. Station 10 is in northern Mid Valley atop thin alluvium overlying a thrust of about 100 m of moderately resistive (100 $\Omega$ m) inferred UCCU-e and about 500 m of resistive (500  $\Omega$ m) inferred LCA over about 500 m of resistive (100-1,000  $\Omega$ m) inferred UCCU-c. A normal fault sub-parallel to the profile between stations 10 and 58 complicates projection of buried structure on the 2-D model. This fault appears as moderately resistive (100  $\Omega$ m) rock between more resistive (200 to 1,000  $\Omega$ m) lower carbonate aquifer formations (LCA). About 300 m of inferred moderately conductive (10 to 50  $\Omega$ m) volcanic tuff confining unit (TCU) is below station 58 that overlies resistive (200 $\Omega$ m) inferred UCCU-c and (200 to 1,000  $\Omega$ m) LCA. About 1 km of moderately conductive (20 to 50  $\Omega$ m) TCU appears as a graben between stations 10 and 58, but its true shape may be complicated by the normal fault sub-parallel to the profile between these stations. There is evidence of nearby thrusted blocks of UCCU-e and LCA exposed southwest of stations 10 and 58, and northeast at Mine Mountain (the Mine Mountain thrust block of Cole and Cashman, 1997). Interpreted LCA depths between stations 10 and 54 were constrained by gravity modeling (Cole and Cashman, 1997). TCU crops out northeast of station 58, and exposures of UCCU-e crop out northeast of station 10 at Mine Mountain (Plate 1). The station spacing north and south of station 58 was too large to determine the northern and southern TCU boundary. A normal fault north of station 54 bounds about 400 m of volcanic aquifer (VTA) above 400 m of conductive (50 Ωm) TCU and 1 km of moderately resistive  $(100\Omega m)$  inferred UCCU-c, that in turn overlies resistive (200-1000  $\Omega m$ ) LCA. Further south, under station 2, about 200 m of resistive (100-200  $\Omega$ m) welded tuff aquifer (WTA) lies above 800 m of 50  $\Omega$ m TCU and 1.5 km of moderately resistive (100 $\Omega$ m) inferred UCCU-c that overlie resistive (200 to 1,000  $\Omega$ m) LCA. Under station 59, about 200 m of WTA overlies about 1 km of conductive (5-50  $\Omega$ m) TCU and 2 km of inferred UCCU-c. VTA and TCU near station 54 are found in nearby wells UE14a

and UE14b (Plate 1). WTA is exposed south of station 2 and all around station 59. UCCU-c between stations 54 and 59 is inferred from outcrops to the east in CP Hills (Plate 1).



**Figure 3**. 2-D resistivity modeling results for Profile MVNS model. Refer to Table 3 for key to geologic unit abbreviations.

#### Profile YFS (Stations 52, 60, 1-8)

The YFS profile (fig. 4) begins at station 52 and runs east, whereas profile MVEW shares its station 52 origin but trends northeast (fig.1). The traverse crosses southern Mid Valley, with station 1 located just north of Jackass Divide. Stations 2 and 3 are on the south edge of Barren Spot. Station 4 is one half mile north of Barren Butte. The profile follows the rugged seasonal stream bed between The Bench and Black Ridge to stations 60, 5, and 6, which are located south of the NTS DAF facility. The profile then crosses Mercury Highway and ends just north of Massachusetts Mountain at station 8. The resistivity values of the 2-D model (fig. 4) indicate lithology in the western half of the profile that is similar to the western end of the nearby MVEW profile. Near station 52, about 600 m of conductive (50  $\Omega$ m) TCU covers a thrust of about 200 m of resistive (200  $\Omega$ m) inferred UCCU-e and 200 m of moderately resistive (200 ohm) LCA. This thrusted block overlies about 100 m of moderately resistive (200  $\Omega$ m) inferred UCCU-c on top of resistive (1,000  $\Omega$ m) LCA. This conductive (50  $\Omega$ m) section of TCU and resistive (200 Ωm) inferred UCCU-c thickens east of station 1 forms a syncline near station 4 whose eastern arm is folded near station 60 from westward thrusting of resistive (200 to 1,000  $\Omega$ m) LCA to within 300 m of the surface. Exposures of TCU, UCCU-c and LCA north of station 60 and mapped CP Thrust (Cole and Cashman, 1997, Plate 1) support this interpretation. Between station 60 and station 5, TCU may thicken to about 1.5 km. The MT data at stations 5 and 6 suffered from electrical noise coming from the DAF facility to the north and a buried powerline nearby of the south, so the thick conductive (50  $\Omega$ m) section beneath these stations is not well determined. It is possible that the stratigraphic section beneath stations 5 and 6 may be similar to that found near station 7 where LCA is only at a few hundred meters depth as seen in nearby Test Well C (Plate 1).



**Figure 4**. 2-D resistivity modeling results for Profile YFS model. Refer to table 3 for key to geologic unit abbreviations.

#### Profile YFN (Stations 45, 46, 62-65)

Profile YFN begins north of Yucca Flat at station 45 between Twin Peaks and Survey Butte. Station 46 and 62 are on the lowest slopes of Quartzite Ridge. As the profile extends to the southeast it traverses south of Smoky Hills (station 63) into the northern part of Yucca Flat (station 64) ending at station 65, which is just east of Yucca Fault and 1.5 miles south of Sedan Crater. Between stations 62 and 63, the profile crosses over the Carpetbag Fault and is near exposed sections of the Tippinip Wrench and CP Thrust Faults. The hydrogeologic interpretation of the 2-D model for profile YFN is presented in figure 5. Beneath station 45, about 1 km of moderately resistive (100 Ωm) LCA is thrust over about 1 km of resistive (200  $\Omega$ m) inferred UCCU-e. Under stations 46 and 62, about 2 km of resistive (200 to 1,000  $\Omega$ m) UCCU-e overlies moderately resistive to resistive (100-500  $\Omega$ m) LCA. The resistivity model exhibits a horizontal contact between LCA and UCCU-e. However, the resolution limits of the resistivity contrast at this depth do not preclude the anticline in UCCU-e mapped at the surface (Cole, pers. comm., 2007). Exposure of UCCU-e and penetration of UCCU-e to about 2.0 km depth in well ER12-2 southwest of station 62 (Plate 1) support this interpretation. East of station 62 and the down-tothe-east Carpetbag Fault, about 0.5 km overburden is comprised of alluvium (AA) and vitric tuff aquifer (VTA), while about 2- to 3-km of buried resistive (200  $\Omega$ m) LCA overlies 0.6 km of conductive (20 Ωm) LCCU (lower Carrara Fm.), with resistive LCCU (lower Cambrian to Late Proterozoic). Geologic interpretations indicate that these units dip approximately 30° west or southwest (Cole, pers. comm.). East of station 64 is the subvertical Yucca Fault. In the trend of this profile (S51E), the LCA and Carrara formation have about 0.5 km of throw relative to their depths under station 64. Between stations 64 and 65, about 1 km of AA and VTA cover 2.0 km of buried resistive (200  $\Omega$ m) LCA. The LCA overlies about 0.6 km of conductive (20 Ωm) LCCU (lower Carrara Fm.), with resistive (1,000  $\Omega$ m) LCCU (lower Cambrian to Late Proterozoic) at its base. Exposure of LCA in the Smoky Hills north of station 63 (Plate 1) supports thrusting of LCA into the upper km. Northeast of the profile, exposure of LCCU, composed of Carrara Formation and Zabriskie Quartzite (Ccz), and Wood Canyon Formation and Stirling Quartzite (Zws), shows the southwest-tilted lower Paleozoic-Proterozoic section relatively intact.



**Figure 5**. 2-D resistivity modeling results for Profile YFN model. Refer to table 3 for key to geologic units.

### Summary

The magnetotelluric (MT) data stations collected by the USGS in 2003 and in 2005 have helped to characterize the deep resistivity structure in the pre-Tertiary geology beneath Mid Valley, CP Hills

and the northern Yucca Flat areas of the Nevada Test Site. The character, thickness, and lateral extent of the Chainman Shale and Eleana Fm. that comprise the Upper Clastic Confining Unit (UCCU) are generally characterized in the upper 5 km across the 2-D profiles. The geologic interpretations of the upper clastic confining units (Chainman shale and Eleana Fm.) in the resistivity profile models are not well determined where conductive volcanic tuff confining unit (TCU) overlies conductive UCCU-c (Chainman Shale), where resistive UCCU-e (Eleana Fm.) overlies resistive lower carbonate aquifer formations (LCA) units, or where resistive vitric tuff aquifer (VTA) rock overlies resistive units of the Eleana Fm. The outlined extent of UCCU-e and UCCU-c presented on Plate 1 results from compilation and refinement of resistivity profiles and interpretations of hydrogeologic structure obtained from this study; publications by Asch and others (2006a and 2006b), Cole and others (1997), and Cole and Cashman (1997); well-logs; and personal communication with James Cole and Patricia Cashman. The interpreted absence of Chainman Shale in the YFN profile constrains its northern boundary to the northernmost extent of the CP Thrust Fault. Previous MT surveys (Asch and others, 2006b), coupled with well-log control, delineated the eastern Chainman Shale boundary along the CP Thrust Fault south of profile YFN through the center of Yucca Flat all the way south to Mine Mountain. Near MT profile YFN, Eleana Fm. appears to be about 2 km thick west of Carpetbag Fault and absent east of it. A 0.6-km thick shaley member of the lower Carrara Fm. is buried over 2 km deep east of Carpetbag Fault, with orthoquartzite members of lower Cambrian to Late Proterozoic Lower Clastic Confining Units beneath it. These units are thrust upward by the CP Thrust (mid-profile) and dropped down at the southeastern end of the profile by the Yucca Fault. Folded, overturned, and altered Chainman Shale beneath CP Hills to depths of 5 km is exhibited by the MVEW profile delineating its eastern extent a few km east of CP Hills. Profile MVNS suggests that about a 3-km thick TCU-Chainman Shale sequence may continue south beyond the southernmost MT station. Our interpretation of profile YFS

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constrains the southeastern extent of Chainman Shale south of the CP Hills. Profile YFS also shows a continuous TCU-Chainman Shale sequence from due south of CP Hills to as far west as the westernmost MT station, although it thins from about 2.5 km thickness in southern Mid Valley to 1- to 2-km thickness that includes about 400 m of thrusted UCCU-e and LCA sandwiched between TCU and UCCU-c near the southern edge of Shoshone Mountain. All four MT profiles delineate thrusted Lower Carbonate Aquifer Units to within a few hundred meters of the surface. Previous MT profiles (Asch and others, 2006b) south of profile YFN and north of profile MVEW also showed thrusted Lower Carbonate Aquifer units to within a few hundred meters of the surface east of the CP Thrust Fault, with a composite Upper Clastic Confining Unit west of CP Thrust Fault that is between 0.5 and 2 km thick. Chainman Shale also appears to be thickest (about 2 km) at the southern end of these MT surveys and about 200 m thick at the southern, appears to have the opposite relationship, namely, thickest (about 2 km) at the northern end of these MT surveys and about 200 m thick at the southern end.

The only gap for southerly ground-water flow in the Mid Valley area appears to be south of CP Hills on profile YFS, where Chainman shale and Eleana Fm. are absent and TCU appears to be constrained in the upper 300 m with LCA directly beneath that may be in contact with Quaternary sediments.

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## Appendix A: Two-Dimensional Resistivity Models, Apparent Resistivities, and Phase Data

Appendix A contains, for each profile, the two-dimensional (2-D) resistivity models and the observed and calculated apparent resistivity and phase curves for each station. The models are presented in the following order: MVEW, MVNS, YFS, and YFN. For each, the 2-D resistivity model is shown followed by the resistivity curves and then the phase curves. The three-dimensional (3-D) electromagnetic response to 3-D geology, as it varies with frequency, is indicated by double-sided arrows above the resistivity curves (Williams and others, 2005c, 2005d, 2005e, and 2007). Where the electrical resistivity structure is subparallel to the profile direction, as indicated by tipper strike data ((Williams and others, 2005c, 2005d, 2005e, and 2007), a double-sided arrow is annotated below the resistivity curves.



Figure A1. Profile MVEW, 2-D resistivity depth section model.



**Figure A2a.** Profile MVEW, 2-D resistivity model—observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT apparent resistivity sounding curves. 3-D label indicates three-dimensional character of electromagnetic response. SP label indicates electrical resistivity structure is sub-parallel to the profile direction. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



**Figure A2b.** Profile MVEW, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT apparent resistivity sounding curves. 3-D label indicates three-dimensional character of electromagnetic response. SP label indicates electrical resistivity structure is sub-parallel to the profile direction. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



**Figure A3a.** Profile MVEW, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT phase sounding curves. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



**Figure A3b.** Profile MVEW, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT phase sounding curves. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



Figure A4. Profile MVNS, 2-D resistivity depth section model.



**Figure A5.** Profile MVNS, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT apparent resistivity sounding curves. 3-D label indicates three-dimensional character of electromagnetic response. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



**Figure A6.** Profile MVNS, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT phase sounding curves. 3-D label indicates three-dimensional character of electromagnetic response. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



Figure A7. Profile YFS, 2-D resistivity depth section model.



**Figure A8a.** Profile YFS, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT apparent resistivity sounding curves. 3-D label indicates three-dimensional character of electromagnetic response. SP label indicates electrical resistivity structure is sub-parallel to the profile direction. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



**Figure A8b.** Profile YFS, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TMorange cross) MT apparent resistivity sounding curves. 3-D label indicates three-dimensional character of electromagnetic response. SP label indicates electrical resistivity structure is sub-parallel to the profile direction. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



**Figure A9a.** Profile YFS, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT phase sounding curves. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



**Figure A9b.** Profile YFS, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT phase sounding curves. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



Figure A10. Profile YFN, 2-D resistivity depth section model.



**Figure A11.** Profile YFN, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT apparent resistivity sounding curves. 3-D label indicates three-dimensional character of electromagnetic response. SP label indicates electrical resistivity structure is sub-parallel to the profile direction. MT station number label is the two digit number appearing in the upper right corner of each individual plot.



Figure A12. Profile YFN, 2-D resistivity model— observed (TE-black circle, TM-black cross) and calculated (TE-green circle, TM-orange cross) MT phase sounding curves. MT station number label is the two digit number appearing in the upper right corner of each individual plot.