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Geophysical Investigation of Kane Springs Valley, Coyote Spring Valley, and Part of the Muddy River Springs Area, Part of the Lower White River Flow System, Using Both Controlled Source and Natural Source Audio-Frequency Magnetotellurics Surveys

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ACRONYMS

1D – one-dimensional

2D – two-dimensional

3D – three-dimensional

amsl – above mean sea level

BARCAS – Basin and Range Carbonate - Rock Aquifer System

CSAMT – Controlled Source Audio Frequency Magnetotellurics

CSI – Coyote Springs Investment

Ex – electric field component parallel to the survey line and transmitter dipole

Ey – electric field component perpendicular to the survey line and transmitter dipole

ft – feet

gpd/ft – gallons per day per foot

GPS – Global Positioning System

Hx – magnetic field component parallel to the survey line and transmitter dipole

Hy – magnetic field component perpendicular to the survey line and transmitter dipole

Hz – hertz, which is a unit of frequency equivalent to an event (or cycle) per second

kHz – kilohertz

km – kilometer

LCWD – Lincoln County Water District

LWRFS – Lower White River Flow System

Ma – mega-annum (10^6 years)

Ω -m – ohm-meters, units of resistivity

m – meter

mi – mile

NSAMT – Natural Source Audio Frequency Magnetotellurics

NSE – Nevada State Engineer

SCS2D – 2D Inversion modeling software program for converting CSAMT/MT data from resistivity/frequency to resistivity/depth

SCSINV – 1D Inversion modeling software program for converting CSAMT/MT data from resistivity/frequency to resistivity/depth

T – transmissivity in gpd/ft

TDS – total dissolved solids

TE – transverse electric

TEM – transient electromagnetics

TM – transverse magnetic

VWC – Vidler Water Company

Zonge – Zonge International, Inc.

ABSTRACT

A series of controlled-source audio-frequency magnetotellurics (CSAMT) and natural source audio frequency magnetotellurics (NSAMT) surveys were conducted in Kane Springs Valley, Coyote Spring Valley, and the Muddy River Springs Area from 2012 to 2021 (fig. 1). To date, these are the largest and most extensive audio frequency magnetotelluric data (publicly available), acquired in the state of Nevada. The CSAMT and NSAMT geophysical methods have several advantages over the other geophysical methods in determining geologic structures and identifying differences in geologic material types.

The study was designed to look at structures buried beneath the alluvium to help determine the best potential site(s) for future groundwater production wells. While recent geologic mapping has been completed in this area, little is known about subsurface geology and geologic structures. Results from the CSAMT and NSAMT surveys indicate a buried geologic feature known as the northern lower White River flow system (LWRFS) boundary fault (plate 1), which is a roughly northwest-southeast striking fault in northern Coyote Spring Valley. The northern LWRFS boundary fault impedes groundwater flow between Kane Springs Valley and Coyote Spring Valley creating a dramatic difference in groundwater elevations in northern Coyote Spring Valley compared to southern Coyote Spring Valley and the rest of the LWRFS. This study was used to determine the location of the Paleozoic carbonate rock that is buried beneath the alluvium throughout both valleys. The Paleozoic carbonate is known to be a prolific aquifer in this area and throughout eastern Nevada and is known as the Basin and Range Carbonate – Rock Aquifer System (BARCAS). The surveys also confirmed mapped geologic structures and numerous unmapped

geologic structures that may control groundwater flow in the study area. The CSAMT and NSAMT geophysical surveys proved to be a reliable and cost-effective method to help geologists and geophysicists determine the location of buried geological formations and geologic structures.

INTRODUCTION

This report describes an ongoing effort to understand the complex structural geology controlling groundwater flow in Kane Springs Valley, Coyote Spring Valley, and the Muddy River Springs Area, part of the LWRFS in southeastern Nevada (fig. 1). A series of CSAMT and NSAMT surveys were conducted in Kane Springs Valley, Coyote Spring Valley, and the Muddy River Springs Area from 2012 to 2021 (plate 1). This study represents more than a 20-year effort by the Lincoln County Water District (LCWD), Vidler Water Company (VWC), and Coyote Springs Investment (CSI) to understand the groundwater resources of this part of the LWRFS.

CSI is developing a large master planned community, Coyote Springs Community, in Coyote Spring Valley that includes commercial, residential, and recreational components. The groundwater resources to be developed in Coyote Spring Valley and Kane Springs Valley would be used to serve the project. The groundwater resources of this area are a significant part of the BARCAS that extends from Idaho, western Utah, almost the entire eastern half of Nevada, and into a small portion of western California (Welch et al., 2007). Groundwater flow through this area is governed by the complex geologic and geological structures that occur throughout these valleys. The geophysical investigation is germane to understanding how the hydrologic system works in these basins.

In 1998, Lincoln County and VWC entered into an agreement in the form of a Memorandum of Understanding for the purposes of developing the Lincoln County Water Plan component of the Lincoln County Master Plan. In 1999, Lincoln County and VWC entered into a Water Delivery Teaming Agreement, which provided joint ownership, development, utilization, and conveyance of water resources within Lincoln County for the benefit of the people of Lincoln County. The northern portion of the Coyote Springs Community Master Planned development is in Lincoln County. The Coyote Springs Community has been identified as a project within the Lincoln County Master Plan. Lincoln County, Nevada is the seventh largest county in the United States with an area that covers 17,220 square kilometers (km²) of which approximately 97.4% is federally managed lands. It has a population of approximately 4,499 people according to 2020 census data. While Lincoln County has a large land mass, it has limited private land, a limited tax base, and limited community infrastructure, which results in very low ad valorem and sales tax income as well as limited technical resources to develop large water resource projects required to generate tax revenue within the County.

This report describes four geophysical CSAMT and NSAMT surveys in Nevada's Lincoln and Clark counties (plate 1). The geophysical survey's intent was to improve the conceptual model of the LWRFS aquifers by constraining the basins geometry and identifying structural geologic features and their subsurface locations. Using the CSAMT and NSAMT methods, geophysicists can infer stratigraphic and structural characteristics of these basins, and thus improve the understanding of the total hydrogeologic system. CSAMT and NSAMT methods were used to map the subsurface along 108 kilometers (km) (67 mi) of survey lines

across Kane Springs Valley, Coyote Spring Valley, and the Muddy River Springs Area.

Combined, these four surveys represent one of the most extensive CSAMT and NSAMT surveys performed in southeastern Nevada offering a rare glimpse into the complex subsurface geology in Kane Springs Valley, Coyote Spring Valley, and the Muddy River Springs Area. These surveys have allowed geophysicists and geologists to interpret the stratigraphy and structural geology controlling groundwater flow in these basins. Combining other published geophysical data with these geophysical surveys presents concrete evidence of a concealed fault that is impeding groundwater flow, creating substantial differences in groundwater elevations between Kane Springs Valley and the rest of the LWRFS (plate 1). Additionally, CSAMT and NSAMT data are extremely useful in siting groundwater wells that have been found to be highly productive in Kane Springs Valley.

Purpose and Scope

The purpose of these geophysical investigations was to identify geologic structures at depth that have the capacity to impact groundwater flow, either as barriers or as conduits. These geophysical surveys were used to assist in siting future water supply wells, and to provide a foundation to understanding groundwater level elevations, and to assist in identifying buried geologic structures that affect groundwater movement. The geophysical surveys were used in conjunction with downhole lithologic logs, downhole geophysical logs, and surficial geologic mapping to correlate the geology with the collected data. These surveys were used in combination with hydrologic data (i.e., water level elevations from wells, and known geologic formations) to help explain groundwater elevation differences between southern Kane Springs Valley and Coyote Spring Valley.

Buried geologic structures were thought to occur at depths throughout southern Kane Springs Valley and Coyote Spring Valley (plate 1). Due to the CSAMT and NSAMT geophysical methods being some of the best methods to identify buried geologic structures, they were chosen for this study area. An effort was made to locate the surveys, such that they were conducted perpendicular to known structures and mapped geologic features such as the Kane Springs Wash fault zone (fig. 6). The geophysical surveys were ground-truthed in bedrock at the basin boundaries, where geologic formations have been mapped and identified. This provided a determination of the resistivity values of known geologic rock types that can then be used to calibrate resistivity values throughout the existing surveys.

This report includes a brief discussion of 1) the Kane Springs Valley, Coyote Spring Valley, and the Muddy River Springs Area geology, 2) CSAMT and NSAMT geophysical methodology, 3) a summary of data acquisition, instrumentation, processing, and 4) a discussion of interpretations of the geophysical results. Cross sections of smooth-model inversion resistivity for each geophysical line are included.

GEOLOGY

Physiography and Topography

Kane Springs Valley is an elongated north-northeast/south-southwest trending valley, which extends from Coyote Spring Valley at the southwestern end, to the northeastern end near lower Meadow Valley Wash and the Clover Mountains, Nevada (fig. 1). Kane Springs Valley is approximately 64 km (40 mi) long, with an average width of approximately 13 km (8 mi). The floor of the valley slopes south-southwest from an elevation of approximately 1,340 meters (m) (4,400 feet [ft]) above mean sea level (amsl) in the northeast

between the northerly piedmonts of the Meadow Valley and Delamar Mountains toward the mouth of the valley, where the elevation is approximately 790 m (2,600 ft) amsl. The Delamar Mountains to the northwest reach 2,353 m (7,720 ft) amsl, while Meadow Valley Mountains to the southeast are considerably lower, with a maximum elevation of 1,730 m (5,676 ft) amsl. Kane Springs Wash drains Kane Springs Valley topographically, and surface water flows into northern Coyote Spring Valley.

Coyote Spring Valley is a north-trending valley located between the Sheep and Las Vegas ranges on the west and the Arrow Canyon Range and Meadow Valley Mountains on the east (fig. 1). Coyote Spring Valley is approximately 100 km (62 mi) long, with an average width of approximately 28 km (17.5 mi). The floor of the valley slopes south-southeast from an elevation of approximately 975 m (3,200 ft) amsl in the northwest from Pahrangat Wash toward the mouth of the valley, where the elevation is approximately 610 m (2,000 ft) amsl. Hayford Peak is the highest point of the Sheep Range rising to 3,020 m (9,920 ft) amsl, located at the south end of the range.

Muddy River Springs Area is a north-south basin located between the Arrow Canyon Range (elevation of 1,590 m {5,218 ft} amsl) on the west and Meadow Valley Mountains (elevation 1,730 m {5,676 ft} amsl) on the east (fig. 1). The length of the basin is approximately 47 km (28.2 mi) long, with the width of the northern half of the area averaging approximately 4 km (2.5 mi), while the width of southern half of the area averages approximately 19 km (11.9 mi). The Muddy River Springs Area has a gradient from the midpoint of the basin at Arrow Canyon (elevation 615 m {2,015 ft} amsl) that trends southeasterly to Moapa Valley (approximate elevation of 555 m {1,820 ft} amsl). The Muddy River Springs Area is also the basin

where the warm carbonate springs originate, which form the headwaters of the Muddy River.

Stratigraphy and Geologic History

The geology of Nevada is the result of hundreds of millions of years of activity between the North American plate and various oceanic plates. Most of the state of Nevada, as well as portions of adjacent states, are part of an area known as the Great Basin. The Great Basin is a physiographic province characterized by alternating mountain ranges bounded by major normal faulting and separated by extensive valley floors. Most of these basins are oriented north south. The Great Basin physiographic province is also characterized by extensive tertiary volcanic activity. Significant to Kane Springs Valley is the Kane Springs Wash caldera complex, Boulder Canyon caldera, and Narrow Canyon caldera. North of Kane Springs Valley is located the Caliente caldera complex, which is separated from Kane Springs Valley by the Helene transverse zone. This combined geologic material and structure influences the hydrologic system of the BARCAS (fig. 2).

The eastern portion of Nevada, in which the project area lies, is characterized by Paleozoic, older than 270 million years (Ma) before present time, alternating sedimentary rocks. These sedimentary sequences are dominated by clastic rocks with minor amounts of limestone or dolomite, or by other carbonate rocks with minor amounts of clastic rocks.

The basin-and-range topography seen today developed during the late Cenozoic Era—since approximately 20 Ma. Mountain ranges were uplifted and eroded during this period, resulting in the alluvial sedimentary deposits that fill the resultant basins. Lakebeds and playa deposits were eventually formed as the climate became drier

following the end of alpine glaciation during the late Pleistocene Epoch (approximately 10,000 years ago). On a local scale, Kane Springs Valley is dominated by thick sequences of folded and faulted Paleozoic carbonate rock, which is intruded and overlain by Tertiary (older than 12 Ma) volcanic rocks and topped by unconsolidated basin-fill deposits (Burbey, 1997). Most of these volcanic rocks consist of ash-flow tuffs erupted from calderas, and form thin, widespread planar sheets of brittle rock (Rowley et al., 2017). The Paleozoic carbonate rocks are composed primarily of limestone and dolomite containing varying amounts of silt with interbedded shale (Page et al., 2003). Carbonate rocks are highly susceptible to dissolution by groundwater. Such dissolution can result in systems of fissures, caves, and eventually karst topography.

Several volcanic episodes occurred in the region during the Tertiary period, producing calderas that are discernable today (Noble, 1968; Novak, 1984, 1985). The Kane Springs Wash caldera complex is in the western central part of Kane Springs Valley. The caldera complex contains rhyolitic and basaltic flows that are likely to be kilometers thick (Noble, 1968; Novak, 1984, 1985). Surficial basin-fill sediments in Kane Springs Valley are 150 to 300 m (500 to 1,000 ft) thick and are composed principally of fine-textured sediments (silt and clay) across the valley floor and coarse-textured sediments at the valley margins. These basin-fill deposits are characterized as unconsolidated to semi-consolidated fine to coarse clastic material derived from fluvial erosion of the surrounding mountains of predominately volcanic origin (Page et al., 2003). Lithologic logs from boreholes drilled near the mouth of the basin revealed predominately microcrystalline carbonate rock (dolostone and limestone), quartzite, and clay beneath the basin fill (URS, 2006a).

Coyote Spring Valley is comprised of four major geologic units: alluvium, Tertiary volcanic rocks, Tertiary basin-fill deposits, and Paleozoic carbonate rocks. Alluvium occurs on the valley floor and comprises interbedded gravels, sands, silts, and clays. The alluvium thickness in the valley ranges between 180 to 260 m (600 to 850 ft). Tertiary volcanic rocks crop out near the northern portion of the basin including tuffs and other volcanoclastic deposits with unknown thicknesses. The Tertiary basin-fill deposit includes the Muddy Creek Formation, which covers large areas of both Lincoln and Clark counties. The Muddy Creek Formation crops out east of the Pahranaagat Wash in the east-central part of the Coyote Spring Valley hydrographic basin (Rowley et al., 2017). The formation is comprised of interbedded fine-grained and coarse-grained sediments, which include claystone, siltstone, and minor sandstones. Gypsum is one of the more fine-grained deposits in the basin as well as conglomerate commonly seen near the margins of the basin. Arrow Canyon, Sheep, and Las Vegas ranges are comprised of thick sequences of limestone, dolomites, and quartzites. The Paleozoic rock outcrops in the higher elevation areas potentially underlie the Muddy Creek Formation under the valley floor in Coyote Spring Valley.

The Sheep Range, which is composed of Paleozoic carbonate rocks, forms the western edge of Coyote Spring Valley. This range contains the leading edge of the Gass Peak thrust fault that was associated with the Sevier orogeny, (200 Ma to 60 Ma) (Rowley et al., 2017). The eastern boundary of Coyote Spring Valley is bounded by the Arrow Canyon Range to the south and the Meadow Valley Range to the north, both of which were formed due to normal faulting associated with Basin and Range physiographic province extension (Rowley et al., 2017). The prominent geologic features of Coyote Spring Valley include the north- to north-

northeast trending faults and the thick sequences of Paleozoic carbonate rocks.

Structural Geology

Within the Basin and Range physiographic province, the continental crust is continually extending and shifting in response to the motion between the Pacific and North American plates and other forces. This extension results in normal faults that result in downthrown blocks (basins), uplifted blocks (mountains), and tilted blocks (combination-mountain and basin [dePolo et al., 2010]).

There were three dominant structural events that shaped this region. These events include, from the oldest to the most recent, the Sevier orogeny, Laramide orogeny, and Basin and Range faulting. The Sevier orogeny resulted in the folding, uplift, and eastward thrusting of Paleozoic sedimentary rocks. The Laramide orogeny moved Paleozoic rocks farther eastward and was also part of a period of uplift, intrusion, and compression (Rowley et al., 2017). Basin and Range faulting produced the north-south trending mountain ranges and basins by broad-scale movement of crustal blocks (Rowley et al., 2017). Normal faulting and extension in the Basin and Range Province continues today. The younger late Cenozoic Basin and Range extension blocked out the present topography into north-trending ranges and intervening basins, which were created by north-striking normal faults. The Basin and Range normal faults in most places obscure the faults and fractures of the older middle Cenozoic episode.

Southernmost Nevada (south of about Interstate 15 [fig.1]), is in the Colorado River extensional corridor, which is a 70 to 100 km (~40 to 60 mi) wide region of moderately to highly extended crust along the eastern margin of the Basin and Range physiographic province in

southern Nevada and northwest Arizona (Faulds et al., 2001). The extensional corridor transitions to a broader region of extension to the north, which encompasses most of the area of interest in this study. The isostatic gravity map shows a north-south grain to most of the area, which was imparted by post-20 Ma Basin and Range tectonism; whereas the aeromagnetic map shows an east-west grain to the area, imparted by Eocene to lower Miocene calc-alkaline calderas and source intrusions. Maps showing these maxima were useful in defining large faults, especially range-bounding faults, and margins of igneous bodies and calderas (Mankinen et al., 2016).

The Pahranaagat shear zone is located along the northwestern side of the southern Delamar Mountains and continues southwest. The Pahranaagat shear zone follows a north-northeast trending gradient in the regional gravity field and topography (Eaton et al., 1978) that separates a region to the south that had 1.5 times more extension than the region to the north (Wernicke et al., 1988), and that may provide a zone of weakness along which to localize deformation (Kreemer et al., 2010). There is independent geological and geophysical evidence for left-lateral motion in the Pahranaagat shear zone (Kreemer et al., 2010). This geologic feature forms the boundary between southern Delamar Valley and northern Coyote Spring Valley. It is a left-lateral, strike-slip transfer fault zone, which connects at both ends with northeast-striking normal faults. Northeast-southwest trending lineaments have also been mapped in the Arrow Canyon Range (McBeth, 1986; Kirk and Campana, 1990). The northern boundary of the Kane Springs and Coyote Spring valleys along the Delamar Mountains coincides with the southern extent of the Pahranaagat shear zone. The two wells drilled by LCWD and VWC at the south end of the Kane Springs Valley were sited near the point where the Willow Springs fault

merges with the Kane Springs Wash fault zone. There is a set of northeast-striking sinistral faults (e.g., the Maynard Lake and Kane Springs Wash faults) that have accumulated <16 km (~10 mi) of sinistral offset (Tschanz and Pampeyan, 1970) since perhaps as early as 7.7 Ma (Jayko, 1990). The Willow Springs fault is a normal fault that bounds the eastern flank of the Delamar Mountains and forms the topographic boundary on the west side of Kane Springs Valley and possibly forms the western boundary of the Kane Springs Wash fault zone.

GEOPHYSICAL METHODS

Introduction to the CSAMT Geophysical Method

Several geophysical methods are available to analyze the lithology, geology, and geological structures that are buried and concealed by alluvial material. One advantage of the CSAMT method is that it provides better near-surface resolution than other deep-sounding electrical resistivity methods. Generally, the CSAMT method provides the most efficient, cost-effective method for obtaining high-resolution subsurface resistivity structural information. For these reasons, it is employed in mineral exploration, water resources exploration, geothermal exploration, and environmental and engineering applications.

The CSAMT geophysical method has several advantages over the other geophysical methods in determining geologic structures and identifying differences in geologic material types. Some of the major advantages of using CSAMT include the ease of field data collection, including small field crew size, use of 4 x 4 pickup truck-sized vehicles, lack of ground disturbance due to an extremely small footprint, which makes this method environmentally responsible, and the extremely

valuable ability to “calibrate” and ground-truth the survey results.

There are several geophysical methods that can be used to acquire resistivity information about the subsurface, each with its own advantages and disadvantages. In the case of CSAMT, an electromagnetic survey method, resistivity is calculated by measuring the electric field and the magnetic field that is output by an electromagnetic transmitter. At some large distance away from the transmitter equipment, computer-controlled equipment with sensors measures the strength of the received electric and magnetic fields. To facilitate processing and interpretation of the resistivity data, measurements are usually made at stations along lines, or transects, along the surface of the ground, although stations that are not in line can be measured and can be useful. The survey logistics, such as the distance between stations, or distance between lines, or depth of investigation are determined by the goals or targets of the survey as well as the local physical environment.

CSAMT has been in use since the early 1980s, when CSAMT equipment was first commercialized. It is not a proprietary method, and by posting the data from these surveys online at <https://pubs.nbmng.unr.edu/Geophysical-investigation-of-Kane-Springs-Valley-p/r061.htm>, it can be used by geophysicists and others to make their own interpretations. This survey data can be replicated or repeated by independent geophysicists. The equipment system used to acquire the data on this project was manufactured by Zonge International, Inc. (Zonge). Zonge’s systems have been purchased and used by numerous government agencies, including the U.S. Geological Survey, universities, national laboratories, as well as private entities.

CSAMT Resistivity Data

Resistivity data are useful in subsurface exploration, because different subsurface materials and different subsurface conditions conduct electricity differently. For example, moist soil conducts electricity better than dry, compacted rock; therefore, the moist soil is said to have a higher conductivity (or lower resistivity) than dry rock. The sandstone layer saturated with groundwater conducts better than an unsaturated sandstone, and a sandstone layer saturated with brine is more conductive than sandstone saturated with low Total Dissolved Solids (TDS) water. By measuring the subsurface resistivity at different locations and different depths, interpretations can be made about the material, structure, and conditions of the subsurface. It is extremely valuable to have a good understanding of the subsurface and aquifer conditions before the CSAMT or NSAMT survey is conducted to help with survey location/design and ensure that the correct hydrogeologic interpretation is made.

The primary measured quantities in CSAMT and NSAMT surveys are the amplitude (labeled magnitude in the data files) and phase of the electric and magnetic fields along an array of grounded electric-field receiver dipoles (fig. 3). The receiver measures the magnitude of the received signal and the absolute phase difference between the received signal and the transmitted signal, which is known via synchronization of the transmitter and receiver. From the measured signals, estimates of Cagniard resistivity (related to the ratio of orthogonal components of the electric and magnetic fields) and impedance phase (phase difference between the electric and magnetic fields) can be computed for each frequency. A geophysical inversion algorithm can then be used to compute an estimated earth resistivity model at various depths from the frequency-based data. No induced

polarization or chargeability information is obtained from a CSAMT or NSAMT survey.

CSAMT and NSAMT data may be collected in either scalar or vector mode. Scalar mode measures only the along-line electric field component, E_x , parallel to the survey line and transmitter dipole, and the across-line magnetic field, H_y (fig. 4). In vector mode both components of the electric field and magnetic field are measured: the along-line components, E_x and H_x , and across-line electric field component perpendicular to the survey line and transmitter dipole, E_y and H_y . By design, the transmitter is oriented so that electric current is directed parallel to survey lines and perpendicular to the assumed geologic strike. Since the survey grids are generally located perpendicular to strike, critical information for this type of survey is generally found in the E_x and H_y components (scalar CSAMT). The assumptions are that (1) geology within the grid is strongly two dimensional (2D), and (2) the survey layout is optimized with regards to the geology. In areas of very complex geology, measuring the complementary components (vector mode) may allow better resolution of three dimensional (3D) features.

Field Data Collection Background and Methodology

In CSAMT surveys the electromagnetic field that is measured along the survey lines is generated using an electromagnetic transmitter, which is injecting a controlled current into a large, grounded dipole, which usually consists of insulated wire laying on the ground, attached to well-grounded metal stakes on the ends of the wire (labeled as the “Source Dipole” in fig. 3). The wires are typically approximately 1.2 km long (4,000 ft) and located from 4 km (3 mi) to 10 km (6 mi) from the survey lines. The signal is transmitted as square waves at a suite of frequencies, typically from 1 Hertz (Hz) to 8192 Hz; low frequencies penetrate

deeper than high frequencies, thus resistivity information can be acquired from very shallow zones (using high frequencies) down to deeper zones (using low frequencies). The depth of investigation depends on frequency and resistivity. The depth of investigation in a CSAMT survey is a complicated function of both ground resistivity and frequency of the transmitted signal. Figure 5 shows this relationship for a simple uniform homogeneous earth. Shown in red, the depth of investigation in low resistivity of 10 ohm-meters (Ω -m) ground at 1 Hz is 1,126 m, but the depth of investigation in the same ground at 1000 Hz (shown in blue) is only 36 m. Thus, in this ideal homogeneous earth of resistivity of 10 Ω -m, a CSAMT survey using a suite of frequencies from 1000 Hz down to 1 Hz would probe from a depth of 36 m to 1,126 m. Since the earth is rarely homogeneous, one dimensional (1D) and 2D inversion models of a suite of frequencies along lines of stations are used to calculate resistivity versus depth to produce 2D cross sections through the earth.

Depending on ground conditions such as contact resistance, CSAMT transmitters typically output up to 20 amperes at up to 800 volts. A Zonge 8-channel GDP-3224 multi-purpose geophysical receiver was used for these surveys. The GDP-3224 instrument is a backpack-portable, 24-bit, microprocessor-controlled receiver that is manufactured by Zonge (fig. 4). Electric field measurements were made at the receiver site along spreads of potential electrodes consisting of grounded, nonpolarizable porous pots filled with copper sulfate solutions (fig. 4) connected to the receiver with insulated 14-gauge wire. The pots were partially buried in small pits approximately 5 cm (2 in) deep, and tap water was added to reduce contact resistance with the ground. Magnetic field data were acquired with a Zonge ANT/6 magnetic field sensor (fig. 4).

Data were collected using 4 to 6 channels per setup or spread. The measurement spread consisted of 4 to 6 Ex E-field dipoles and 1 Hy magnetic field measurement located at the center of the E-field dipoles. The electric field dipoles were 61 m (200 ft) in length (i.e., the station spacing). In this configuration, Ex is the electric field measurement made in the along-line x-direction (parallel to the transmitter dipole), and Hy is the magnetic field measurement in the across-line or y-direction (fig. 3). Coordinates for each station center are included in files with the digital delivery of this report.

The signal source for this project was a Zonge 30 kilowatt GGT-30 transmitter. Transmitter power was provided by a Zonge ZMG-30 motor-generator. The transmitter was controlled by the XMT-G transmitter controller. Data collection requires time and frequency synchronization between the GDP-3224 receivers and GGT transmitter, which was achieved via Global Positioning System (GPS) timing.

The other audio frequency magnetotellurics geophysical method that has been used is based on the electromagnetic energy naturally occurring in the atmosphere as the source. The natural source or NSAMT method is described in Cagniard (1953) and Vozoff (1991). Although the resulting datasets are the same, in this project the axial line running along the axis of Kane Springs Valley is referred to here as NSAMT instead of CSAMT to distinguish the geophysical source type used to collect these data. Since the NSAMT line segments were reliant on natural sources of the electromagnetic field, the signal strength is weaker than the man-made controlled source dataset (CSAMT). This is because there is a naturally occurring "dead band" in the AMT band causing the data acquisition time along the natural source line segments to be substantially longer than the CSAMT lines. In addition, it is useful to note that CSAMT is more

sensitive to resistors buried in conductive material than NSAMT, but NSAMT is more sensitive to conductors in resistive material. The insensitivity of inductive geophysical methods, like Transient Electromagnetics (TEM) to buried resistors is usually a disadvantage for those methods relative to CSAMT because resistive structure embedded in a conductive host may be missed completely. In most aspects, the same principles apply to CSAMT and NSAMT, and the resulting data sets are equivalent, but in some specific environments one method may be more advantageous than the other.

One very useful method to calibrating the geophysical survey data is to compare the CSAMT or NSAMT data collected to resistivity data collected from wells that are near or in-line with the geophysical surveys. Once a well has been completed to depth, a suite of resistivity logs can be run in the open borehole. The borehole resistivity log data from the Kane Springs monitor well (KMW-1) and the production well (KPW-1) are very useful in "calibrating" surficial CSAMT or NSAMT survey data. Resistivity logs are used to collect downhole resistivity data that inform the geologist/geophysicist as to the type of lithologic materials encountered during the drilling process. These data, combined with the lithologic cuttings of the materials drilled through, provides a detailed geologic log of the borehole for the depth of the well. The downhole resistivity data combined with the lithologic log can be used to "calibrate" the surficial CSAMT geophysical survey data and can provide a data point along the CSAMT or NSAMT transect. This, in turn, provides confidence in the geophysical interpretation of geologic materials across the CSAMT or NSAMT transects without the necessity of an expensive drilling program. This combined with ground-truthing of the CSAMT or NSAMT geophysical surveys provides measured confidence in the geologic interpretations of both the geologic structure and geologic materials that

occur at depth and that are covered by basin-fill materials.

Ground-truthing of the CSAMT or NSAMT geophysical surveys means extending the data collection to areas of mapped geology. Typically, when an area is under investigation, one of the first references that is incorporated into the assessment is the relevant geologic map of the area. For the CSAMT or NSAMT geophysical surveys of southern Kane Springs Valley the geologic reference that was initially relied on was Swadley et al. (1994) that mapped the southern extent of the Delamar Mountains and the confluence of the Willow Springs and Kane Springs Wash fault zones. These geologic maps were extremely valuable in identifying possible well site locations and the geologic material encountered during the drilling. The CSAMT geophysical surveys of northern Coyote Spring Valley and the surveys in the central portion of Coyote Spring Valley and the Muddy River Springs Area were ground-truthed based on the extensive geologic mapping work of Rowley et al. (2017). In addition to the geologic references, the downhole resistivity log and lithologic log of Southern Nevada Water Authority's monitor wells CSVN-4, CSV3009, and CSV3011M (URS, 2006b) located in northern Coyote Spring Valley were also used to calibrate the CSAMT geophysical surveys of this area. The transects were intentionally extended to include the mapped formations of the Meadow Valley Mountains to the east and the southern Delamar Mountains to the north, and for the central Coyote Spring Valley CSAMT geophysical surveys, the exposed geologic formations of the Arrow Canyon Range. It is in this manner that the resistivity responses are "ground-truthed" to mapped geologic formations that are exposed in outcrops.

Figure 6 is a map showing the location of the transects, through southern Kane Springs Valley and northern Coyote Spring Valley. Figure 7 is a

map showing the location of the geophysical surveys (transects) through and near the Arrow Canyon Range of central Coyote Spring Valley and the southern part of Coyote Spring Valley and the Muddy River Springs Area.

CSAMT Data Modeling and Analysis

Observed and modeled data for the project are presented in several types of plots in this report. All plots and maps are included as digital images in PDF format. Numeric observed and modeled data are included digitally as ASCII comma-separated value files and Excel files (tables) and can be accessed at:

<https://pubs.nbmng.unr.edu/Geophysical-investigation-of-Kane-Springs-Valley-p/r061.htm>.

The CSAMT and NSAMT data are presented graphically as inversion models showing 1D or 2D depth cross sections of resistivity.

The CSAMT and NSAMT survey data have been modeled using 1D or 2D inversion algorithms to generate model cross sections of the estimated subsurface resistivity. The resistivity inversion cross sections are computed using Zonge's 2D inversion modeling software program for converting CSAMT/MT data from resistivity/frequency to resistivity/depth (SCS2D).

The 1D inversion model assumes that subsurface resistivity varies only vertically, and stations are inverted individually, with no influence from adjacent stations or off-line effects. This inversion process commonly detects narrower features than 2D or 3D models, which tend to smooth through narrow features. While the 1D inversion is robust and preserves detail, commonly illuminating sharp vertical features, 1D modeled results can also be distorted when data is strongly controlled by 2D and 3D geology.

SCS2D inverts observed apparent resistivity and impedance phase data from a line of frequency

based CSAMT or NSAMT soundings to determine resistivities in a model earth cross section. Either transverse magnetic (TM) mode data, defined in this case as line parallel E-field, or transverse electric (TE) mode data, line perpendicular E-field, may be inverted. The starting model for the 1D inversion is generally computed from a moving average of the apparent resistivity data over the section.

During the inversion, model-section-pixel resistivities are adjusted iteratively until calculated apparent resistivity and impedance phases are as close as possible to observed data, consistent with model constraints. Model constraints include background-model constraints, which restrict the difference between the inversion, and background model sections, which represent known geology, and smoothness constraints, which limit resistivity variation from pixel to pixel. To calculate apparent resistivity and impedance phase for a given model section, SCS2D uses a 2D, finite-element algorithm to calculate far-field CSAMT or NSAMT data. To model the terrain, the finite-element mesh is draped over an along-line topographic profile. Either TM or TE mode data can be calculated for scalar, vector, or tensor survey configurations for frequencies ranging from less than 0.01 to 10 kilohertz (kHz). For this project, a TM mode inversion was performed on the CSAMT data.

Geophysical inversion models always represent a non-unique earth model from an infinite number of models that may fit the observed data equally well. The 'smooth-model' inversion cross sections are unique in the sense that they represent a unique average of the entire solution space of models, subject to the user-imposed constraints. Additionally, calibration and ground-truthing with mapped datasets of surface geology and borehole geophysical surveys make these unique.

For interpretive purposes, inversion resistivity models are presented in this report as color-contoured cross sections, an example of which is included as figure 8. In these model cross sections, stations are labeled in feet along the top of the section, with cool colors (blues, greens) representing high resistivity and warm colors (orange, red, pink) representing low resistivities.

The 1D inversion models for this project are sensitive to a depth of about 975 m (3,200 ft), though resolution decreases with increasing depth and "near-field" effects may complicate the interpretation at depths greater than about 610 m (2,000 ft) in this case. Depth of investigation for the CSAMT method is a function of frequency, background resistivity, the distance from the transmitter to the receiver, and geology between and around the transmitter and receiver dipoles.

DATA PROCESSING

Software

All raw, averaged, and inversion model data and images are included digitally as part of this report and can be found here:

<https://pubs.nbmng.unr.edu/Geophysical-investigation-of-Kane-Springs-Valley-p/r061.htm>.

Zonge in-house software was used for processing and modeling the CSAMT survey data using the following programs:

- Zonge CSAVGW v1.20r
(visualizing, averaging, and editing raw data)
- Zonge ASTATIC v3.70i
(visualizing and static corrections of averaged data)
- Zonge SCS2D v3.20
(1D and 2D inversion modeling)
- Zonge SCSPLOT v3.21k
(plotting 1D model sections)

- Geosoft/Surfer v8.5.1 (final database, plotting, and visualization models)

plotting with the in-house Zonge scripts in SCSPLOT.GX

A brief outline of data processing and modeling steps is given below:

- Prepare *.mde (Survey configuration and processing control file) and *.stn (station coordinate) files.
- Process raw data files (.cac) using the CSAVGW program. CSAVGW is a CSAMT and NSAMT data averaging and quality-control utility program, displaying the data in pseudosection, sounding curve, or data point graphs to allow skipping of outlier data. Data are saved as averaged data in *.avg files.
- Process averaged data with the ASTATIC algorithm using the ASTATIC program. Individual sounding curves are viewed, and final removal is made of individual measurements that are affected by noise. Static corrections or corrections for high contact resistance are also made using the program ASTATIC. Static corrections were tested on the Coyote Springs project data, but very little static effects were evident, and the static corrections resulted in little to no change in the results in many cases. In cases where static corrections were used, a note is included in the data files and plots.
- Perform 1D inversion modeling using 1D inversion modeling software for converting CSAMT/MT data from resistivity/frequency to resistivity/depth (SCSINV) smooth inversion programs. Run SCSINV using *Ex.avg files to get 1D model resistivity cross section (depth profile) models.
- Model results (*.mtm files) were imported into Geosoft of Surfer for

Data Access

The digital data for these geophysical surveys can be found here:

<https://pubs.nbmj.unr.edu/Geophysical-investigation-of-Kane-Springs-Valley-p/r061.htm>.

The digital data files made available include raw, unprocessed data files, processed (stacked and averaged) data files, and inversion model result data files. A format description for each file type is also provided so that researchers can use their own processing programs on the raw data, or they may use their own inversion model programs on the processed data. The model result data files are also provided so that researchers can use their own graphics programs as interpretation tools of these model results.

Data Quality

Data quality is monitored in the field by the operator. Real-time standard-error values can be displayed during the acquisition. In addition, multiple measurements at a range of frequencies are displayed graphically as resistivity versus frequency curves with error bars showing the data scatter. This allows a visual evaluation of the data quality and remedial action to be taken if necessary. Numerous measurements of the received E-field and H-field are made at each frequency at each station to average out background noise and to provide a statistical evaluation of the data quality. Resistivity values are calculated and displayed for the operator to evaluate repeatability of the data. In addition, if two different receiver systems are used on a single line, or if two different transmitter dipoles are used on the same line due to long line length, several stations are always repeated with

both receivers or transmitters to ensure that the data are consistent and repeatable.

The processed digital data files (AVG files) also contain percentage error values for the E-field and H-field measurements at each frequency and each station, as well as absolute error values of the impedance phase data from the E-field and H-field measurements. A relative apparent resistivity percentage error is calculated and included for use in data weighting in inversion models and final interpretation.

GEOPHYSICAL DATA RESULTS

The CSAMT and NSAMT data sets that have been collected in Kane Springs Valley, Coyote Spring Valley, and the Muddy River Springs Area are discussed below based on the year that the data set was collected. The NSAMT method was used to collect data along the axis of the Kane Springs Valley. The rest of the data was collected using the CSAMT method.

Geophysical Data Collection

LCWD and VWC conducted an extensive geophysical survey using the CSAMT method by Zonge in 2012. Axial transects, consisting of four lines (Lines A, B, C, and D) were collected along the axis of the southern part of the Kane Springs Valley using the NSAMT method. The axial transects were oriented in a southwest to northeast direction (fig. 9). The four axial transects total in length of approximately 17.7 km (11 mi). Additionally, six lines (lines 1, 2, 3, 4, 5, and 6) perpendicular to the axial transects were oriented in a northwest-southeast direction using the CSAMT method. The total length of the perpendicular lines is approximately 30.6 km (19 mi).

LCWD and VWC contracted Zonge to perform an additional CSAMT survey at the boundary of Kane Springs Valley and northern

Coyote Spring Valley in 2019. The intent of this survey was to determine the location of a structural feature that was believed to be impeding groundwater flow from Kane Springs Valley into Coyote Spring Valley. This geophysical survey in northern Coyote Spring Valley added an additional two lines (lines 10 and 11) in the northwest-southeast orientation totaling approximately 23.5 km (14.6 mi) in length and a west-east orientation line (line 12), which intersected lines 10 and 11 totaling in length of approximately 14.2 km (8.8 mi) (fig. 10).

In 2019, CSI also contracted Zonge to perform a CSAMT survey in the southern portion of Coyote Spring Valley in Clark County, Nevada (fig. 7). The intent of this survey was to determine the extent of basin-fill material and subsurface structural features that are not evident at the surface that may influence groundwater flow. Two west-east oriented lines (lines A and B) were run to help identify normal faulting found in this area. The total length of lines A and B was 8.9 km and 7.7 km (5.5 mi and 4.8 mi, respectively). Line C totaling 6 km (3.7 mi) in length had a southwest-northeast orientation. The intent of line C was to identify previously mapped subparallel faults between Coyote Spring Valley and the Muddy River Springs Area (fig. 7).

LCWD and VWC contracted Zonge to perform an additional CSAMT survey in northern Coyote Spring Valley in 2021. The geophysical survey was intended to provide verification and additional delineation of a buried subsurface fault structure interpreted in prior surveys that may cause the difference in the carbonate-rock aquifer water levels between Kane Springs Valley and the southern part of Coyote Spring Valley and the Muddy River Springs Area. The two new survey lines in 2021 (lines 13 and 14) were perpendicular to lines 10 and 11, and intersected lines 10 and 11. The locations of lines 13 and 14 were chosen to

delineate the location of the fault interpreted between lines 10 and 11, as well as to establish an orientation of the fault. Lines 13 and 14 were both 5.3 km (3.3 mi) in length (fig. 11).

All totaled LCWD, VWC, and CSI performed over 108 km (67 mi) of CSAMT geophysical surveys. This dataset represents one of the most extensive geophysical datasets undertaken that focuses on geologic structures to better understand and characterize basin groundwater hydrology and the ability of groundwater to flow through the extensive BARCAS that occupies in the eastern portion of Nevada.

Kane Springs Valley and Coyote Spring Valley CSAMT Cross Section Model Discussion

All survey results are included as resistivity cross sections of 1D smooth-model inversion results, with station numbers in feet across the top and elevation in feet down the left side of the cross section, as well as elevation in meters down the right side of the cross section. Resistivity values are shown in Ω -m with low resistivities shaded toward the red end of the spectrum and high resistivities shaded toward the blue end of the spectrum. Resistivities in this area generally range from less than 10 Ω -m to as much as 10,000 Ω -m.

KANE SPRINGS VALLEY AND NORTHERN COYOTE SPRING VALLEY CSAMT INVESTIGATION

An extensive geophysical survey using the CSAMT method was conducted by Zonge in 2012 to further refine potential well locations in Kane Springs Valley. Several geophysical transects were conducted perpendicular to the axis of the Kane Springs Valley (fig. 9). For the transects conducted in the northern Coyote Spring Valley in 2019, the same northwest-southeast orientation was used to assist in evaluating the geologic structures in this area. To enhance understanding of the geologic

structures in northern Coyote Spring Valley, a review of the first geophysical transects, lines 1 and 2 (figs. 12 and 13, plate 2), through the southern end of Kane Springs Valley is warranted. These transects in both southern Kane Springs Valley and northern Coyote Spring Valley are plotted on an excerpt (fig. 6) of the most recent geologic map of this area by Rowley et al., (2017).

SOUTHERN KANE SPRINGS VALLEY CSAMT INVESTIGATION

Line 1 of Kane Springs Valley CSAMT transect is provided in figure 12 and plate 2. This transect was ground-truthed by conducting the survey over an exposed Devonian Simonson Dolomite outcrop. Additionally, this transect was calibrated by using the downhole geophysics and the geologic logs from wells KPW-1 and KMW-1. These wells were drilled adjacent to the exposed outcrops of Devonian Simonson Dolomite, part of the Paleozoic carbonate rock sequence that is illustrated and identified by the geologic units in plate 1. These wells also intersect the Willow Springs fault (fig. 6) at a depth of 408 m (1,340 ft) below land surface. The geophysical transect confirmed the exposure of dolomite, the attitude (dip) of both geologic units, and the occurrence of the Kane Springs Wash fault zone. The ground-truthing of the CSAMT data across the exposed dolomite outcrop in the center of Line 1 (fig. 12 and plate 2) is demonstrative of the usefulness of ground-truthing the CSAMT survey data with known mapped geology.

The CSAMT transect of Line 1 (fig. 12 and plate 2) does not extend to the exposed bedrock outcrops of either the Delamar Mountains or the Meadow Valley Mountains. Other important features shown on Line 1 include faulting within the Kane Springs Wash fault zone at stations 8100 through the end of this transect and faulting on

west side of well KPW-1 near the basin boundary at Station 2100.

Beginning on the right (east) side of Line 2, illustrated in figure 13 and plate 2, the data exhibit a very highly resistive block from land surface to final investigation depth. This demonstrates “ground-truthing” of the CSAMT method, as this is an exposed block of Paleozoic carbonate rocks mapped by Rowley et al. (2017). From station number 15100, the high resistivity values occur adjacent to low resistivity values and are representative of faulting in this area. These data also correlate with faulting at this location on the Rowley et al. (2017) geologic map. These values represent the eastern boundary of the Kane Springs Wash fault zone (fig. 13 and plate 2).

The next significant feature shown on figure 13 (plate 2) is the block of high resistivity that occurs between stations 7500 and 8500 with a maximum elevation of approximately 460 m (1,500 ft). This feature ties directly to the Devonian Simonson Dolomite mapped at the mouth of Kane Springs Valley (fig. 6), between Lines 1 and 10. Beneath this high resistivity block is a zone of low resistivity. This zone of low resistivity is most likely a result of poor resolution of the deep CSAMT sounding.

The northwest side of the transect of Line 2 (fig. 13 and plate 2) confirms the presence of the mapped Willow Springs fault on the geologic map (fig. 6). This occurs between stations 500 to 700 (fig. 13 and plate 2). The geophysical data show several other faults that occur in this area that are concealed by the surficial basin-fill deposits.

Line 3 illustrated in figure 14 and plate 2, shows similar features as line 2 (fig. 13 and plate 2). Beginning on the right (east) side, the data exhibit a very highly resistive block from land surface to final investigation depth. Faulting is interpreted where the highly resistive block meets the lower resistivity values around station 10900. These

values represent the eastern boundary of the Kane Springs Wash fault zone. The block of high resistivity seen in line 2 (fig. 13 and plate 2) that represents the Devonian Simonson Dolomite is also found in line 3 (fig. 14 and plate 2) but at a greater depth suggesting that this block is dipping to the northeast. This block occurs between stations 5700 and 8300 with a top elevation of approximately 15 m (50 ft) amsl. Line 3 (fig. 14 and plate 2) did not extend to the Willow Springs fault on the geologic map.

Line 4 is illustrated in figure 15 and plate 2. Beginning on the right (east) side, the data exhibit a highly resistive block that is downthrown. This downthrown highly resistive block ends at station 8700 and has a top elevation of 300 m (1,000 ft). This correlates well with the normal faulting of the Kane Springs Wash fault zone as shown on the geologic map (Rowley et al., 2017). Numerous faults are seen throughout the basin-fill material, as the station numbers decrease in value to the west.

The Kane Springs Wash fault zone is again seen in Line 5 on the east side of the transect (fig. 16 and plate 2). The Kane Springs Wash fault is seen at station 26100 with a downthrown block of Paleozoic carbonate rocks extending from station 22700 to 26100. Deep basin-fill deposits are present from station 11100 to 22700 with minor faulting. Line 5 (fig. 16 and plate 2) comes into contact with a Miocene ash-flow tuff at station 11100. Several large faults are seen at stations 1900, 4700, 7100, 9900, and 10700.

Line 6 (fig. 17 and plate 2) was in the Kane Springs Wash caldera complex. The western edge of the line shows a low resistivity basin fill that is dipping to the east. This unit is approximately 120 m (400 ft) thick. A highly resistive block is found underlying basin-fill deposits potentially composed of denser volcanic caldera material. The highly resistive block appears to be dipping to the

east. Faulting can be seen at stations 1900, 5700, 7700, 12300, and 17500.

KANE SPRINGS VALLEY NSAMT AXIAL LINE INVESTIGATION

Unlike the other survey lines in this project, the line along the axis of Kane Springs Valley, called the axial line (segments A, B, C, and D), was acquired using natural sources, the NSAMT method, instead of generated controlled sources. This is for two reasons: first, not knowing the geometry of the basin, the NSAMT method is useful because it can “look” deeper into the earth with more accuracy. Secondly, and more practically, the long line through the axis of the valley would require relocating the transmitters to areas with poor access, resulting in more time and expense.

The axial line of the NSAMT transect is broken up into four axis lines (axis lines A, B, C, and D [fig. 9]). Axis line A begins at the mouth of Kane Springs Valley from the southwest station -900 and ends at station 16500 (fig. 18 and plate 2). Overall, axis line A has relatively low resistivity from station -900 to station 3900 with elevations between 0 to 850 m (0 to 2,800 ft). The beginning of the line appears to be on the downthrown side of the Willow Springs fault mapped as a strike slip-fault (fig. 18 and plate 2). Axis line A has multiple locations where the resistivity is at its lowest point between the elevations of 600 to 850 m (2,000 to 2,700 ft) representing basin fill above the downthrown carbonate rock. Station 4500 through station 16500 show higher resistivity between elevations of 0 to 500 m (0 to 1,750 ft) that is interpreted as Paleozoic carbonate formations.

NSAMT axis line B begins at station 16700 and runs through 31100, and this is also shown on fig. 19 and plate 2. Line B has larger sections of low resistivity within elevations of 550 to 850 m (1,500 to 2,500 ft). Just above the low resistivity area at

stations 17700 to 18100, axis line B shows high resistivity within elevations of 650 to 850 m (2,000 to 2,800 ft). Axis line B shows a continual high resistivity area between 0 to 500 m (0 to 1,750 ft) elevation, which was seen in Axis Line A and is interpreted as a continuation of the Paleozoic carbonate rocks. Stations 21100 through 31100 of axis line B have relatively low resistivity overall, with few zones of low resistivities indicating that there are more clays and silts in the basin-fill materials, with patches of moderately high resistivity interpreted as dry gravelly sand material.

NSAMT axis line C (fig. 20 and plate 2) has some high resistivities and low resistivity patches between stations -900 through 3900. The higher resistivity seen in axis line C is located between elevations 550 to 950 m (1,750 to 3,000 ft). Axis line C shows a moderate resistivity area ranging from station 3900–16800 throughout elevations 0 to 975 m (0 to 3,000 ft). The interesting feature of axis line C is the lack of identifiable structure through the section line. There is some potential cross-faulting occurring perpendicular to the orientation of the Kane Springs Wash fault zone that can be identified at station -100, and stations 1700 and 1900.

NSAMT axis line D (fig. 21 and plate 2) has moderate resistivity values. Axis line D has a patch of higher resistivity at elevations from 750 to 850 m (2,500 to 2,750 ft) between stations 6100 and 6700. There is very little structure identified, and the material is likely Lower Miocene and Holocene basin fill of volcanic origin (i.e., weathered from local tuff and other volcanic deposits) or other geologic materials related to the caldera located farther to the northeast.

The axial line was very useful in identifying where geologic structure(s) are present. It was also very useful in identifying basin-fill or non-carbonate materials. One of the most interesting features of the axial surveys is that the exposed

carbonate formation at the mouth of Kane Springs Valley dips to the northeast in the basin. The target producing aquifer system in Kane Springs Valley was the geologic structure of the indurated rock formations that are buried and may not be evident from surficial mapping. The drilling and testing of production well KPW-1 and monitor well KMW-1 suggest that the fault structures in Kane Springs Valley, including the Willow Spring fault and the Kane Springs Wash fault zone, are preferential groundwater flow paths through Kane Springs Valley. In identifying the various geologic materials throughout the basin, it is highly probable that the basin-fill material is likely saturated but perhaps not as transmissive as the Paleozoic carbonate formations.

The drilling and testing of production well KPW-1 and monitor well KMW-1 suggest that the wells were sited near the Willow Springs fault and the Kane Springs Wash fault zone. This is an area of extensive tectonic activity, leading to significant fracturing of the carbonate rock aquifer. Drill cuttings observed in both wells show evidence of fracture planes and fine-scaled solution fractures (i.e., vugs) indicative of karst development. Additionally, quartzite was encountered in each well around 408 m (1,340 ft) below ground surface. A clay unit was found directly above the quartzite, with the samples resembling fault gouge (URS, 2006a).

A seven-day constant-rate test of KPW-1 was conducted at a rate of 6,814 liters per minute (1,800 gallons per minute), during which time water level data were collected in both KPW-1 (pumping well) and KMW-1 (monitor well). The resulting drawdown at the end of the test was 52 m (172 ft), which yields a specific capacity of 2.17 liters per second, per meter (10.5 gallons per minute, per foot) of drawdown. It is evident from the aquifer testing of well KPW-1 that the residual recovery data represent fault-induced high transmissivity

(T). The carbonate rock aquifer behaved as a porous media similar to an alluvial aquifer system and thereby can be analyzed as such. Applying the Theis (1935) equation yields a T value of approximately 3,725 m²/day (300,000 gpd/ft) using residual drawdown data from the monitor and production wells. Applying the Hantush (1960) method for a leaky confined aquifer, yielded a T value of approximately 1,120 m²/day (90,000 gpd/ft) using drawdown data from the monitor well (URS, 2006a).

2019 NORTHERN COYOTE SPRING VALLEY CSAMT INVESTIGATION

New geophysical data were collected in February and March 2019 in northern Coyote Spring Valley, just south of the Kane Springs Valley (lines 10 and 11; fig. 10). Two new CSAMT geophysical transects, in Coyote Spring Valley, were conducted parallel to the previously collected lines 1 and 2, in southern Kane Springs Valley.

The southwestern-most transect in Kane Springs Valley, line 1 (fig. 10, plate 1), includes wells KPW-1 and KMW-1. The new transects in Coyote Spring Valley are labelled lines 10 and 11 (figs. 22 and 23, plate 2), with line 10 (fig. 22) the most northerly transect closest to the mouth of Kane Springs Valley. Both transects are in a northwest-southeast orientation, perpendicular to the known Kane Spring Wash fault zone and the Willow Springs fault identified on the geologic map of the area (Rowley et al., 2017). A third transect, line 12 (fig. 24, plate 2), was conducted in an east-west alignment in northern Coyote Spring Valley and intersected both lines 10 and 11 (figs. 22 and 23).

Transect line 12 (fig. 24) was oriented in an east-west direction to try and confirm where the significant change in the resistivity values that occurs between lines 10 and 11 (figs. 22 and 23) is located. This change in resistivity turns out to be

very close to line 10. Line 12 was also used to confirm and cross the three large, inferred faults shown on the geologic maps (Rowley et al., 2017). The orientation of line 12 was also influenced by available areas for the transmitter dipole.

The northernmost transect (line 10) in Coyote Spring Valley (fig. 22, plate 1) is located just southwest of the exposed outcrop of Devonian Simonson Dolomite at the mouth of Kane Springs Valley (fig. 10). Monitor well CSVN-4 is also located to the southwest of station 13900 on line 10. There are several significant features that can be identified on CSAMT line 10 (fig. 22, plate 2). The transect is dominated by high resistivity blocks. From the ground-truthing discussed previously for lines 1 and 2 (Kane Springs Valley CSAMT Lines 1 and 2 [figs. 12 and 13]), and line 10 at its far southeast end, these high resistivity blocks are most likely carbonate rocks. This transect also shows the downthrown nature of the boundary fault on the far southeastern end near or encompassing stations 23900 to 24300. This fault occurs to the western side of the Meadow Valley Mountains and forms the eastern boundary of the Kane Springs Wash fault zone (figs. 6 and 22), which is consistent with the geologic map (Rowley et al., 2017). This fault can be traced through these transects (fig. 22, plate 2) from Kane Springs Valley into Coyote Spring Valley (fig. 23).

Well CSVN-4 was drilled near the highly resistive block of exposed dolomite in Coyote Spring Valley. This block of dolomite is not exposed at the surface where CSVN-4 was drilled but can be traced from Kane Springs Valley through the geophysical transect of line 10 (fig. 22) in northern Coyote Spring Valley. The concealed Delamar thrust fault drawn on Rowley et al. (2017), cannot be identified or is not present on CSAMT transect of line 10 (fig. 22, plate 2). If present, it would be located at approximately station 4100. Faulting does occur from stations 8300 to 10700.

This would agree with the concealed strike-slip fault identified on Rowley et al. (2017), along the northwest edge of the outcrop of Devonian Simonson Dolomite at the mouth of Kane Springs Valley (fig. 22, plate 2). The highly resistive block that crops out as Devonian Simonson Dolomite at the mouth of Kane Springs Valley extends beneath the surface as shown in line 10 (fig. 22). This occurs from stations 13500 to 16300. There are numerous faults that occur from station 16300 through station 24300, which is representative of the Kane Springs Wash fault zone.

CSAMT line 11 (fig. 23, plate 2) is located approximately 3,800 m (12,500 ft) to the southwest of line 10 (fig. 22). Monitor well CSVN-4 is located approximately 3,560 m (11,700 ft) to the northeast of station 31100 of line 11 (fig. 23). There are several significant features that can be identified on CSAMT line 11. The most striking difference of line 11 from line 10 is the virtual lack of the highly resistive blocks that dominate the transect of Line 10 (fig. 22, plate 2). This transect also shows the downthrown nature of the southeastern boundary fault at station 46000. This fault occurs to the western side of the Meadow Valley Mountains and forms the eastern boundary of the Kane Springs Wash fault zone (fig. 23, plate 2; stations 45300 to 45700).

The concealed strike-slip fault that forms the western boundary of the Kane Springs Wash fault zone (Rowley et al., 2017) may be located at approximately station 26700 on line 11 (fig. 23, plate 2). The low resistivity zones may be the result of thicker volcanics versus higher resistivity carbonates, or it may just be different materials in the alluvial cover (i.e., more or less clays in some alluvial sediment layers than others). In addition, along some parts of the line, there are multiple low resistivity layers (stations 30000 to 39700, for example). Comparison of line 10 to line 11 suggests that there is a structural boundary between

southern Kane Springs Valley and northern Coyote Spring Valley. This fault boundary is further refined using additional transects with data collected in 2021, as discussed below.

CSAMT line 12 (fig. 24, plate 2) is an east-west transect that intersects both CSAMT lines 10 and 11 at stations 23800 and 42700, respectively, at a 45-degree angle (fig. 10). The Gass Peak thrust fault (a very large, regional structural feature) does not appear to be present at station 3500 (fig. 24, plate 2). Low resistivity values occur at the land surface on the western side of this transect and correlate with an area of surface vegetation, which is an indication of a source of water supported by the low resistive materials.

Remnants of Kane Springs Wash fault zone (i.e., the strike-slip fault identified on Rowley et al., 2017), along the northwest edge of the outcrop of Devonian Simonson Dolomite at the mouth of Kane Springs Valley, occur from approximately stations 38300 through 43100 (fig. 24). Specifically, there is an obvious change between the layering of resistivities west of approximately station 22700 (fig. 24, plate 2). Well logs from monitor wells CSV3009 and CSV3011M (located at approximately stations 17800 and 26900, respectively) confirm the presence of unconsolidated or alluvial materials (i.e., silts, clays, sands, and gravels) to at least an elevation of approximately 480 m (1,580 ft) below land surface (fig. 24, plate 2) as compared to the eastern portion of the transect, where high resistivity occurs at relatively shallow depths that indicate Paleozoic rocks. This is an excellent example of the difference in resistivity in the CSAMT data between different geologic materials.

The 2021 geophysical survey was intended to provide verification and additional delineation of a buried subsurface fault structure. This fault was labeled the northern LWRFS boundary fault for

discussion purposes (plate 1). The interpretation of the fault was based on a strong difference in resistivity values between the two 2019 CSAMT survey lines 10 and 11 (figs. 22 and 23), which were parallel to each other, near where the southwest end of Kane Springs Valley meets the Coyote Spring Valley. The high resistivity values of CSAMT line 10 can be definitively identified as carbonate rocks based on the downhole resistivity data and downhole lithologic data from both wells drilled in the area, as well as ground-truthing at exposed carbonate rock outcrops.

The two new survey lines in 2021 (lines 13 and 14 [figs. 25 and 26]) were perpendicular to the 2019 lines, (CSAMT lines 10 and 11 [figs. 22 and 23]) in order to delineate the location of the fault interpreted between the 2019 lines, as well as to establish an orientation of the fault (fig. 27). The 2021 survey data and resulting computer models show very good correlation and consistency to the data acquired in 2012 in Kane Springs Valley, as well as with the data acquired in 2019 at the boundary between Kane Springs Valley and Coyote Spring Valley. A significant fault is evident on line 13 (fig. 25, plate 2) centered at station 13100, between lines 10 and 11; a second fault, which appears to accommodate offset of the Paleozoic even deeper is seen at station 5500. On line 14 (fig. 26, plate 2), a significant fault is seen in the vicinity of 14500, near the intersection with line 10. An offset of the Paleozoic carbonates is not seen at this location, but low resistivities associated with the basin fill to the southwest terminate at that location. A second fault that accommodate offsets of deeper Paleozoic carbonates is seen at station 11300.

Figure 28 shows the 2021 CSAMT lines 13 and 14 on the left in Coyote Spring Valley and the Kane Springs Valley 2012 axis line oriented in the same direction, northeast, starting approximately 2,290 m (7,500 ft) from the northeast ends of CSAMT

lines 13 and 14, and extending 18 km (11 mi) along the axis of Kane Springs Valley. The northern 11 km (7 mi) of the axis line show moderate and low resistivities (shaded green), suggesting very thick basin-fill material more than 1,000 m (3,200 ft) thick, north of approximately station 5500 of the axis line. A significant concealed fault is interpreted at that station. The area north of station 5500 appears similar to the data in Coyote Spring Valley, where basin-fill is known to be thick as shown from borehole data. In addition, the increasing thickness of the basin-fill material to the northeast of station 5500 of the axis line is in good agreement with the interpreted geologic cross sections through Kane Springs Valley in Swadley et al. (1994). The southwest part of the axis line, however, has moderately shallow high resistivities, and very shallow high resistivities on the last few stations on the southwest end, indicating shallow high resistivity Paleozoic carbonate rocks. Moving farther to the southwest, these high resistivities are also seen on the northeast ends of 2021 CSAMT lines 13 and 14 (fig. 28). As lines 13 and 14 extend out into Coyote Spring Valley, the high resistivities are offset across faults dropping deeper into thick basin fill.

To understand the geometry of the structure and lithologic materials that occur in northern Coyote Spring Valley, a modified fence diagram was developed using these data. Figure 29 provides the basis for the modified fence diagram. This figure focuses on the three CSAMT lines for the elevation of 450 m including the axial Kane Springs Valley CSAMT line and CSAMT lines 13 and 14.

Figure 29 shows a summary of these resistivity results in map view at an elevation of 450 m (1,475 ft) overlain on the Rowley et al. (2017) geologic map for reference. High resistivity, in this case associated with Paleozoic dolomites and limestones, is shown shaded toward blue. Moderate and low resistivities are shaded green to

orange to red, in this case associated with basin-fill material. The high resistivity block of material is clearly seen in dark blue at the southwest end of Kane Springs Valley along line 10 and at the northeast ends of lines 12, 13, and 14 where they intersect line 10 (fig. 29). High resistivity blocks occur on the northeast third of the 2021 CSAMT line 13 (fig. 25), the northeast end of the 2021 CSAMT line 14 (fig. 26), on the northeast end of the 2019 CSAMT line 12 (fig. 24), and the southwest end of the 2012 CSAMT axis line (figs. 18 through 21). Moderately shallow high resistivities extend northeast along Kane Springs Valley for approximately 6 km (4 mi). On figure 29, the high resistivity block of material as described extends from the northern LWRFS boundary fault identified on the figure as the dashed blue line approximately 10.4 km (5.7 miles) northeast to station 5500 of the axis line. Northeast of that, high resistivity Paleozoic carbonates are not observed for the remaining 11 km (7 mi) to the end of the 2012 axis line, likely indicating very thick basin-fill material (fig. 28) in that area of Kane Springs Valley.

Combining the 2021 CSAMT lines with the 2012 and 2019 CSAMT lines verifies the presence of a high resistivity large block of material consistent with Paleozoic carbonates at the southwest end of Kane Springs Valley. This high resistivity block is bounded on the southwest by several major faults; southwest of these faults in Coyote Spring Valley the high resistivity Paleozoic carbonates are offset deeper, and the overlying basin-fill material (moderate and low resistivity material) is substantially thicker.

SOUTHERN COYOTE SPRING VALLEY AND THE MUDDY RIVER SPRINGS AREA CSAMT INVESTIGATION

In addition to the 2019 CSAMT Survey conducted in northern Coyote Spring Valley, a

CSAMT survey was conducted in southern Coyote Spring Valley, including a portion of the Muddy River Springs Area in 2019. This CSAMT investigation included three CSAMT lines labelled A, B, and C, (fig. 7). These CSAMT surveys, as with all previous surveys, were used to interpret lithologies based on known resistivity values.

The CSAMT line A is shown in figure 30 and plate 2; the west end of the line was located approximately 150 m (500 ft) east of Highway 93. Cultural interference (i.e., man-made features such as fences, power lines, pipelines, etc.) was experienced due to very large powerlines located 700 m (2,300 ft) west of station 0. In addition, infrastructure was being constructed in the vicinity of stations 2000 to 3000 resulting in very noisy data at these stations due to buried man-made cultural features. The very unusual resistivity data near the west end of the line in the upper 300 m (1,000 ft) of the section, centered at station 2100, is likely the result of noise interference, and it is not likely a valid geologic structure. East of approximately station 3300, the data appear reasonable.

The dominant feature on the CSAMT Line A (fig. 30, plate 2) is a block of very high resistivity material from station 8800 to 10800, which is in very good agreement with the Rowley et al. (2017) geologic map that shows an isolated outcrop of Mississippian limestone (identified as MD on the Rowley et al., 2017 map) at that location. This feature is likely a horst structure, where the related graben structures are deeper than the geophysical survey was able to detect. The CSAMT data and the Rowley et al. (2017) map differ, however, in that the concealed faults are likely much closer to the outcrop than shown on the geologic map.

It should be noted that the basin fill and underlying material are very different west of the outcrop than east (fig. 30, plate 2). On the west, two distinct low resistivity layers (shaded orange to red)

are evident in the upper 460 m (1,500 ft) of material. The shallowest layer likely represents basin fill (saturated and/or fine-grained), while the deeper layer appears to be lower in resistivity, thicker, and plunging to the west slightly more steeply. In contrast, east of the outcrop, two low resistivity layers are also seen, but they are almost identical in resistivity and are both almost horizontal from the limestone outcrop to the east for almost 3 km (2 mi), where they appear covered by very high resistivity material beginning at about station 19700. In addition, moderate resistivities extend up from depth to shallower levels east of the outcrop relative to west of the outcrop.

Near the east end of the line, at station 26800 (fig. 30), the CSAMT transect crosses a concealed fault shown on the geologic map; an abrupt change to high resistivities is seen at the location consistent with Ordovician dolomite also part of the Paleozoic carbonates, mapped as cropping out in that vicinity (fig. 30, plate 2). The Rowley et al. (2017) geologic map shows a very narrow outcrop of dolomite from station 27200 to 28000, though station 28200 (the end of the line) is also very highly resistive, suggesting that the basin fill is extremely thin at the end of the transect (fig. 30, plate 2). In this case the geophysics confirmed the presence of a fault in this area, although farther west than the geologic map suggests.

On the east half of this transect (fig. 30, plate 2) is a section of the line where a very high resistivity surface layer (shaded blue) is observed, beginning at about station 19700, and thickening very gradually to the east toward the dolomite outcrop. This high resistivity layer may represent large-grained, dry, eroded material from the dolomite cropping out on the east end of the line. Beneath the high resistivity layer, the low resistivity layers discussed above are distorted, and the deeper layer thickens substantially, with low values extending to depths of 760 m (2,500 ft) in the cross section (fig.

30, plate 2). This thick zone of low resistivities could indicate that the area centered on station 22900 was at one time a topographic low, such as a narrow valley, and has been filled in with a substantially thicker layer of fine-grained basin-fill material. An alternative interpretation would be that the CSAMT line crosses a substantial, broad fault zone, centered approximately on station 22900 and as much as 1,830 m (6,000 ft) wide. A north-south fault is shown on the geologic map approximately 600 m (1,000 ft) north of the line, as the contact between the Ordovician dolomite of the Meadow Valley Mountains on the east and the basin fill on the west. A broad fault zone is not specifically labeled on the geologic map in this area, though one is labeled in Kane Springs Wash fault zone farther to the north. If this thicker, deep low resistivity zone represents a broad fault zone, this may represent a preferred flow path for groundwater. If, however, the low resistivities are the result of a much thicker “deposit” of very fine-grained basin-fill material such as clay, the area may represent a flow barrier.

CSAMT line B is shown in figure 31 and plate 2. Similar to line A, line B is oriented east-west, and used the same transmitter as line A. Although the west end of line B is 1,830 m (6,000 ft) east of Highway 93, the large power lines are only 335 m (1,100 ft) west of station 0. In addition, smaller, single-pole power lines cross the line near station 5300, and large, double-pole power lines cross the line near station 6100. Data at stations 5700, 5900, and 6100 were too noisy to use in modeling of this transect.

Similar to line A, the dominant feature on line B is a very high resistivity block in the middle of the line, centered at station 10300 (fig. 31, plate 2); the geologic map shows Mississippian limestone from station 9000 to 11500 near the northernmost edge of the Arrow Canyon Range. It is possible that the resistive block in the center of line A is a

continuation of the resistive block on line B, and that if CSAMT lines had been run between lines A and B, the resistive limestone block would be evident as well. The basin-fill material and possible underlying volcanics that are west and east of the limestone block show similar resistivity levels to line A (fig. 30), but unlike line A, multiple low resistivity layers are not seen on line B. The concealed faults on the geologic map on each side of the outcrop are very close to the outcrop on this line, in good agreement with the CSAMT data. A buried fault is also evident in the CSAMT data in the vicinity of station 18300, which may be the actual location of a concealed fault on the map at station 19600 (fig. 31, plate 2). Near the west end of the line, another buried fault is indicated by the CSAMT in the vicinity of station 2500; again, this may be the actual location for a concealed fault on the map at station 4000. Although faults are mapped on the Rowley et al. (2017) geologic map, there is evidence from the survey that these faults actually occur west of the mapped locations in both cases.

The resistivity results for line C are shown in figure 32, plate 2. Line C was oriented northeast-southwest (fig. 7), and therefore a different transmitter location was needed. Power lines and State Route 168 intersect this line in the vicinity of station 13300 (fig. 32, plate 2). According to the geologic map, the entire survey line was on basin-fill material, with no mapped outcrops. The map indicates that this line crossed a concealed strike-slip fault in the vicinity of station 3500 and a second, roughly parallel concealed fault in the vicinity of station 13200. The CSAMT data indicate faults near those two locations that have normal slip, and the line as a whole has the appearance of a very large (on the order of miles) horst-and-graben feature. The fault on the southwest near station 3500 has high resistivity material southwest of the fault, across the fault from moderately low

resistivity toward the center of the line. The fault on the northeast near station 13200 has high resistivity northeast of the fault, across the fault from moderately low resistivity toward the center of the line. The line is thus divided into three segments: high resistivity from the southwest end to station 3500, moderately low resistivity from station 3500 to 13200, and high resistivity from 13200 to the northeast end of the line.

In the center segment of the line (fig. 32), several very small, anomalous, isolated areas are seen in the deepest data; these features are likely noise in the low-frequency data and are not necessarily valid geologic anomalies. For example, the likely noise from low frequency data is seen at stations 10500 and 12100 (fig. 32, plate 2). In the near-surface, upper 150 m (500 ft) of the section, this line is very similar to the others, with low resistivity basin-fill material hiding deeper structure. The southwest end of the line has lower resistivities in the near surface than the northeast end, with the low resistivity near surface material weakening and becoming thinner as the line extends to the northeast. The east end of line B approaches but does not cross line C. The general appearance of the resistivity structure on the two lines in this area is very similar.

CORRELATIONS TO GEOPHYSICAL GRAVITY DATA

In addition to correlating the CSAMT survey data with mapped surface geology as verification and as an aid in interpretation, the survey data available were also compared to other geophysical data. There is little publicly available data in Kane Springs Valley and Coyote Spring Valley in the vicinity of the CSAMT lines. Phelps et al. (2000) described gravity measurements in the area, some of which are near three of the CSAMT survey lines. In geophysical gravity surveys, measurements are made at many points on the ground of the gravity

anomaly (relative to an oblate spheroid of uniform density) to determine changes in the density of subsurface material, from which subsurface structure can be interpreted. Although gravity surveys are measuring a different physical characteristic of the subsurface than CSAMT, the two surveys do commonly (though not always) show very similar results. For example, compacted, tight rock such as granite is more dense than unconsolidated, loose basin-fill material. Similarly, dense, tight rock such as granite is usually more resistive electrically than unconsolidated basin-fill material, particularly where fine-grained clays and silts are present in the basin fill. Since there are other influences on the electrical resistivity of subsurface material (such as fluids), there is not always a one-to-one correspondence between high density and high resistivity. In the Kane Springs Valley and Coyote Spring Valley, however, the unconsolidated basin-fill material does appear to be electrically moderate to low resistivity and low density, which contrasts with the relative to the higher resistivity, higher density of the primarily Paleozoic carbonate bedrock. Some basin fill, where coarse grained and dry, can have high resistivity but still be low density. As a result, both gravity and CSAMT survey data/results appear to be useful in delineating contacts between the basin fill and Paleozoic carbonate rocks as well as thickness of the basin-fill material.

In Phelps et al. (2000) gravity results were presented as simple two-layer cross sections along survey lines of basin-fill material (usually labeled Cs for Cenozoic basin fill) overlying high-density bedrock (labeled Paleozoic for Paleozoic carbonate rock). Figures 33, 34, and 35 all include a plan view map of the gravity survey line in relation to the nearby CSAMT line, the gravity model cross section from Phelps et al. (2000), and the equivalent segment of the nearby CSAMT line. The CSAMT and gravity lines are not coincident, or

even parallel, but the data sets are close enough to allow at least a general correlation of results. The gravity and CSAMT cross sections have been scaled and cropped in order to show the same length and depth of the survey results.

U.S. Geological Survey Gravity Line N2 and CSAMT Line 11

Figure 33 shows the correlation of the Phelps et al. (2000) gravity line N2 with the southeast segment of CSAMT line 11. The map (A) shows that the angle between the lines is approximately 30 degrees, but both lines are on or near outcropping bedrock on the eastern end of the lines, and both extend out into the valley to the west and northwest. Figure 33 (B) shows the gravity model cross section, with high density (shaded blue) Paleozoic material at the surface on the east. These Paleozoic carbonate rocks deepen quickly in the easternmost 1 km of the line, as the basin-fill material thickens, extending more than 1 km deep. On the far western end of the gravity line, the Paleozoic carbonates are becoming shallower, though at this location along the line the Paleozoic carbonates are still 600 m below the surface.

Similarly, in figure 33 (C), CSAMT line 11 shows very high resistivity material (shaded blue) on the east end of the survey line, dropping off over a very short distance in the vicinity of a concealed fault on the geologic map. West of the fault, resistivities in general are moderate to low (green to red) to the depth of the survey, in very good agreement with the gravity cross section showing very thick basin-fill material. As the CSAMT line extends west out into the valley, the highly resistive carbonate material (blue) reappears at depth, although it reappears farther east than indicated in the gravity cross section. The CSAMT line shows considerable variation in the resistivity of the basin-fill material due to variations in grain size and fluid characteristics (such as TDS), which

would not be evident in the gravity measurements. In general, the gravity and CSAMT data sets show very good agreement in this area, particularly with respect to the eastern ends of the lines; both show a steep drop-off of Paleozoic carbonates rather than a very shallow, slow thickening of basin-fill material as the lines move out into the valley.

U.S. Geological Survey Gravity Line N1 and CSAMT Line 10

Figure 34 shows the correlation of the Phelps et al. (2000) gravity line N1 with the southeast segment of CSAMT line 10. The map (A) shows that the angle between the lines is approximately 25 degrees, but both lines are near outcropping bedrock on the southeastern end of the lines, and both extend northwest and intersect very near the outcropping dolomite at the mouth of Kane Springs Valley. Figure 34 (B) shows the gravity model cross section, with high density (shaded blue) Paleozoic carbonate material at the surface on the east. Unlike gravity line N2, the cross section for line N1 is almost entirely Paleozoic material (blue), with high density material very close to the surface along most of the gravity line. These Paleozoic carbonate rocks are essentially at the surface in the middle of the line, even though surface mapping indicates Cs basin-fill material. West of the outcropping dolomite at the mouth of Kane Springs Valley, basin fill (Cs) begins to thicken somewhat.

Similarly, figure 34 map (C), CSAMT line 10 shows very high resistivity material (shaded blue) dominating the cross section. Some moderate and low resistivity values are seen along the line, likely indicating local variations within the Paleozoic carbonates, rather than basin-fill material. The large resistive block of material at the mouth of Kane Springs Valley interpreted based on the other CSAMT lines (including line 10) is consistent with

the primarily high-density material seen here on gravity line N1.

U.S. Geological Survey Gravity Line S1 and CSAMT Coyote Spring Line B (CS Line B)

Figure 35 shows the correlation of the Phelps et al. (2000) gravity line S1 with the western segment of CSAMT line B in Coyote Spring Valley. In map (A), these two survey lines are approximately parallel, and approximately 0.9 km apart. CSAMT Coyote Spring line B crosses outcropping carbonates in the center of the line, but the gravity measurements were made along a road north of the outcrop and were physically on basin-fill material. Figure 35 map (B) shows the gravity model cross section, with high density (shaded blue) Paleozoic carbonate material near the surface on the east end of the line as expected, and very shallow Paleozoic carbonate material in the center of the line north of the outcrop. Very shallow Paleozoic carbonate materials are also seen near the 3 km distance mark, west of which is what appears to be a fault and deep trough of basin fill.

The CSAMT line B cross section (C), shows very high resistivity material (shaded blue) near the surface (but not cropping out) on the eastern 2 km of the survey line. The outcropping carbonates in the center of the line are evident as a zone of very high resistivity, bounded by steeply dipping faults on the east and west side in good agreement with geologic surface mapping. In this case, the CSAMT data suggest that low resistivity basin-fill material (shaded green to red) is very thick east of the outcrop; this contradicts the relatively thin basin-fill material shown in the gravity cross section. West of the outcrop, the thickness of basin-fill in the CSAMT cross section shows a similar trend to the gravity line. The “trough” of thick basin fill seen in the gravity line appears to be shifted to the west

in the CSAMT line, but it is present though not bounded on the west in the CSAMT line.

Correlations to U.S. Geological Survey CSAMT Data

Although numerous CSAMT and NSAMT surveys have been acquired in Nevada since the 1980s when CSAMT systems became commercially available, most of the survey results are confidential as proprietary data held by various mineral, oil, and natural resource companies. As a result, it is difficult to correlate the current Kane Springs Valley and Coyote Spring Valley data sets with other CSAMT data as verification and as an aid in interpretation. The U.S. Geological Survey published CSAMT data acquired in Nye County, Nevada (Macy et al., 2012) and can be used, at least for a general comparison of the applicability of the CSAMT data. In that case, the U.S. Geological Survey and the Nye County Nuclear Waste Repository Project office acquired CSAMT data, as well as TEM and direct current resistivity, to better understand structures buried beneath the alluvium near the Highway 95 fault with regards to improving the understanding of groundwater flow.

The U.S. Geological Survey CSAMT survey data were acquired similarly to the Kane Springs and Coyote Spring CSAMT lines. Five survey lines were acquired, and the data were processed and modeled similarly using the same smooth-model inversion technique; coincidentally the equipment system the U.S. Geological Survey used was the same Zonge GDP32II model equipment that was used on the Kane Springs Valley and Coyote Spring Valley surveys. In a very general sense, the survey environment was similar in the two cases, both being primarily basin fill overlying deep Paleozoic carbonate rocks. In the Highway 95 study, however, there are also low resistivity tuffs present above the deep Paleozoic carbonate rocks.

Figure 36 shows the smooth model inversion cross section from the U.S. Geological Survey CSAMT line A. As with the Kane Springs Valley and Coyote Spring Valley data, station numbers are across the top of the cross section and elevation (in m) is down the side. The resistivity data are color-shaded and contoured on a logarithmic scale, but an important graphic difference is that the U.S. Geological Survey cross section shows low resistivities shaded toward blue, and high resistivities shaded toward red, while the Kane Springs Valley and Coyote Spring Valley cross sections are the reverse. In figure 36, the top (A) shows the resistivity cross section, and the bottom (B) shows the same cross section but with the geologic interpretation labels as an overlay.

Keeping in mind that inverted color scales were used on the two surveys, the results are very similar overall. The buried Paleozoic carbonate material (south end of the survey line) is high resistivity compared to the rest of the survey line, which consists primarily of low resistivity tuffs. The Highway 95 fault is seen as a near-vertical change in resistivity, similar to the basin-bounding fault seen in the Kane Springs Valley and Coyote Spring Valley survey near the southeast end of line 11 (fig. 23), for example. The depth of investigation of the two surveys was very similar, extending to approximately 900 m (2,950 ft). The resistivity contrast between the Paleozoic carbonate and the overlying basin fill and tuffs is not as strong in the U.S. Geological Survey cross sections as it is the Kane Springs Valley and Coyote Spring Valley surveys, but the two surveys are likely sensing different carbonate materials locally. For example, the U.S. Geological Survey cross section indicates that the Paleozoic carbonate rocks are approximately in the range of 60 to 250 Ω -m, while the Kane Springs Valley and Coyote Spring Valley cross sections indicate that the carbonates start at about 250 Ω -M and range into the thousands.

However, in the U.S. Geological Survey's 500 m TEM survey, the model results did also show Paleozoic carbonates more than 1000 Ω -m in resistivity in the deeper sections of that survey line. Based on Macy et al. (2012), the U.S. Geological Survey CSAMT survey provided valid useful data of the buried structures in vicinity of the Highway 95 fault and supports the interpretation of a block of resistive Paleozoic carbonate beneath more conductive units. Similarly, one result of the Kane Springs Valley and Coyote Spring Valley CSAMT survey is the identification of a resistive block of Paleozoic carbonate rocks at the southwest end of Kane Springs Valley, which would also influence groundwater flow in that area.

USE OF THE GEOPHYSICAL SURVEYS TO EXPLAIN THE HYDROGEOLOGY OF THE LOWER WHITE RIVER FLOW SYSTEM

The purpose of the geophysical investigation in southern Kane Springs Valley and northern Coyote Spring Valley was twofold: (1) to determine the best potential well sites for future groundwater production wells, and (2) to help explain the significant differences in water level elevations between measured water levels in wells from southern Kane Springs Valley and the rest of the LWRFS.

A groundwater elevation map was constructed using data available from wells completed in the BARCAS and in the Neogene basin fill of southern Kane Springs Valley, a portion of Coyote Spring Valley, and a portion of the Muddy River Springs Area (fig. 37). The well data including well name, well location, well completion information, groundwater level elevation data, and other pertinent information for the wells used to construct the groundwater elevation map shown in

figure 37 is provided in table 1. The data for this table can be found at the Nevada State Engineer's website at:

<https://tools.water.nv.gov/WaterLevelData.aspx>

(NSE, 2025). The water level elevation data was used to construct the groundwater elevation map as measured from 1998 to 2024. None of the data are from pumping wells and would reflect an aquifer under dynamic equilibrium conditions.

The wells used to develop the groundwater elevation map are completed in the BARCAS except for wells CSV3009M and CSV3011M in northern Coyote Spring Valley. Although these

two wells are comparably deep (>457 m or 1,500 ft below ground surface) and having deep perforated intervals, they are completed in the basin fill (table 1). The water levels in these two basin-fill wells correlate nicely with and are likely influenced by water levels in the Paleozoic carbonate rocks of the BARCAS as shown in figure 37. Together, all of the water levels in the wells listed on table 1 and shown on figure 37 would represent heads in the regional aquifer system that extends from southeastern Idaho, western Utah, and throughout eastern Nevada (see figure 2, showing portions of the BARCAS in eastern Nevada and western Utah).

Table 1. Water level elevation and well data used to construct water elevation map

Well Name	Well Depth (ft bgs)	Land Surface Elevation (ft)	Latitude DD NAD	Longitude DD NAD	Groundwater Elev (ft)	First Water Level Measurement	Last Reported Water Level Measurement	Beginning Screened Interval	Ending Screened Interval	Comments
KPW-1	2,017	2,870.60	37.01677	-114.86558	1,877	3/23/2007	12/12/2023	1,020	2,002	Carbonate
CSVM-3	1,230	2,650.68	37.05251	-114.98336	2,205	5/29/2003	1/3/2024	380	1,180	Carbonate
CSVM-4	1,605	2,842.38	36.99108	-114.88648	1,872	5/28/2003	12/19/2022	800	1,580	Carbonate
CSV3009M	1,580	2,595.09	36.98359	-114.96542	2,101	12/18/2008	11/14/2008	1,058	1,558	Basin-Fill
CSV3011M	1,580	2,665.72	36.98198	-114.9318	1,914	12/18/2008	11/14/2022	854	1,534	Basin-Fill
CE-VF-2	1,221	2,468.35	36.87426	-114.94669	1,856	10/16/1998	11/14/2022	860	1,220	Carbonate
CSI-2	1,019	2,208.95	36.8094	-114.90274	1,816	9/15/2005	12/19/2022	525	1,006	Carbonate
CSI-3	1,156	2,334.51	36.82542	-114.91654	1,818	10/20/2006	12/29/2022	572	1,132	Carbonate
CSI-4	1,397	2,511.40	36.85	-114.95452	1,818	9/19/2006	12/19/2022	894	1,374	Carbonate
CSVM-1	1,060	2,160.60	36.79119	-114.88621	1,818	3/20/2003	1/4/2024	320	1,020	Carbonate
CSVM-6	1,200	2,251.66	36.83252	-114.90916	1,816	3/28/2003	1/3/2024	420	1,160	Carbonate
MX-4	669	2,177.02	36.79567	-114.8928	1,818	10/16/1998	1/2/2024	ND	ND	Carbonate
MX-5	628	2,176.13	36.79513	-114.89191	1,819	5/29/1998	1/4/2024	ND	ND	Carbonate
RW-2	720	2,200.06	36.79394	-114.89442	1,815	3/5/2002	11/18/2022	460	700	Carbonate
UMVM-1	1,785	2,061.88	36.7581	-114.82324	1,815	7/15/2003	1/4/2024	960	1,760	Carbonate

Note: ND = No Data

Groundwater elevations range from a high of 672 m (2,205 ft) at well CSV3M-3 in northern Coyote Spring Valley to a low of 553 m (1,815 ft) at well RW-2 in Coyote Spring Valley and well UMVM-1 in the Muddy River Springs Area (fig. 37). In Kane Springs Valley, the one available water level data point is 572 m (1,877 ft) from the monitor/production well pair (KMW-1 and KPW-1) located at the very southern end of Kane Springs Valley. It is reasonable to infer that groundwater levels continue to rise in the direction up valley with the topography of Kane Springs Valley, hence the interpretation of a 579-m (1,900-ft) groundwater elevation contour interval northeast of the Kane Springs Valley monitor/production well pair (fig. 37).

This interpretation of the direction of groundwater flow is supported by water levels from well CSV3M-4, a monitor well with a groundwater elevation of 571 m (1,872 ft), located approximately 3,353 m (11,000 ft) southwest of the southern end of Kane Springs Valley into northern Coyote Spring Valley. This is approximately 1.5 m (5 ft) less than the groundwater level elevation at the Kane Springs Valley monitor/production well pair and indicates that the direction of groundwater flow is to the southwest through Kane Springs Valley and then into Coyote Spring Valley.

The purpose of the geophysical transects of lines 10 through 12 (figs. 22 through 24, respectively) and lines 13 and 14 (figs. 25 and 26) was to understand the buried geologic structures of southern Kane Springs Valley, northern Coyote Spring Valley, and southern Coyote Spring Valley. Geophysical transects were proposed to help determine the cause of the more than 18 m (60 ft) difference in groundwater level elevation between southern Kane Springs Valley and the exceptionally flat-water table of southern Coyote Spring Valley. The geophysical transects led to the discovery of several faults that occur in northern

Coyote Spring Valley, just south of the mouth of Kane Springs Valley. Finding and identifying the fault structures of the northern LWRFS boundary fault explained this difference in head. Although groundwater flows from Kane Springs Valley into Coyote Spring Valley, this groundwater flow is attenuated. We found that the relatively higher groundwater level elevations in Kane Springs Valley are due to the overarching local geologic structure (figs. 22, 23, and 24 [lines 10, 11, and 12, respectively] and figures 25 and 26 [lines 13 and 14]).

Groundwater level elevation data from well CSV3M-3 (completed in the carbonate) and wells CSV3009M and CSV3011M (completed in the basin fill) indicate groundwater flow from the west to the southeast into Coyote Spring Valley from Pahranaagat Valley. Well CSV3011M provides a very consistent data set showing a groundwater level elevation centered around 584 m (1,915 ft) amsl since approximately 2011. This, however, is approximately 13 m (43 ft) higher than the water level in CSV3M-4, which has a water level elevation of 571 m (1,872 ft) amsl.

The groundwater levels from these wells indicate that groundwater flows from Pahranaagat Valley in a southeastern direction toward Coyote Spring Valley. This groundwater flow runs directly into the southwest extension of the Kane Springs Wash fault zone, which causes the groundwater levels to be higher in this area due to restriction by the fault zone. Based on the groundwater level elevations in CSV3011M, CSV3M-4, and KMW-1/KPW-1, the 579-m (1,900-ft) groundwater level elevation contour is extended along the northern/western boundary of the Kane Springs Wash fault zone north of the KMW-1/KPW-1 pair in Kane Springs Valley (fig. 37).

It appears that the western boundary of the Kane Springs Valley Wash fault zone causes

monitor well CSV3011M's water level to be consistently higher. That is, the massive fault zone is a barrier to groundwater flow (figs. 22 and 23, lines 10 and 11). There is approximately 18 m (60 ft) of groundwater level difference between the area of southern Kane Springs Valley and the center of Coyote Spring Valley. There is also approximately 12 m (40 ft) head difference west of southern Kane Springs Valley and the western portion of Coyote Spring Valley due to the Kane Springs Wash fault zone (fig. 37).

The Kane Springs Wash fault zone has an apparent left-lateral offset and extends approximately 41 km (25 mi) through Kane Springs Valley, with displacement of approximately 14 km (~9 mi) and the total fault zone width of approximately 5 km (~3 mi) (Reid, 2022). The Kane Springs Wash fault zone is bounded on the east by the bounding fault that runs the length of Kane Springs Valley, where it abuts the Meadow Valley Mountains. On the west side of Kane Springs Valley, the Kane Springs Wash fault zone boundary could be as far west as the Willow Springs fault and its extension into Coyote Spring Valley (Reid, 2022). Figures 22, 23, and 37 show these features in both cross section and plan view.

Figure 37 shows the groundwater level elevation map with the structures identified on the map. Figure 23, line 11 identifies numerous normal faults occurring in the Kane Springs Wash fault zone, which supports the concept of a transfer zone of accommodation/extension in northern Coyote Spring Valley (Reid, 2022).

The northern LWRFS boundary fault has been confirmed and can be seen on geophysical transects provided in figures 22, 23, 25, and 26 (lines 10, 11, 13, and 14, respectively). This is another example of the complexity of the groundwater flow through the LWRFS and how the buried geologic structures

influence groundwater flow directions, hydraulic gradients, and groundwater level elevations. Figure 22, line 10, indicates the presence of a high (shallow, near surface) shelf of Paleozoic carbonate rocks. Groundwater that occurs in the BARCAS in northern Coyote Spring Valley runs into a "wall" of fine-grained materials, identified as Lower Miocene to Holocene basin fill, as shown in figure 23 (line 11). Line 11 is approximately 3,810 m (12,500 ft) southwest of line 10 (fig. 22) as shown on the location map (fig. 1). The fine-grained materials back up the groundwater flow in this area due to the significant change in hydraulic conductivity from the BARCAS to the basin fill, causing the higher heads seen in the Kane Springs Valley monitor/production well pair versus the lower (more than 18 m or 60 ft) heads in wells in southern Coyote Spring Valley and in the Muddy River Springs Area (fig. 37). In summary, it appears that the higher heads northeast of the northern LWRFS boundary fault occur because of the higher hydraulic conductivity nature of the BARCAS versus the lower conductivities of the basin-fill materials that groundwater encounters.

Wilson (2019) conducted a study of the water levels and the regional potentiometric surface of the Upper Carbonate Rock Aquifer in Clark County. Wilson's (2019) map indicated groundwater flow from west to east from the Sheep Range; however, it did not extend through the Lincoln County portion of Coyote Spring Valley. The data between Wilson's study and the regional groundwater level elevation map (fig. 37) provided in this report are consistent. Wilson (2019) also indicated an exceptionally flat area of groundwater levels within the southern Coyote Spring Valley, especially as compared to the groundwater level data in southern Kane Springs Valley and northern Coyote Spring Valley.

A hydraulic gradient of 0.35 m/km (1.9 ft/mi) can be estimated from Kane Springs Valley into

northern Coyote Spring Valley from well CSVN-4 to well CE-VF-2. Note that historic data from CE-VF-2 was useful before the casing broke, which allowed alluvial water to enter the borehole causing a rise in water levels (NSE, 2025). Looking at the groundwater level elevation contours 671 m (2,200 ft) to 579 m (1,900 ft), the hydraulic gradient from Pahrnatagat Valley into Coyote Spring Valley is much steeper at 11.6 m/km (61.5 ft/mi). However, once again, when this groundwater flow hits the massive Kane Springs Wash fault zone, it is impeded by the faulting that then causes a near zero gradient below/farther down gradient.

There is likely another fault or faults that occur in the vicinity of the 564 m (1,850 ft) water-level elevation contour interval. The 564 m (1,850 ft) contour interval separates groundwater level elevations above 564 m (1,850 ft) amsl from those that are centered around a groundwater level elevation of 554 m (1,816 ft) amsl in the southern portion of Coyote Spring Valley and the broad Muddy River Springs Area. In a span of approximately 2.41 km (1.5 mi) from well CE-VF-2 to well CSI-4, the hydraulic gradient steepens to approximately 0.68 m/km (3.5 ft/mi) from 0.35 m/km (1.9 ft/mi) to a near zero hydraulic gradient in the southern portion of Coyote Spring Valley. The water level elevations in this area can be conceptualized as a “stair-step” system, where the vicinities of the faults represent the vertical portion of the “stair”, and the “steps” are the areas of very similar water levels, a virtually flat-water table. In this “stair-step” system, the faults impede groundwater flow creating higher groundwater elevations above the stairs and lower groundwater elevations below the stairs.

The results from the CSAMT geophysics investigations explain what is seen in the groundwater level data from these wells, especially in southern Kane Springs Valley and northern Coyote Spring Valley. Before the geophysical data

were collected, the groundwater level elevation data from these wells were poorly understood in relation to groundwater elevation data in nearby parts of the Coyote Spring Valley. The geophysics are highly valuable in providing a basis for explaining physical conditions and thereby allow better understanding of this hydrologic system. Once the physical conditions are understood, the focus can then change to address other issues such as impact to springs, wells, other water users in the basin.

DISCUSSION

Recent studies performed in southeastern Nevada have helped shed new light into the complex geological history and hydrology of the area. Kreemer et al. (2010) analyzed data from GPS stations and modeled the strain rate tensor field using horizontal GPS velocities and earthquake focal mechanisms. Data were used to create a strain rate tensor model that indicates a zone of high strain rates ($20\text{--}30 \times 10^{-9}$ /year) that coincides with the southern Nevada transverse zone, which is interpreted overall as accommodating left-lateral shear. This shear is locally referred to as the Pahrnatagat shear zone. The Pahrnatagat shear zone follows a north-northeast trending gradient in the regional gravity field and topography (Eaton et al., 1978) that separates a region to the south that had extraordinary—1.5 times more—extension compared to much more modest extension in the region to the north (Wernicke et al., 1988), and that may provide a zone of weakness for localized deformation (Kreemer et al., 2010). There is independent geological and geophysical evidence for left-lateral motion in the Pahrnatagat shear zone (Kreemer et al., 2010). The sinistral Pahrnatagat shear zone is required to kinematically accommodate the different strain rates between the distributed zone of extension to the south (i.e., Mojave Desert and northern Arizona seismic belt)

and the much more rigid central Great Basin to the north (Kreemer et al., 2010). The CSAMT and NSAMT surveys performed in northern Coyote Spring Valley and Kane Springs Valley have confirmed a set of northeast-striking sinistral faults that have accumulated sinistral offset in the Kane Springs Wash fault zone, which is a result of a zone of weakness created by the Pahrnagat shear zone.

The distinctive extensional forces of the Basin and Range were exemplified throughout the CSAMT and NSAMT surveys, examples of which can be found in plate 2. These figures illustrate a “stair-step” faulting of downthrown blocks that are illustrative of extensional forces versus compression (which is also present in the Basin and Range, i.e., the Pahrnagat shear zone versus other mapped thrust faults). The “stair-stepping” of extensional faulting would affect groundwater flow or the hydrology of these basins by juxtaposing differing material types with different hydraulic conductivities adjacent to each other, which then in turn would affect the ability of the materials to transmit groundwater flow.

Geophysical methods are widely used around the world to measure physical properties of materials that are used to infer information about the surface and subsurface of the Earth. The CSAMT and NSAMT geophysical methods that have been used in the investigations reported throughout this report are proven useful in characterizing known buried structures, identifying new structures, and identifying lithologies in the area of investigation. In this study, the CSAMT method was performed to help identify geologic features in Kane Springs Valley, Coyote Spring Valley, and the Muddy River Springs Area that have relevance to and would provide specific, local information on the hydrogeology of the areas investigated. The CSAMT surveys provided both quantitative and qualitative information in these basins. The

CSAMT surveys were calibrated with lithologic logs, geological maps, downhole geophysical logs, and ground-truthing on exposed geological formations. The calibrated surveys thereby provided a known resistivity value for those geologic formations, which were applied to subsurface measurements.

The CSAMT surveys identified numerous faults throughout both basins that were not identified in previous investigations and have confirmed and refined the location of surficially mapped features such as the Kane Springs Wash fault zone, which is a massive geologic feature that extends from the Kane Springs Valley caldera complex in northern Kane Springs Valley all the way into northern Coyote Spring Valley. More importantly, these CSAMT surveys have identified a buried fault, the northern LWRFS boundary fault, that may be the controlling factor in the dramatic differences between water level elevations in monitor wells in Kane Springs Valley, and those in southern Coyote Spring Valley, and the Muddy River Springs Area. The northern LWRFS boundary fault (plate 1) is marked by the difference between the highly resistive Paleozoic carbonate rocks found in line 10 (fig. 22) and the much less resistive basin fill in line 11 (fig. 23). The exact location of the fault was found in detail in lines 13 and 14 (figs. 25 and 26), which confirmed the downthrown nature of the boundary fault. There is over 800 m (2,500 ft) of vertical offset of the Paleozoic carbonate rocks seen between lines 10 and 11. This fault significantly impedes the flow of groundwater from Kane Springs Valley and northern Coyote Spring Valley into the southern portion of Coyote Spring Valley, south of the transect of line 10. This agrees with the location of steep hydraulic gradients illustrated on figure 37.

In southern Coyote Spring Valley, numerous known faults were confirmed, and previously unknown faults were discovered in the CSAMT

surveys. Some of these newly identified faults may also impede groundwater flow, which may explain the difference between the groundwater elevations on the western side of the valley and those on the eastern side of the valley (fig. 37). Additionally, the extent of highly resistive Paleozoic carbonate rock locations were further delineated in this study, which enhanced the understanding of the complex geology in this area.

SUMMARY

Geophysical methods are useful in determining subsurface structures and changes or differences in lithology. Geophysical methods are employed for many reasons that include, but may not be limited to (1) performing preliminary site investigations of the project area, (2) refining a location of interest, (3) siting supply wells when there are limited funds available, and (4) investigating the deep subsurface, e.g., up to thousands of kilometers below the surface that would otherwise be cost prohibitive if undertaken through a drilling program.

In this project specifically, the geophysical methods located and delineated a resistive block and associated faults at the southwest end of Kane Springs Valley and helped provide a better understanding of groundwater flow in that area, as well as explaining unexpected differences in groundwater elevations between Kane Springs Valley and Coyote Spring Valley in wells in the area. In addition, the geophysical data will be useful in planning the locations and depths of future wells in both Kane Springs Valley and Coyote Spring Valley, particularly in the Muddy River Springs Area.

In addition to this study, LCWD and VWC have conducted similar geophysical investigations in Dry Lake Valley, Clover Valley, and the Tule Desert hydrographic basins. We found this tool

invaluable in further understanding of the geologic structure of these basins, specifically to better understand the BARCAS that occurs extensively throughout eastern Nevada and is the target of water resource development projects. LCWD and VWC have run over 227 km (140 mi) of geophysical surveys in these basins. All totaled, in this study including the geophysical surveys conducted in Kane Springs Valley and Coyote Spring Valley, LCWD, VWC, and CSI have run over 328 km (203 mi) of combined CSAMT and NSAMT surveys.

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Figure 1. Location map of Kane Springs Valley, Coyote Springs Valley, Muddy River Springs Area, and the lower White River flow system

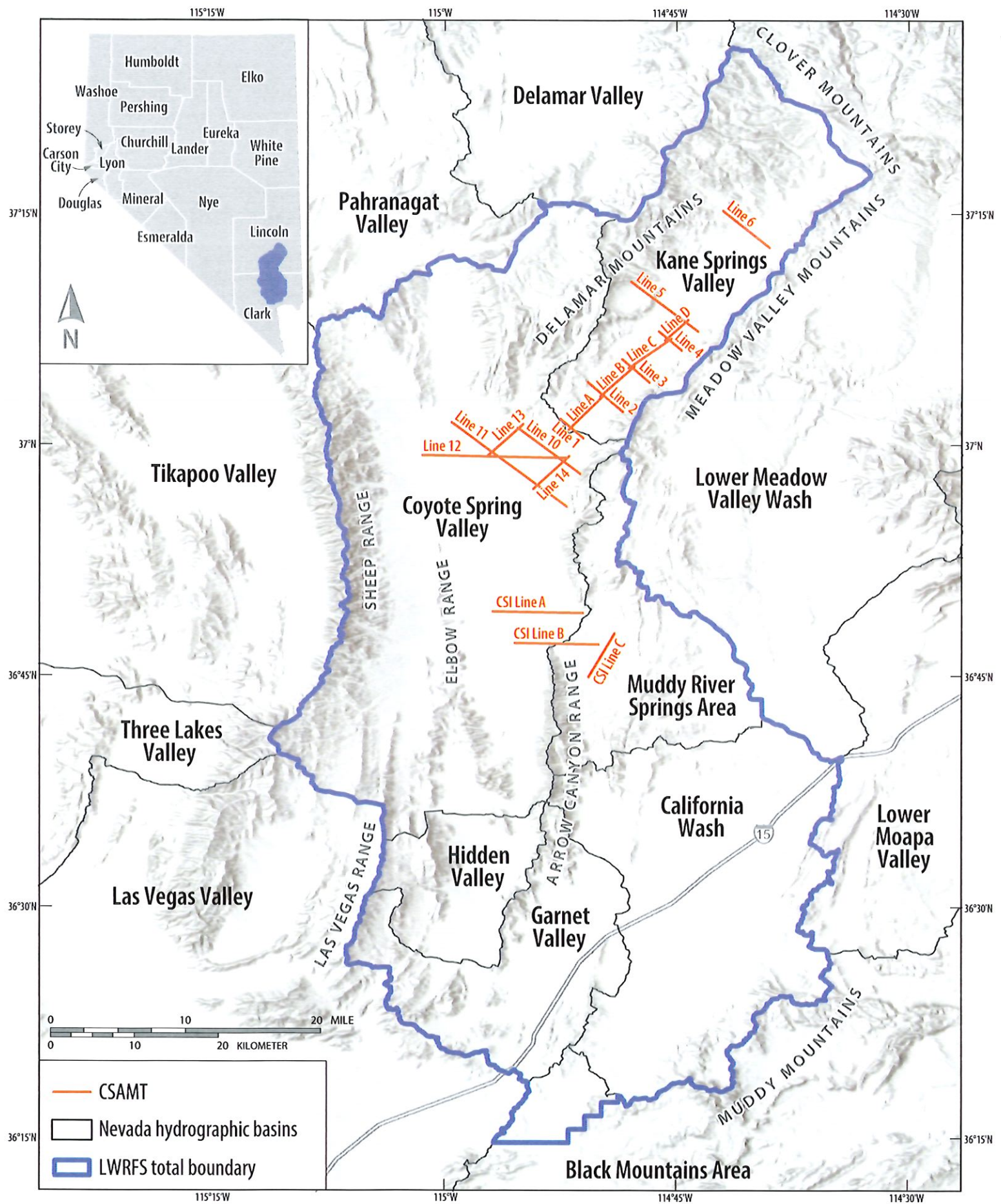
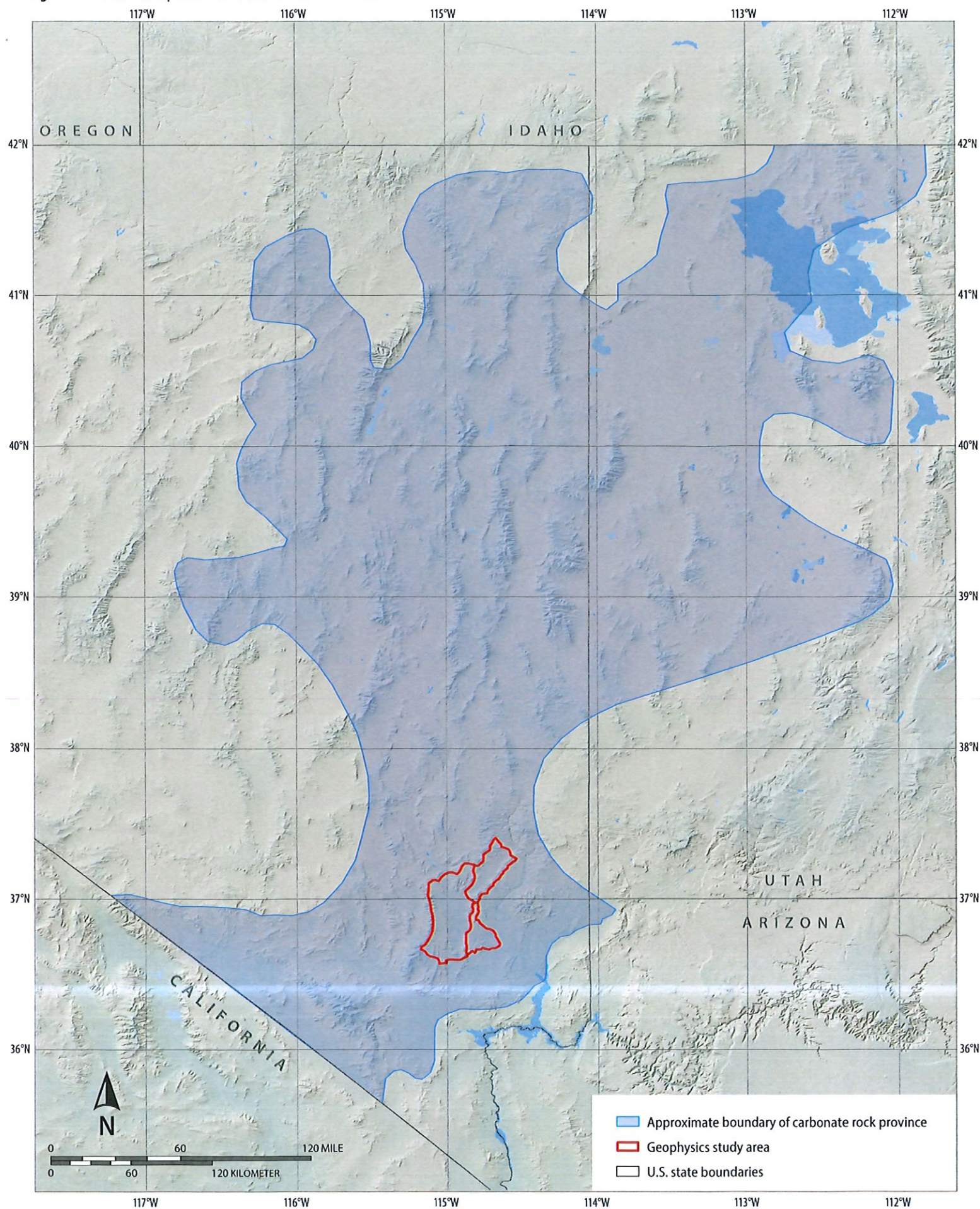


Figure 2. Carbonate rock province of eastern Nevada and western Utah



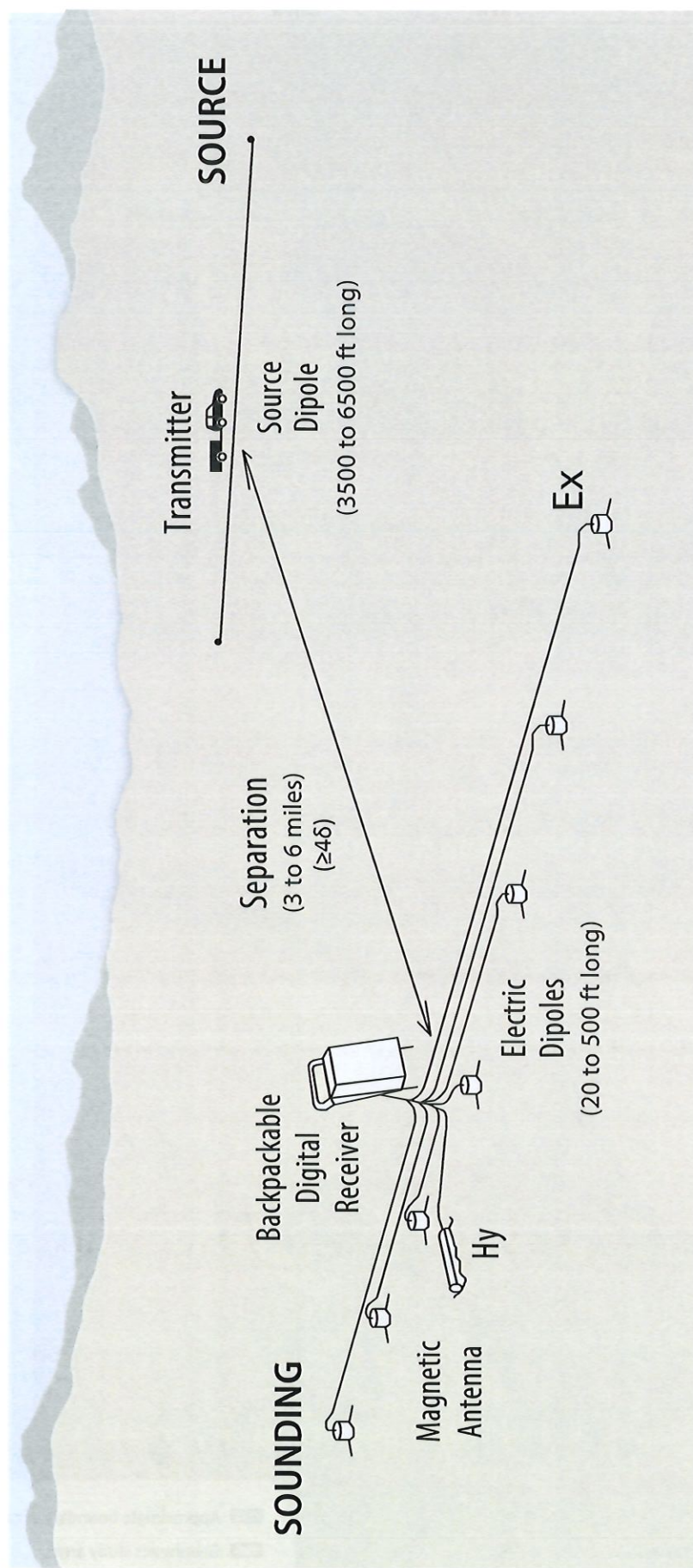


Figure 3. CSAMT field survey set-up schematic (not to scale)

Source: Zonge International Manuals

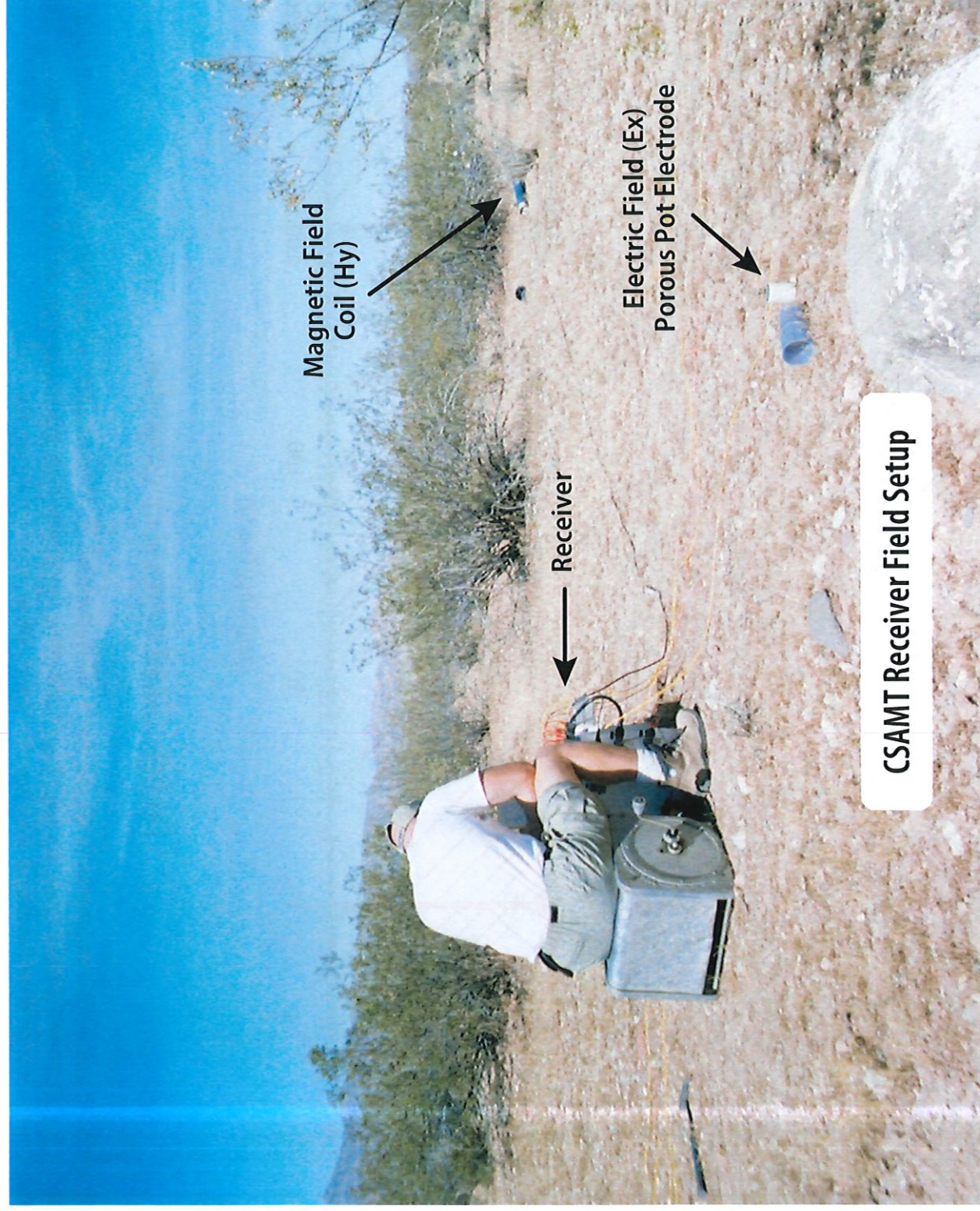
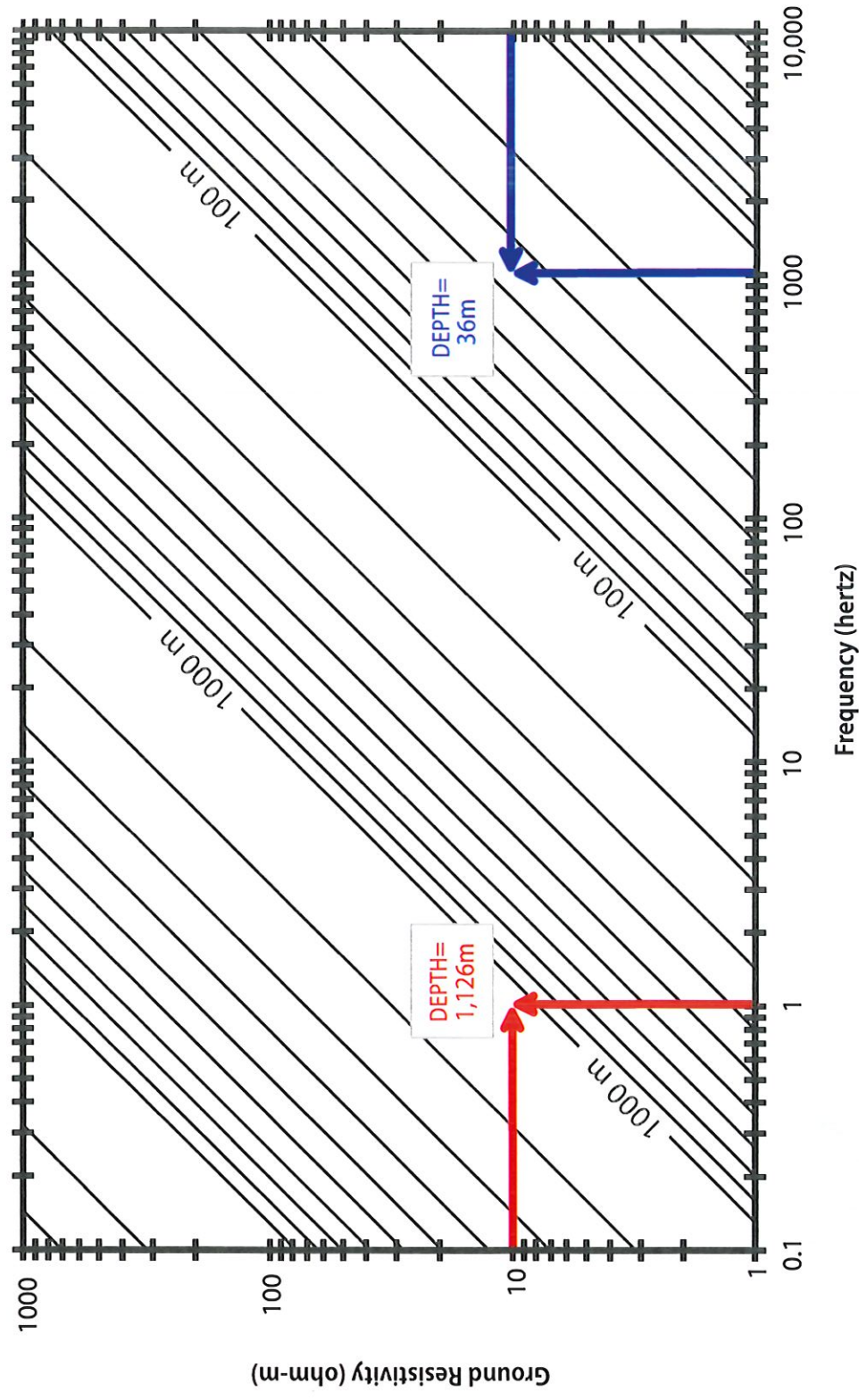


Figure 4. CSAMT receiver set-up in the Tule Desert, Lincoln County, Nevada.
Source: Zonge International Manuals.



Far field CSAMT depth of investigation

Figure 5. In a simple homogeneous earth, the depth of investigation of far-field CSAMT is dependent on both resistivity and frequency. At a given ground resistivity, high frequencies sense shallower-than-low frequencies, and at a given frequency, high resistivities allow penetration deeper than low resistivities. (Redrawn from Zonge, K.L., 1992).

Figure 6. Geologic map and location map of CSAMT and NSAMT transect through southern Kane Springs Valley and northern Coyote Spring Valley

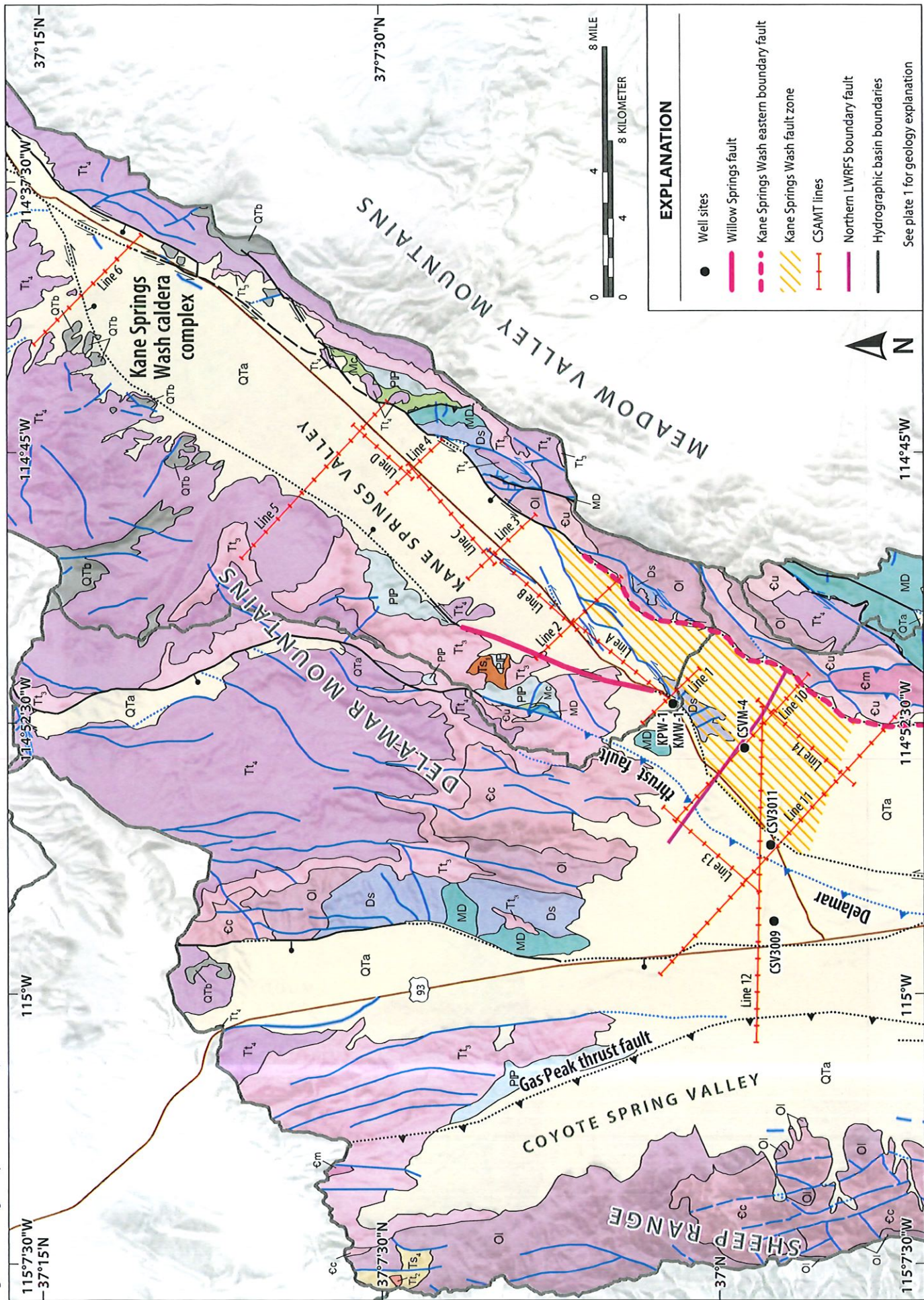
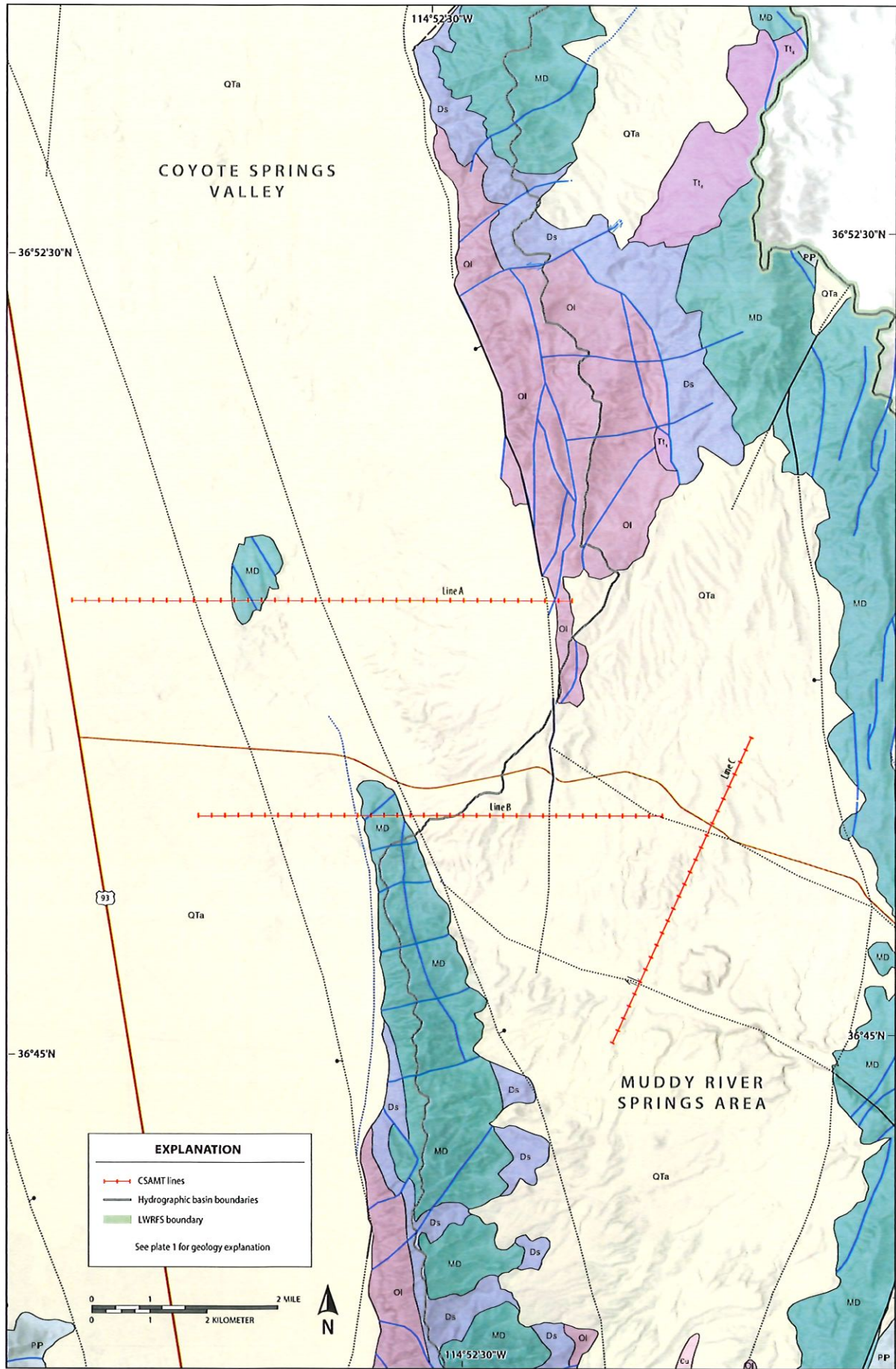


Figure 7. Location of CSAMT transects through and near the Arrow Canyon Range in central Coyote Spring Valley and the Muddy River Springs Area



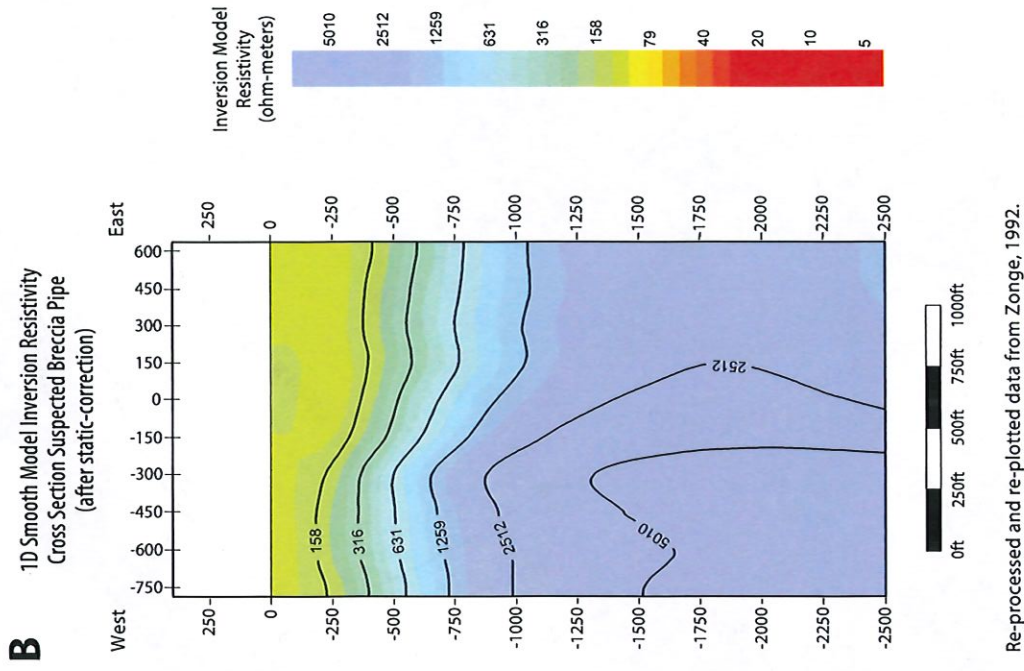
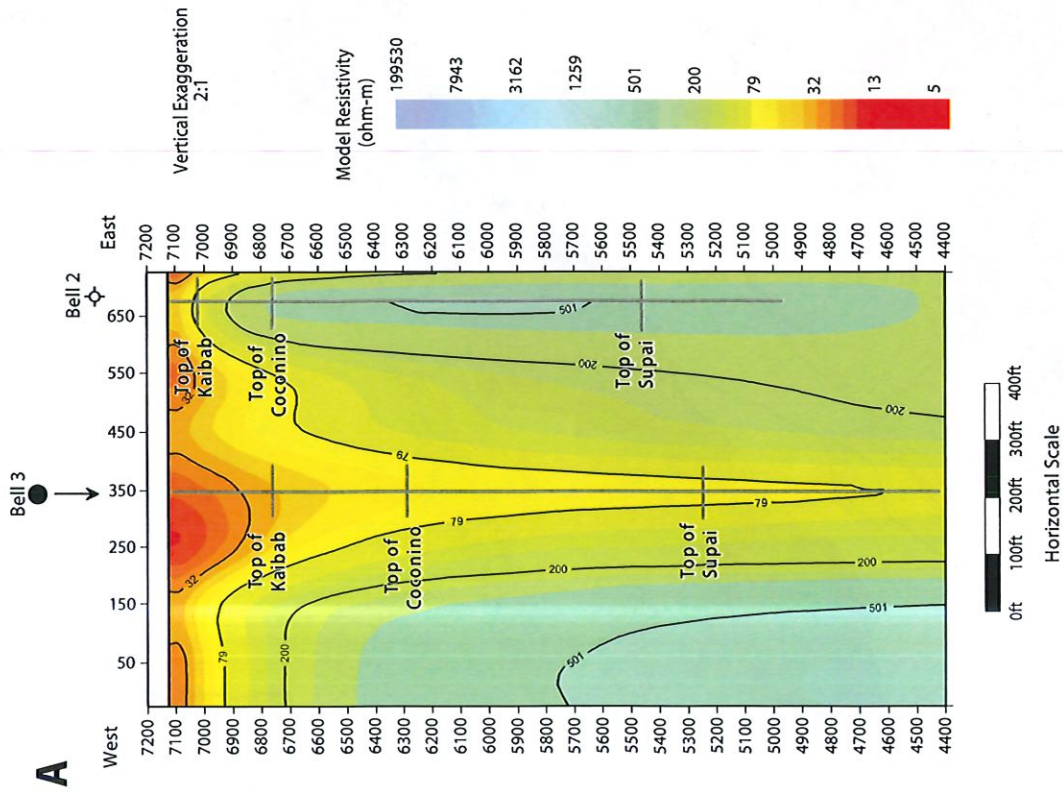
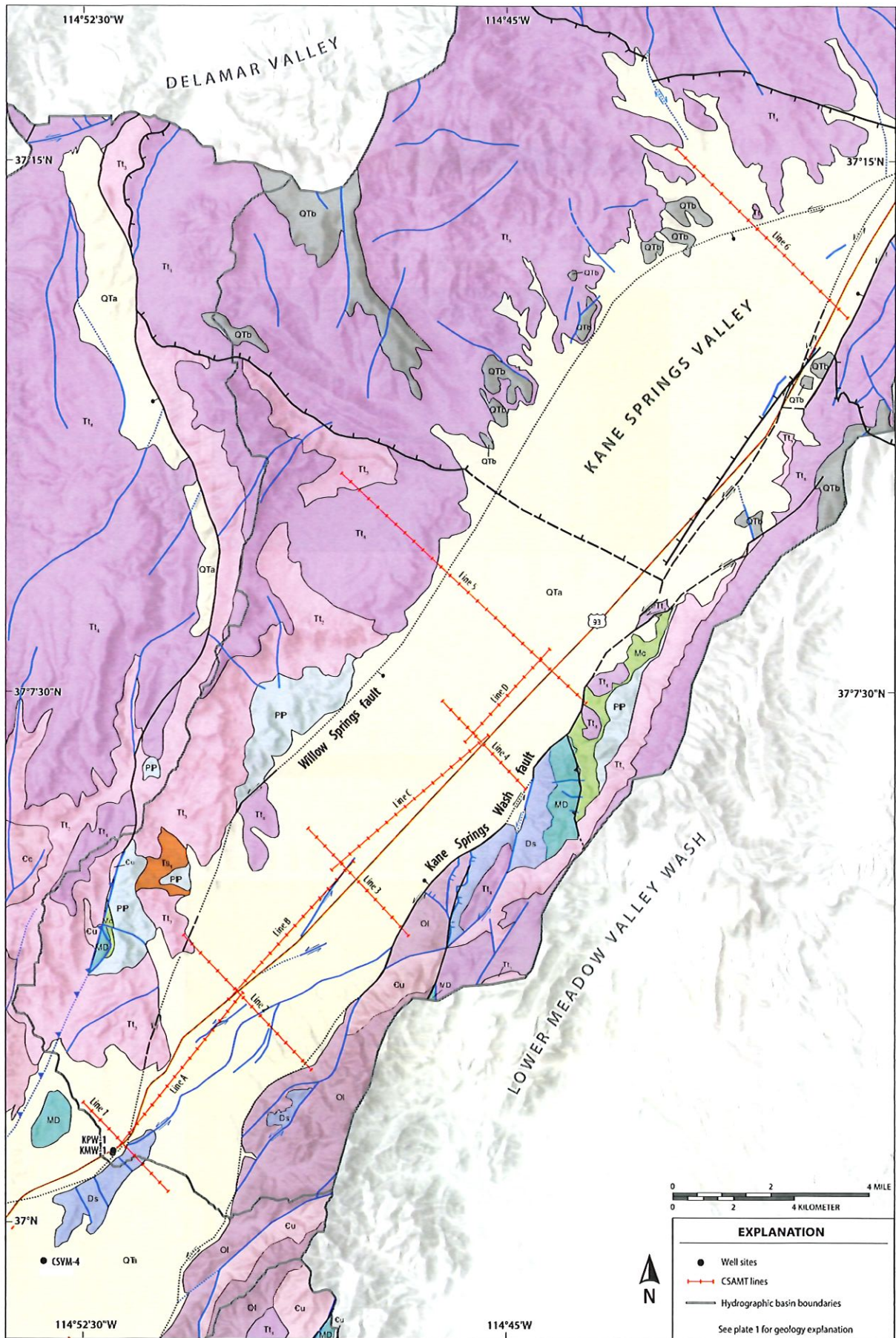


Figure 8. Example of color-contoured cross sections showing faults in two CSAMT data sets as A) a narrow vertical low resistivity zone at Station 350, versus B) as an offset layering at station -150.

Figure 9. 2012 CSAMT and NSAMT survey line locations in Kane Springs Valley



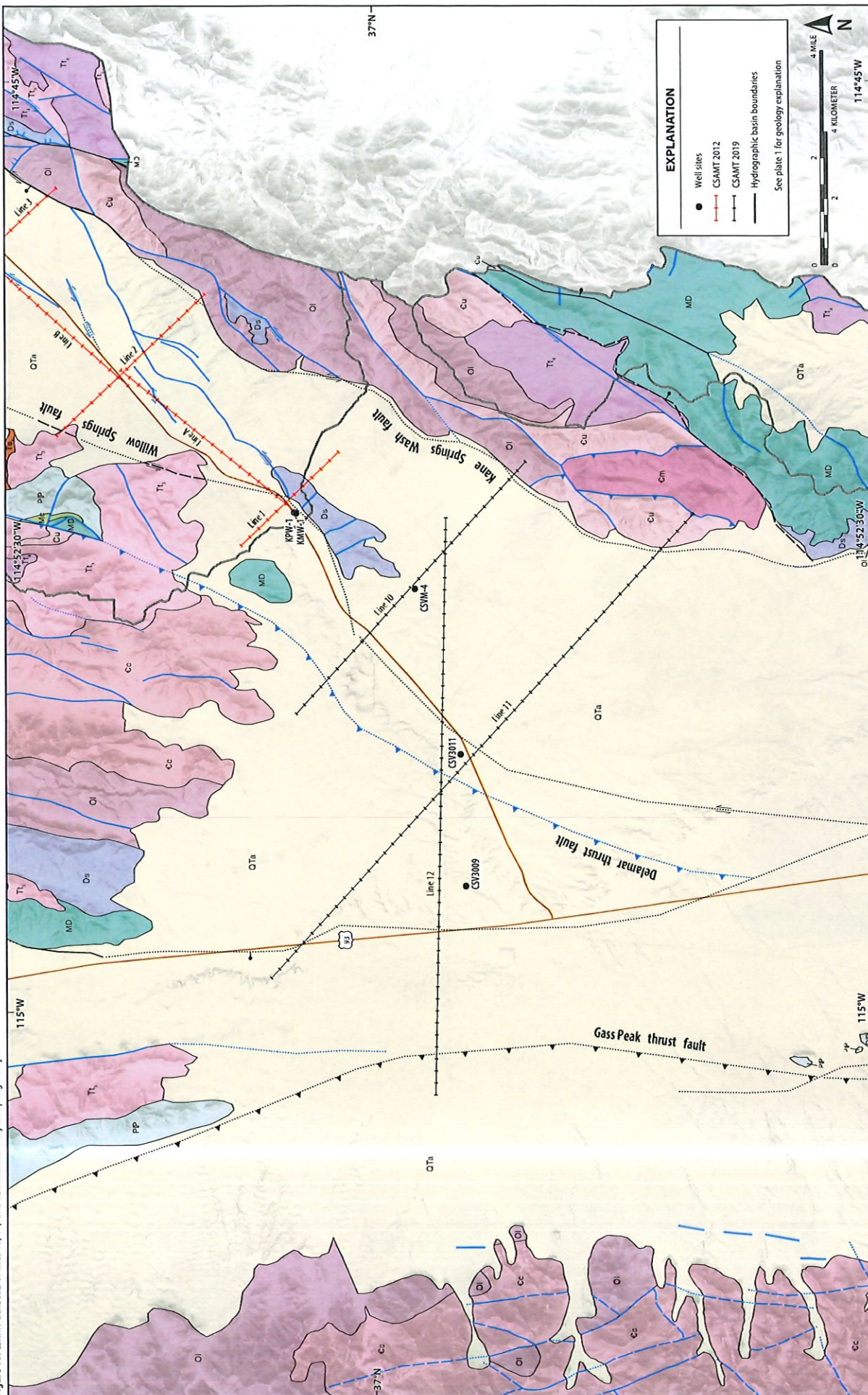
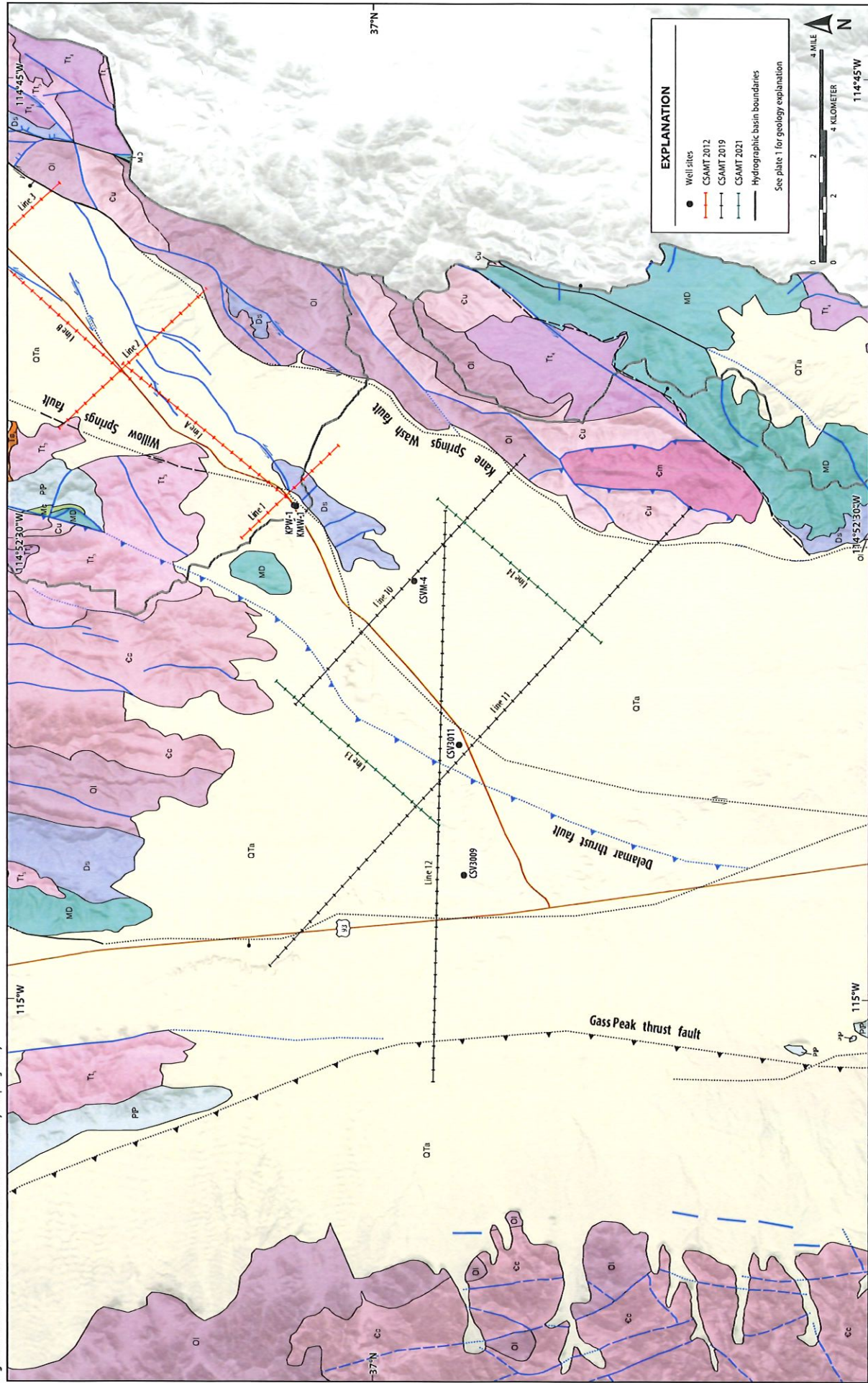


Figure 11. CSAMT and transects of lines 13 and 14 in northern Coyote Spring Valley



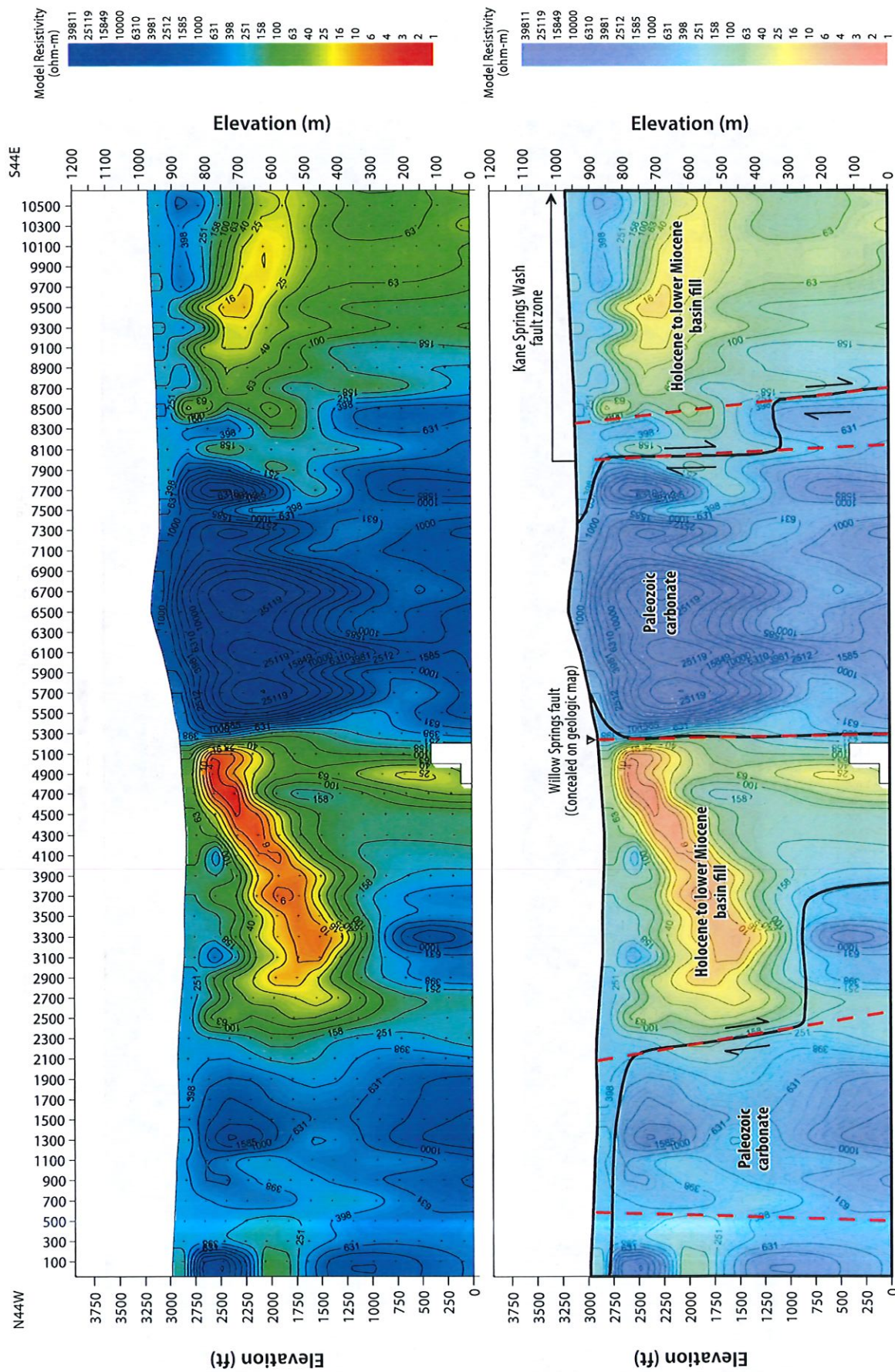


Figure 12. CSAMT transect of line 1 through well KPW-1 of Kane Springs Valley

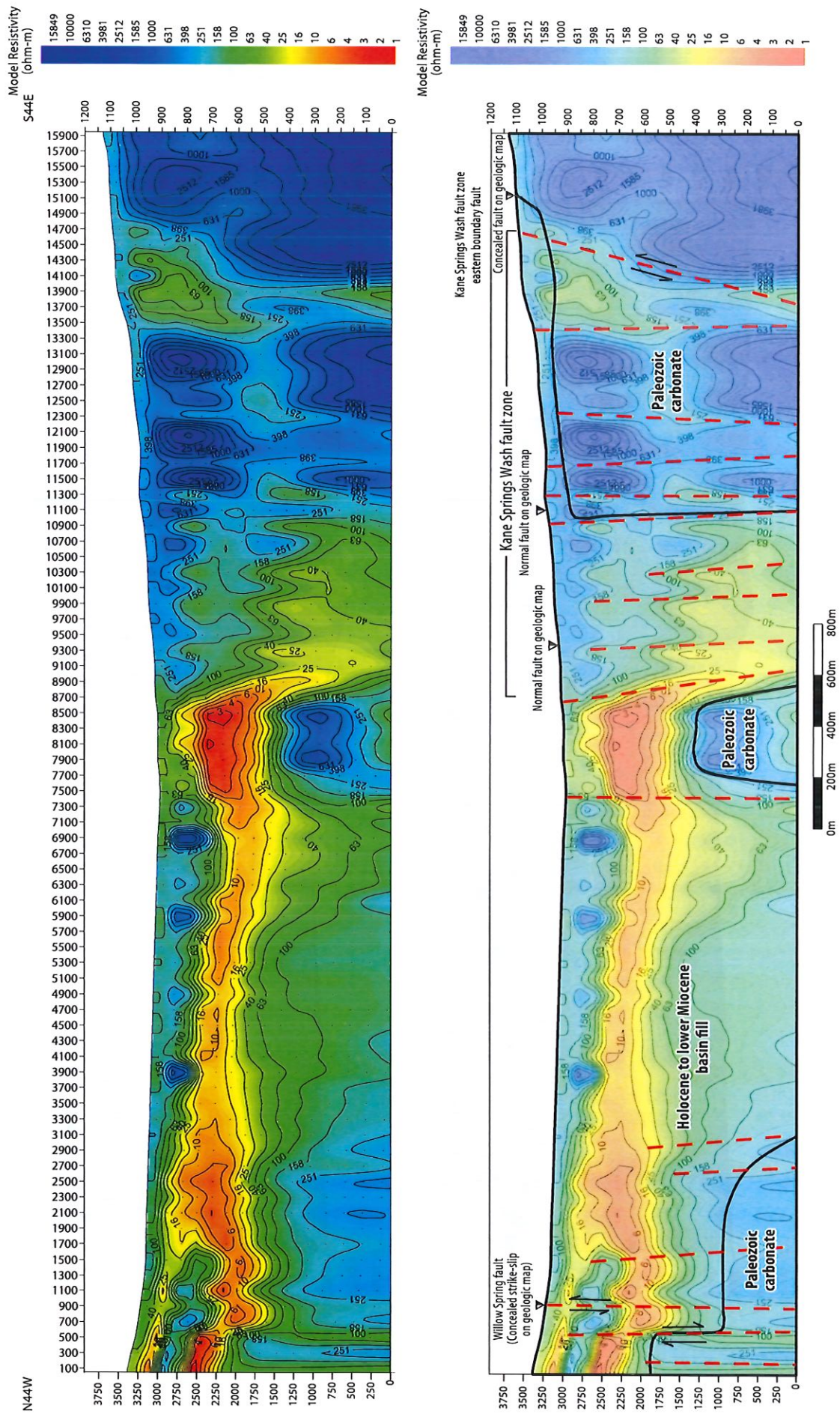


Figure 13. CSAMT transect of line 2 through southern Kane Springs Valley

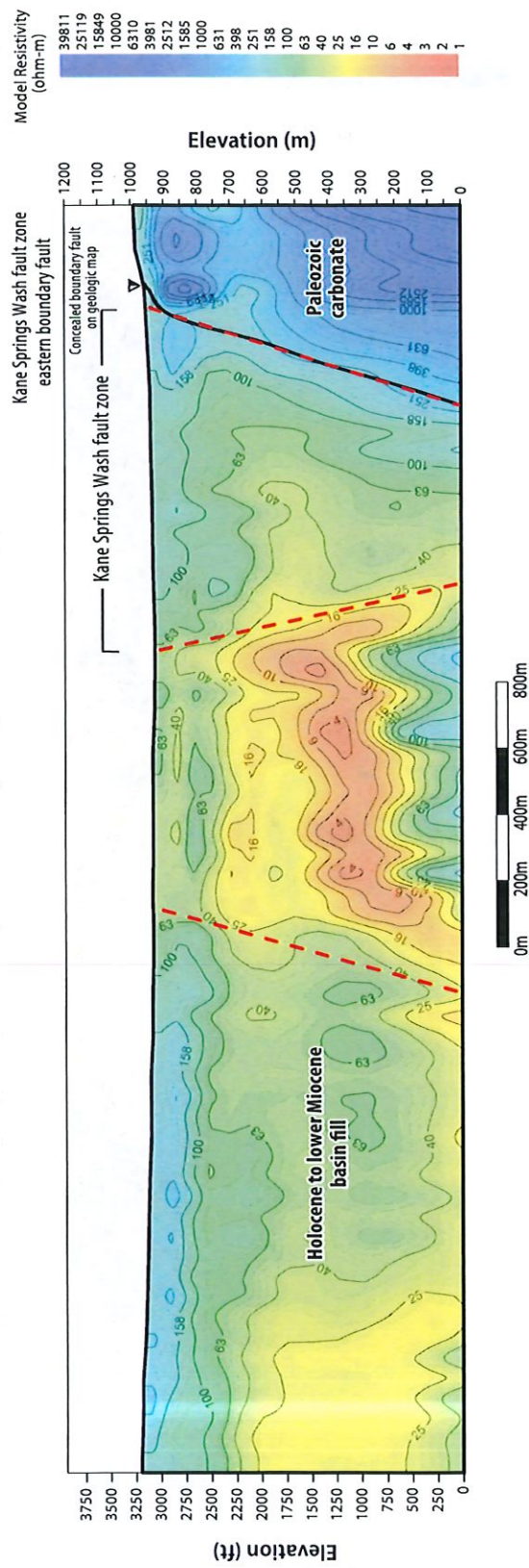
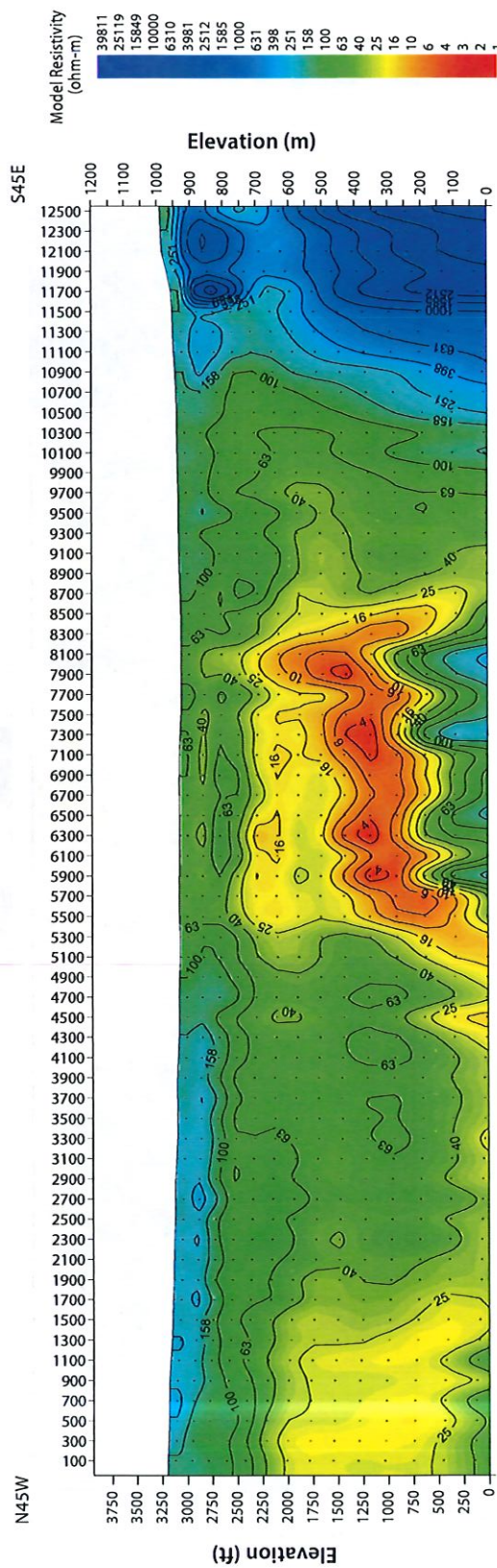


Figure 14. CSAMT transect of line 3 through northeast-central Kane Springs Valley

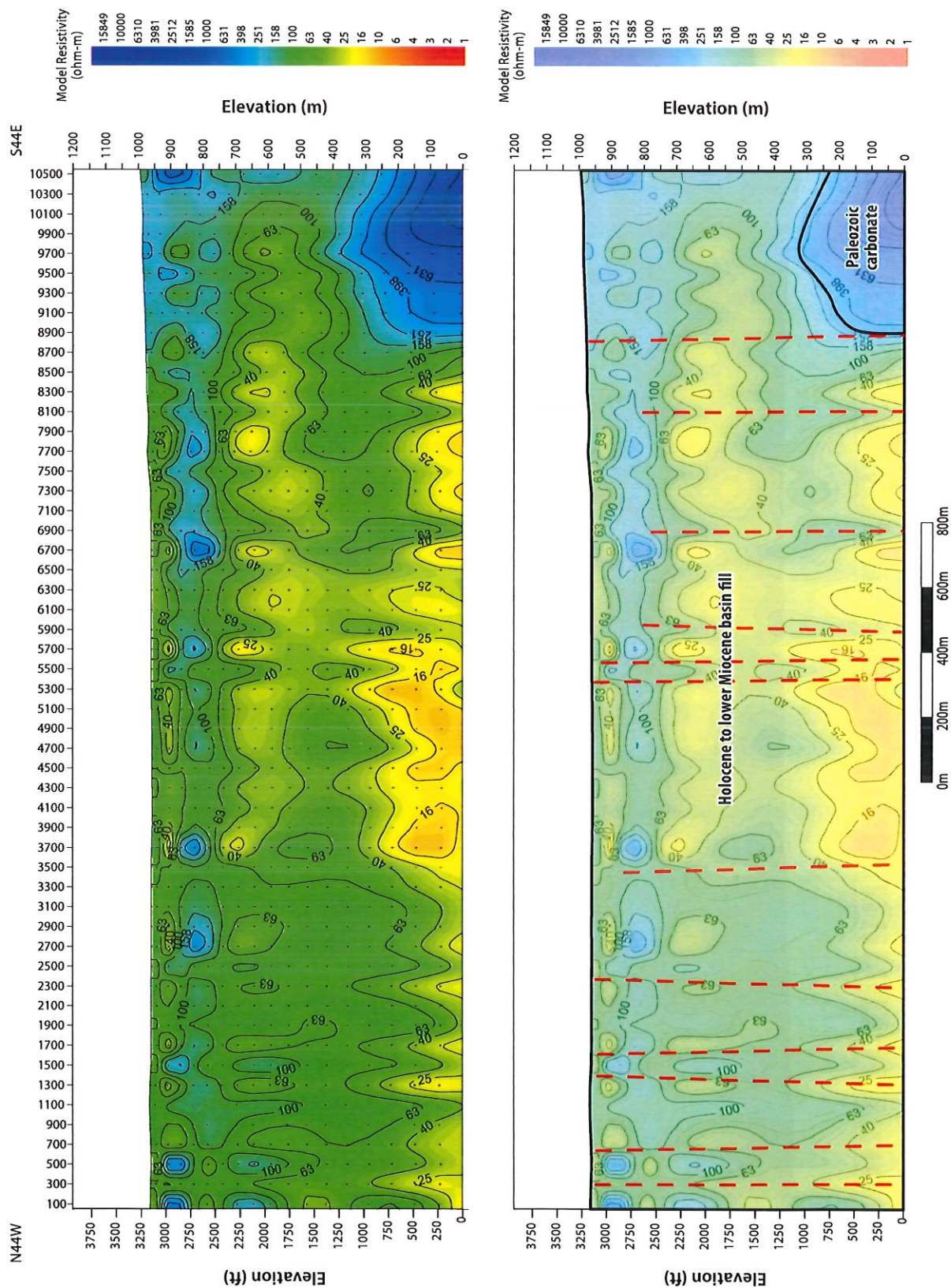


Figure 15. CSAMT transect line 4 through northeast-central Kane Springs Valley

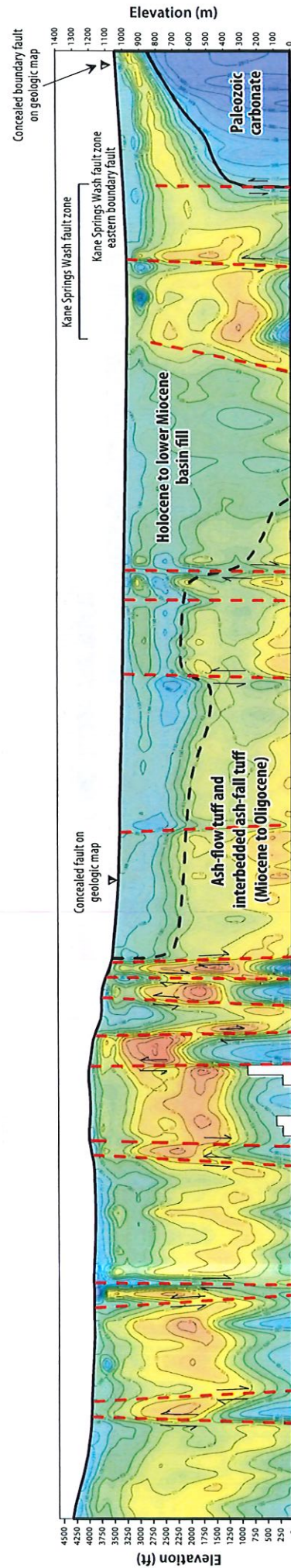
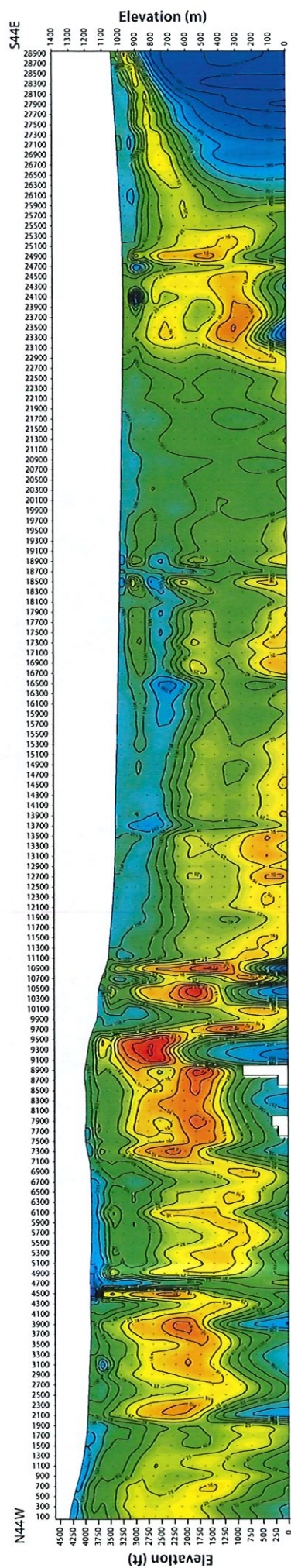


Figure 16. CSAMT transect of line 5 through northeast-central Kane Springs Valley

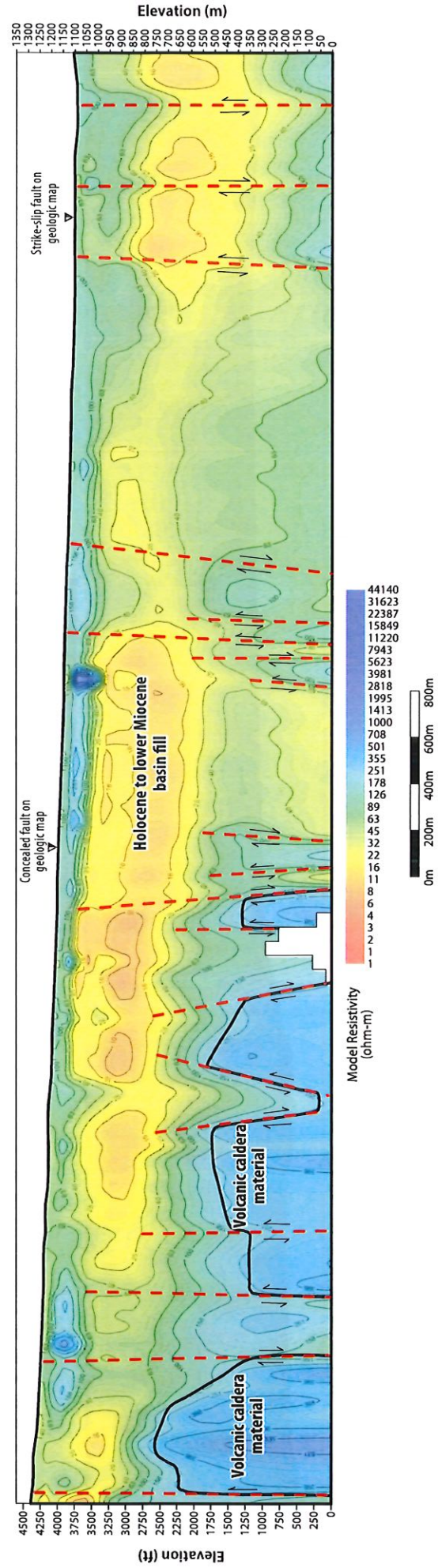
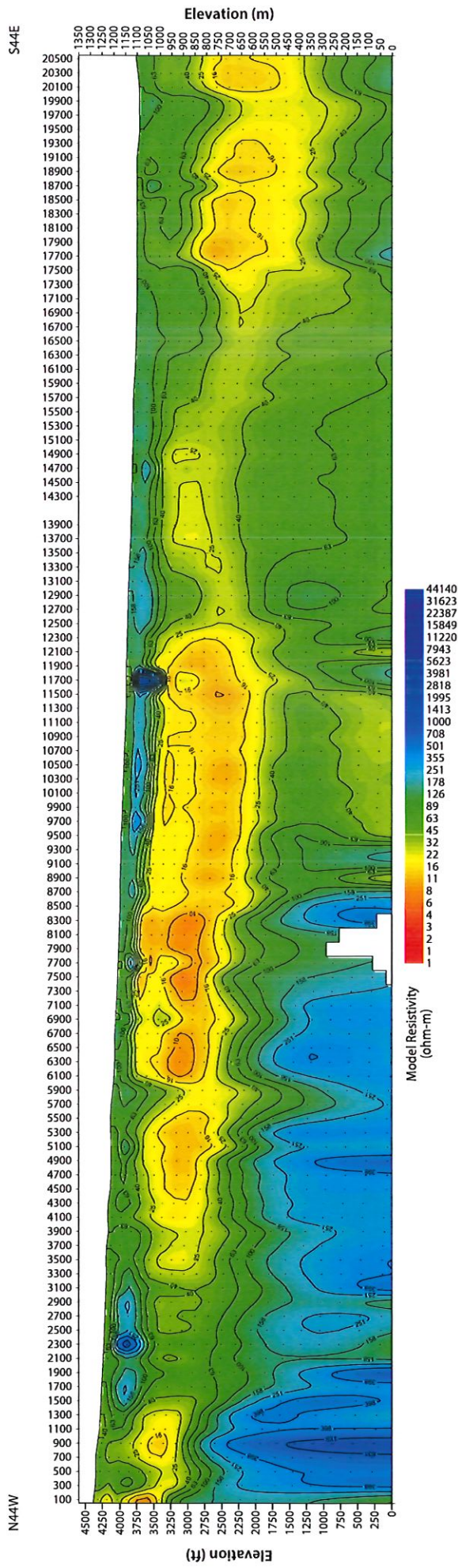


Figure 17. CSAMT transect of line 6 in the vicinity of the Kane Springs Valley Wash caldera complex

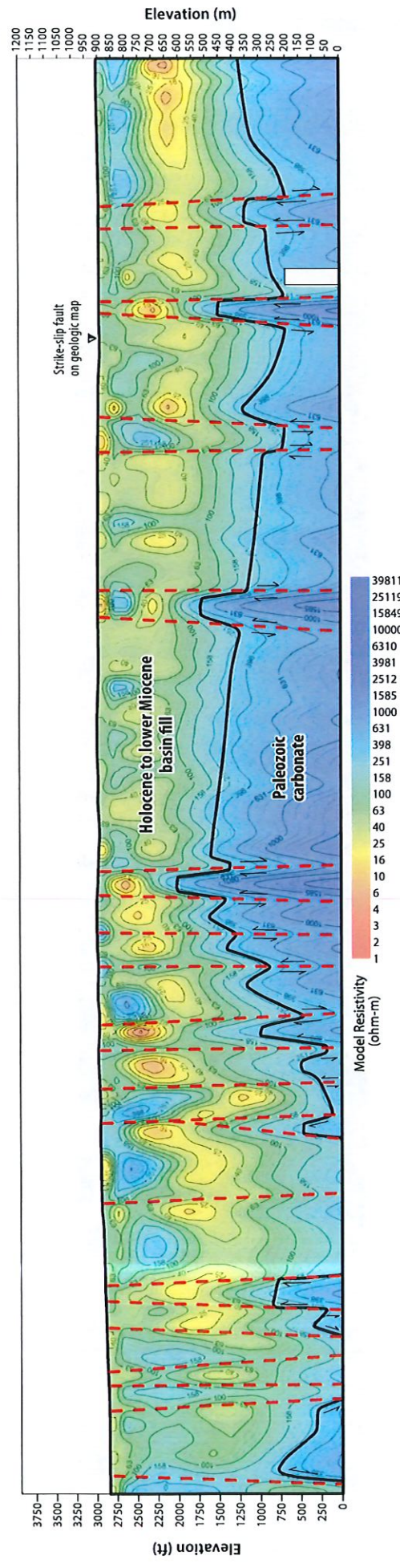
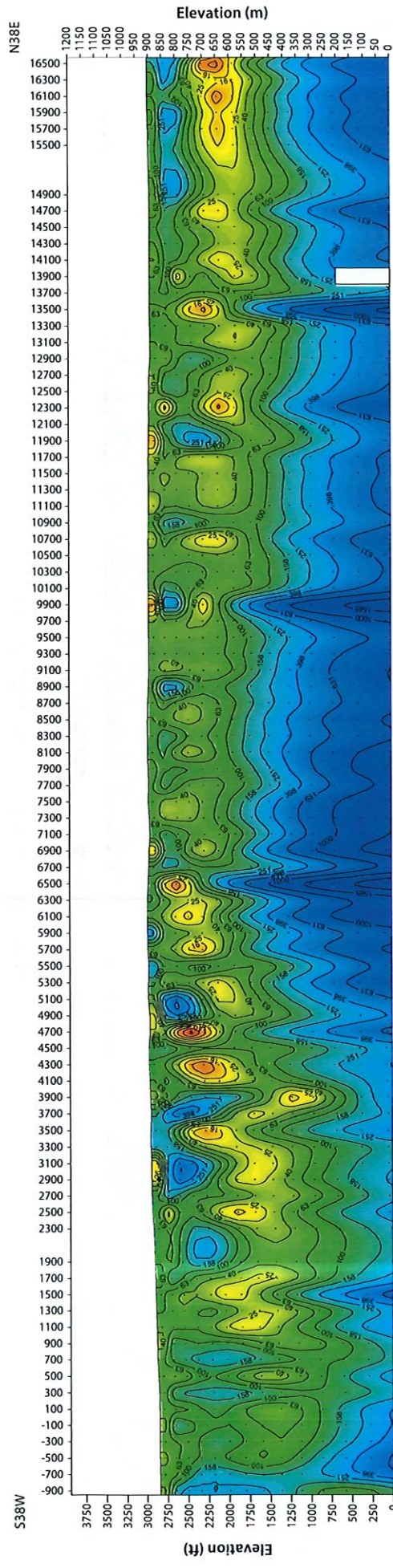


Figure 18. NSAMT axial transect line A of Kane Springs Wash

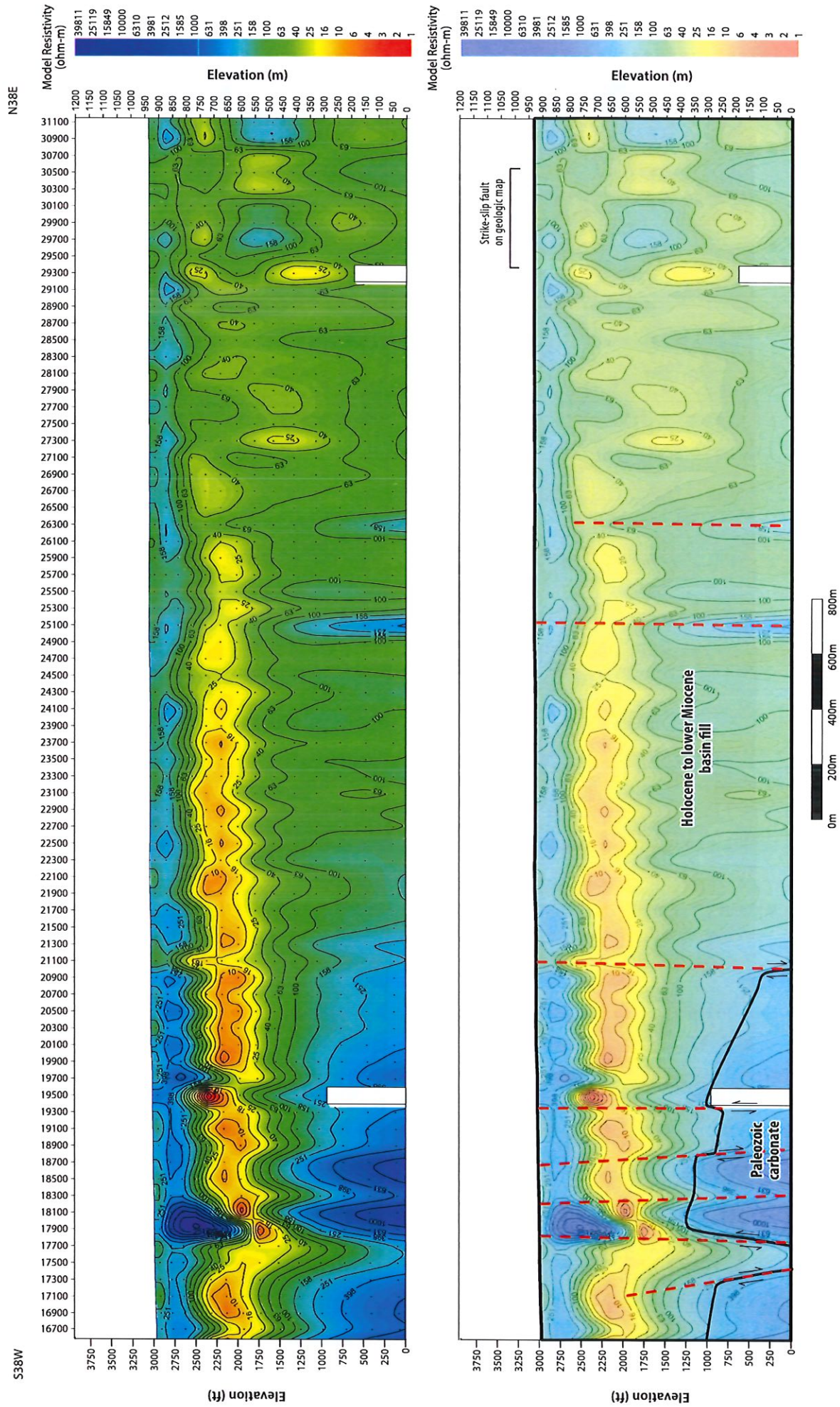


Figure 19. NSAMT axial transect line B of Kane Springs Wash

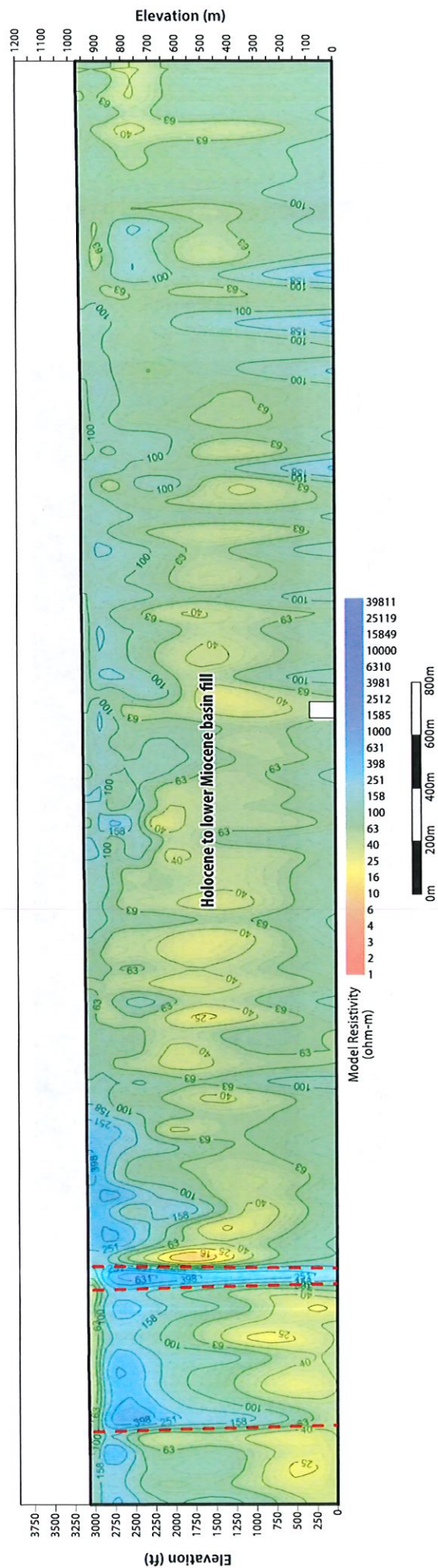
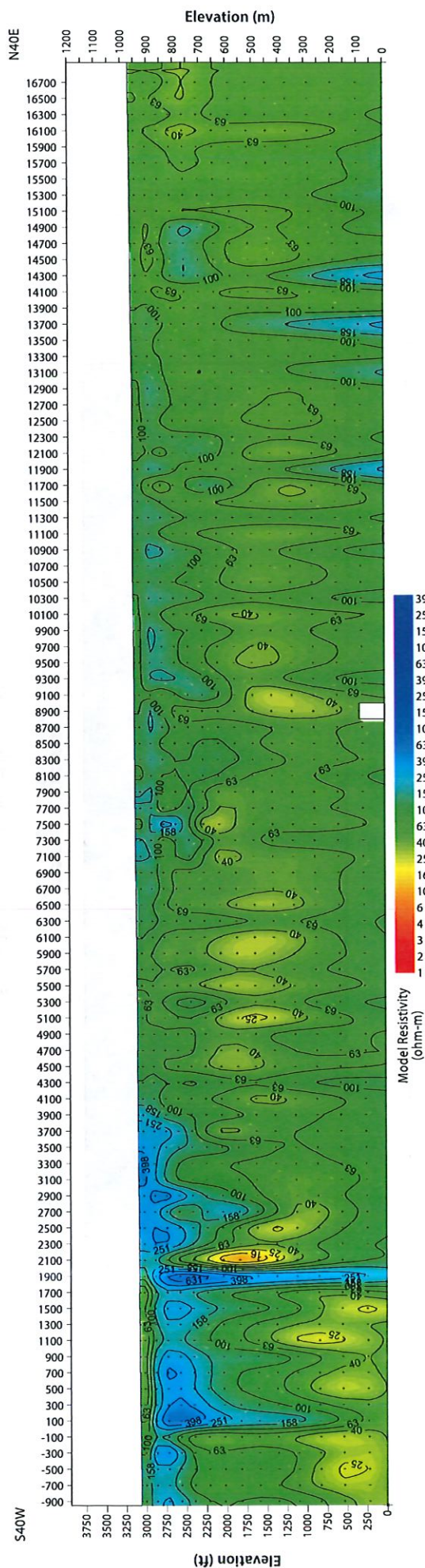


Figure 20. NSAMT axial transect line C of Kane Springs Valley

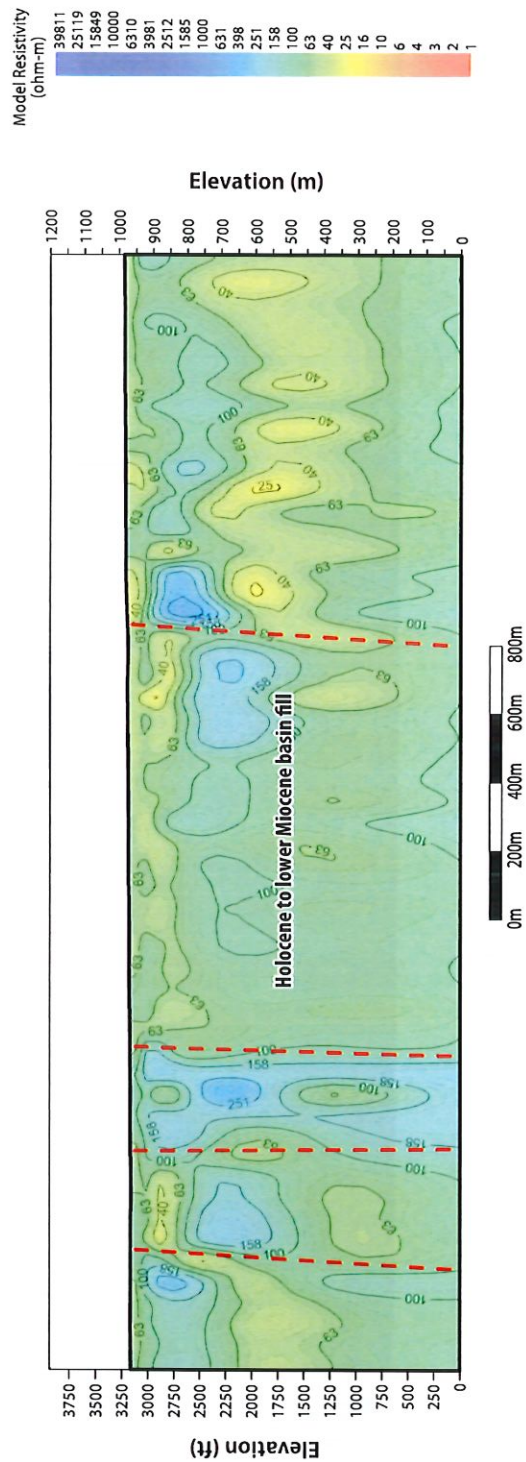
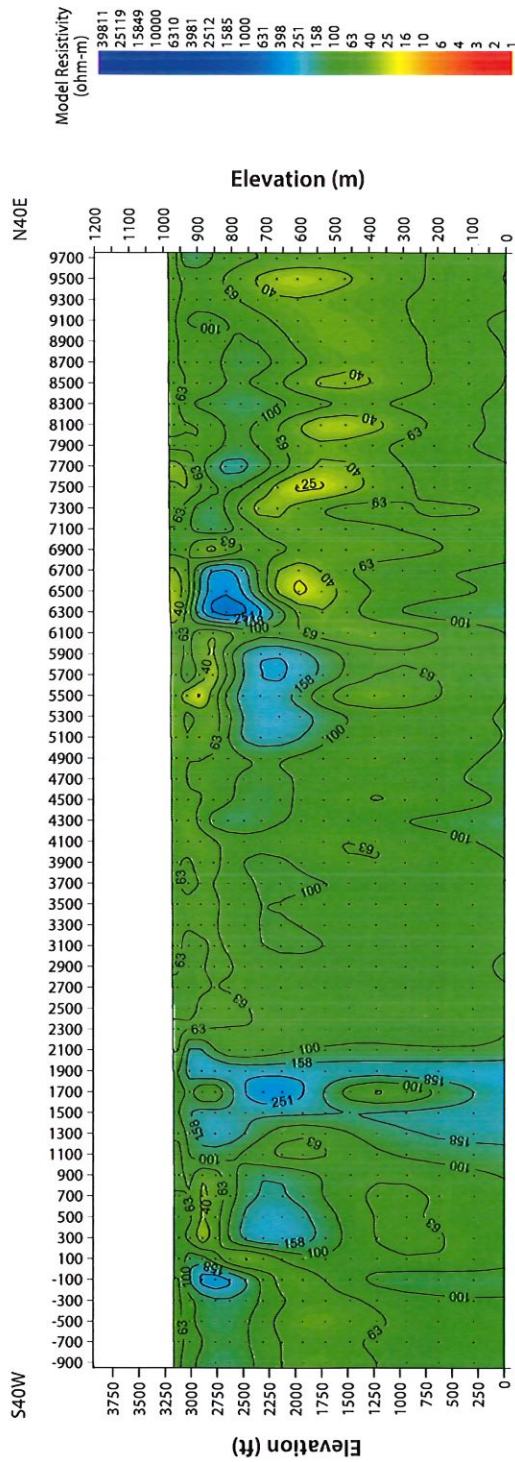


Figure 21. NSAMT axial transect line D of Kane Springs Valley

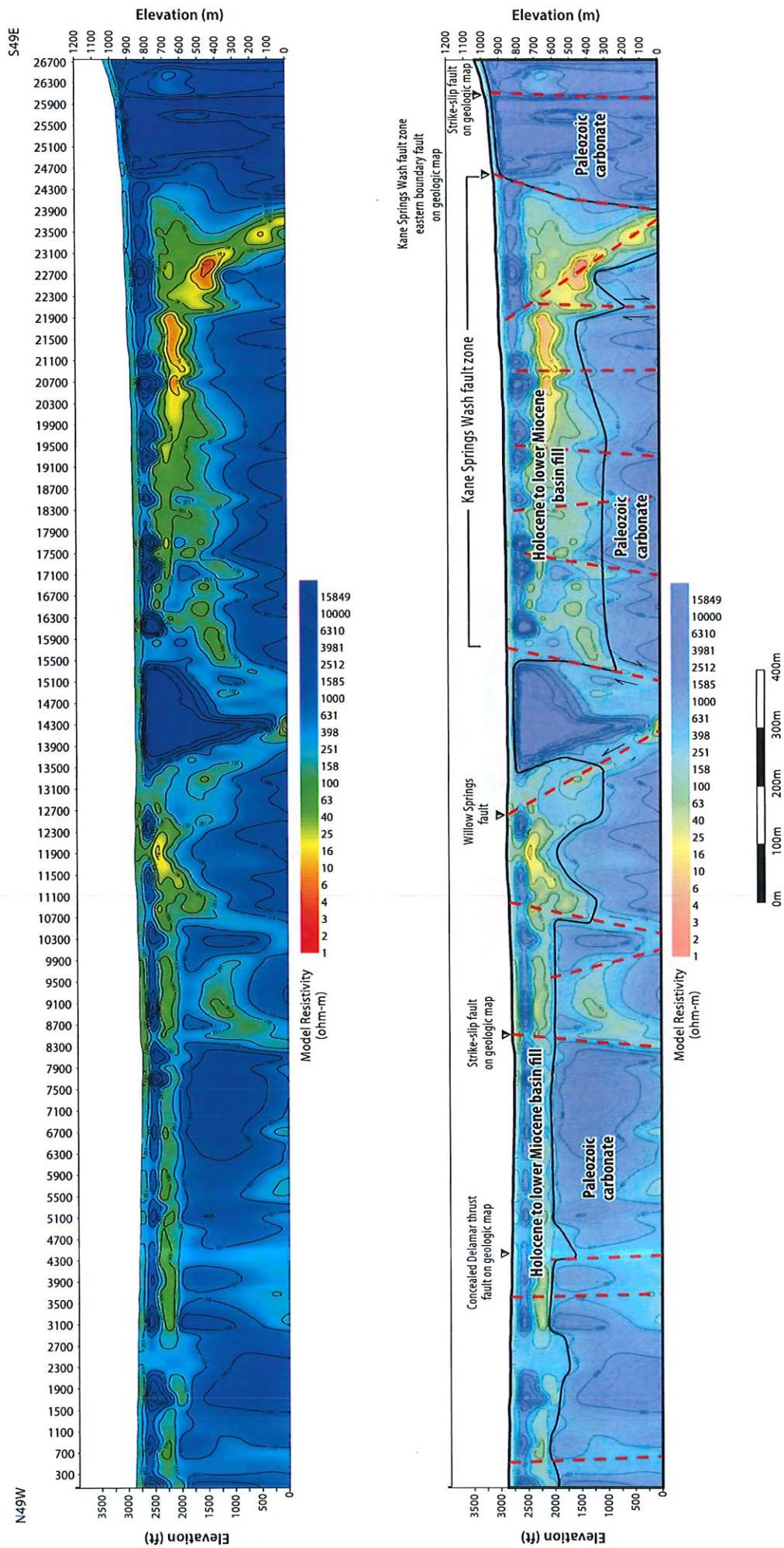


Figure 22. 2019 CSAMT transect for line 10 through northern Coyote Spring Valley

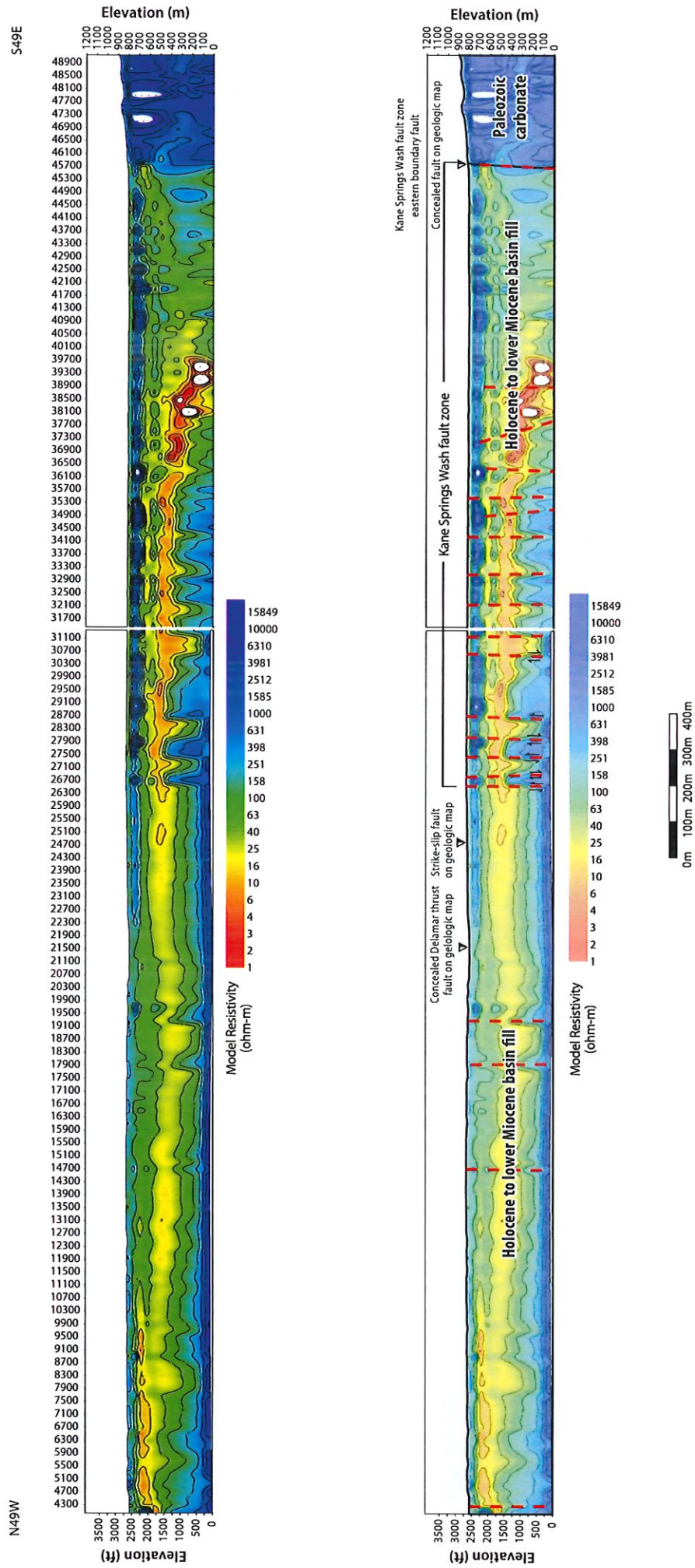


Figure 23. 2019 CSAMT transect for line 11 through northern Coyote Spring Valley

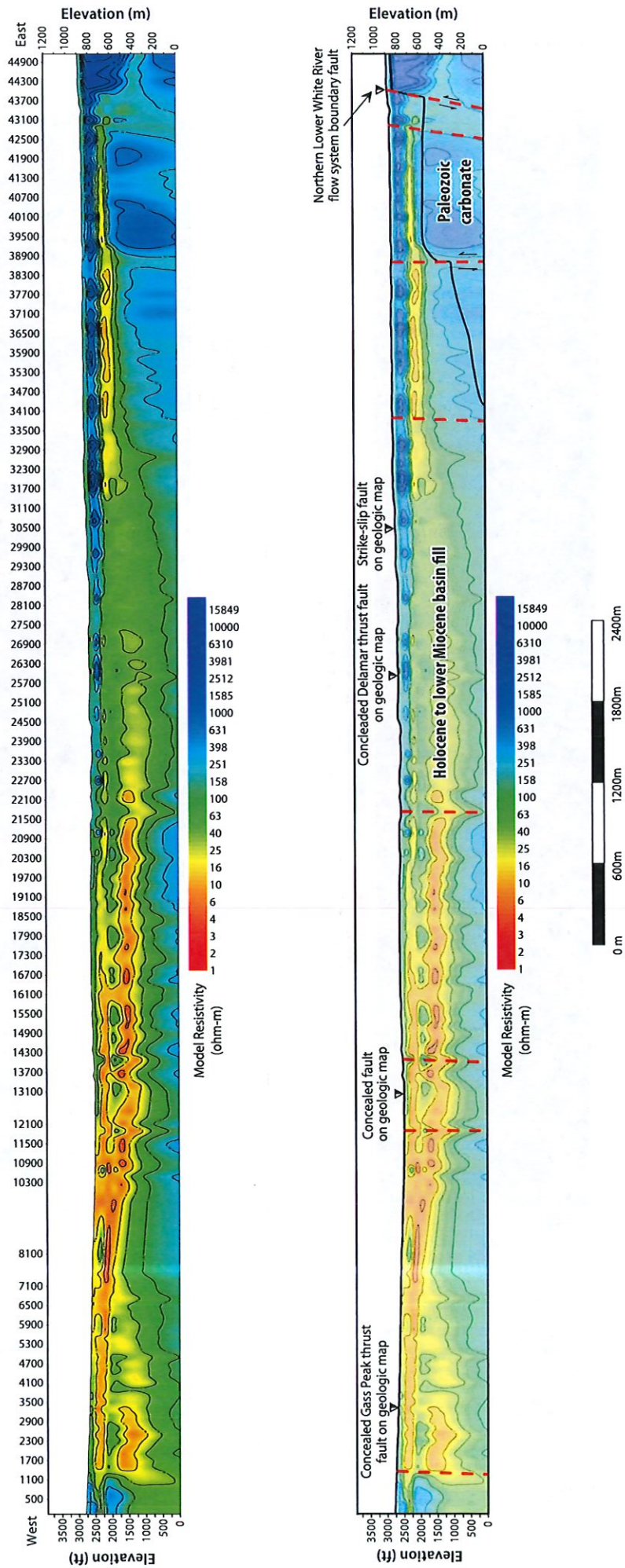


Figure 24. 2019 east-west CSAMT transect of line 12 through northern Coyote Spring Valley

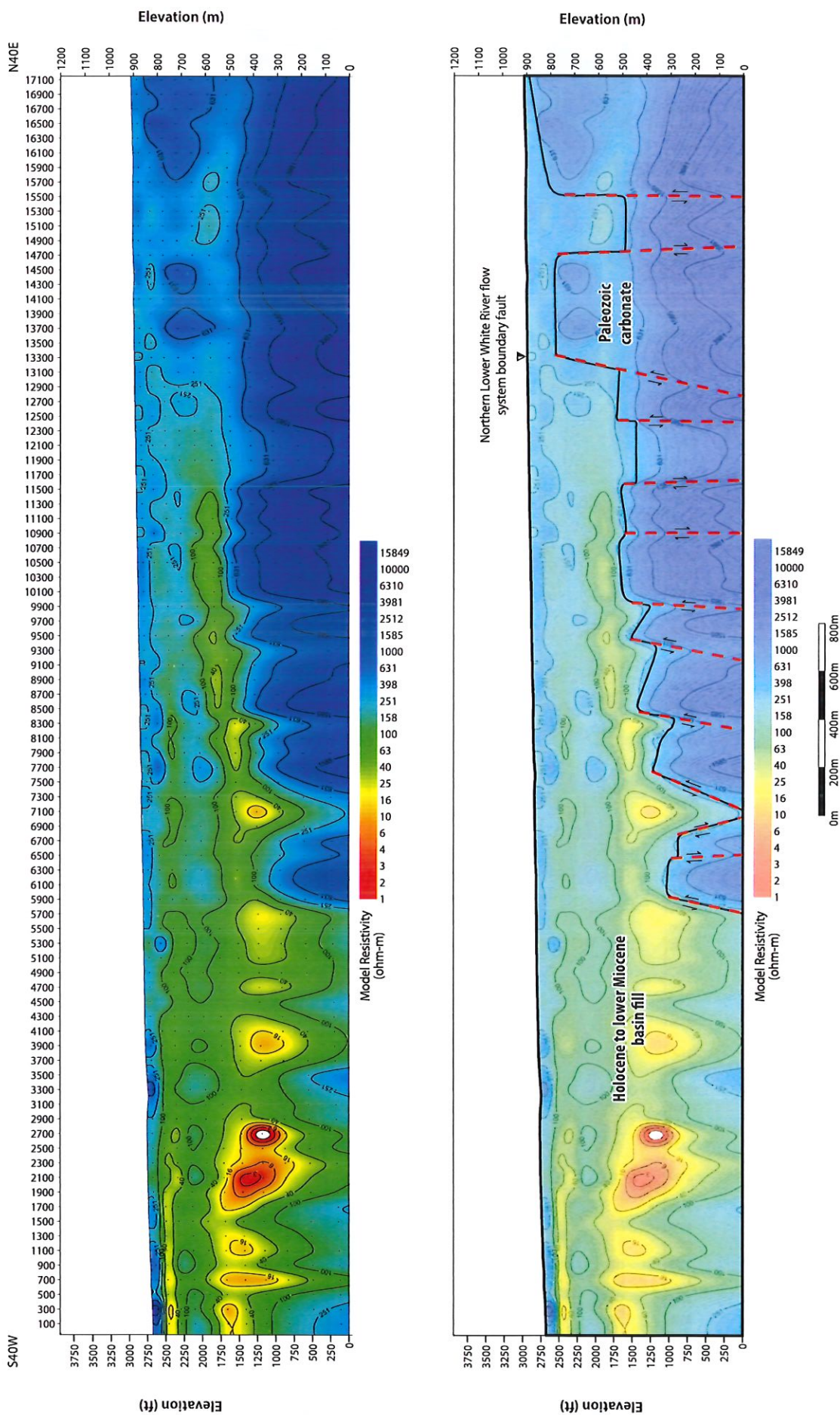


Figure 25. CSAMT transect of line 13 perpendicular to and located on the northwest end of CSAMT line 10 and line 11 in northern Coyote Spring Valley

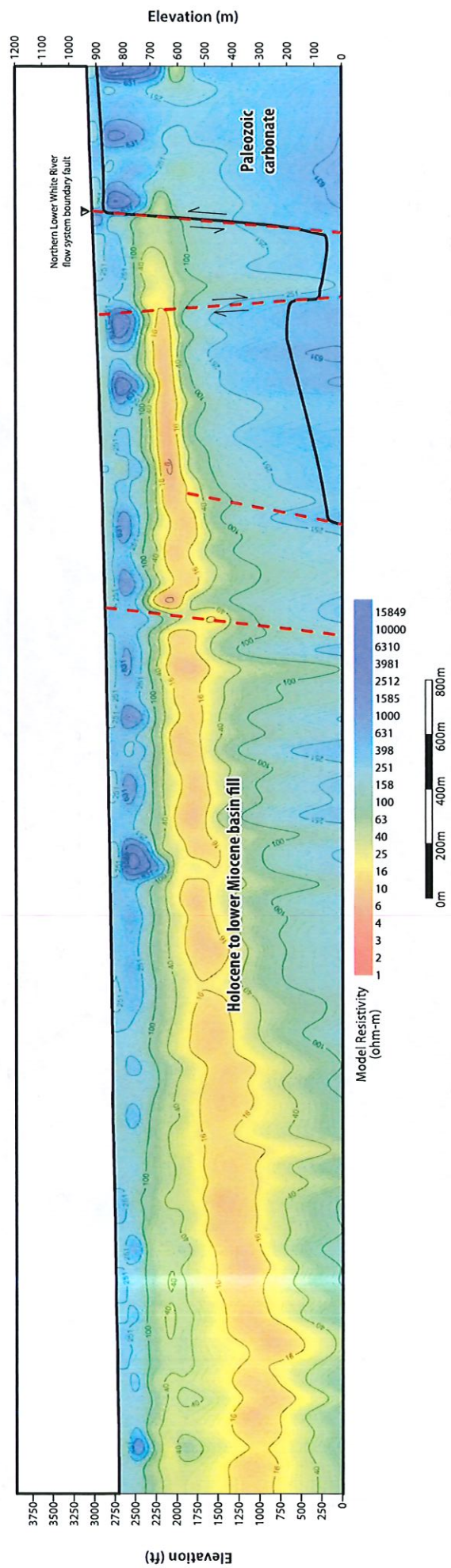
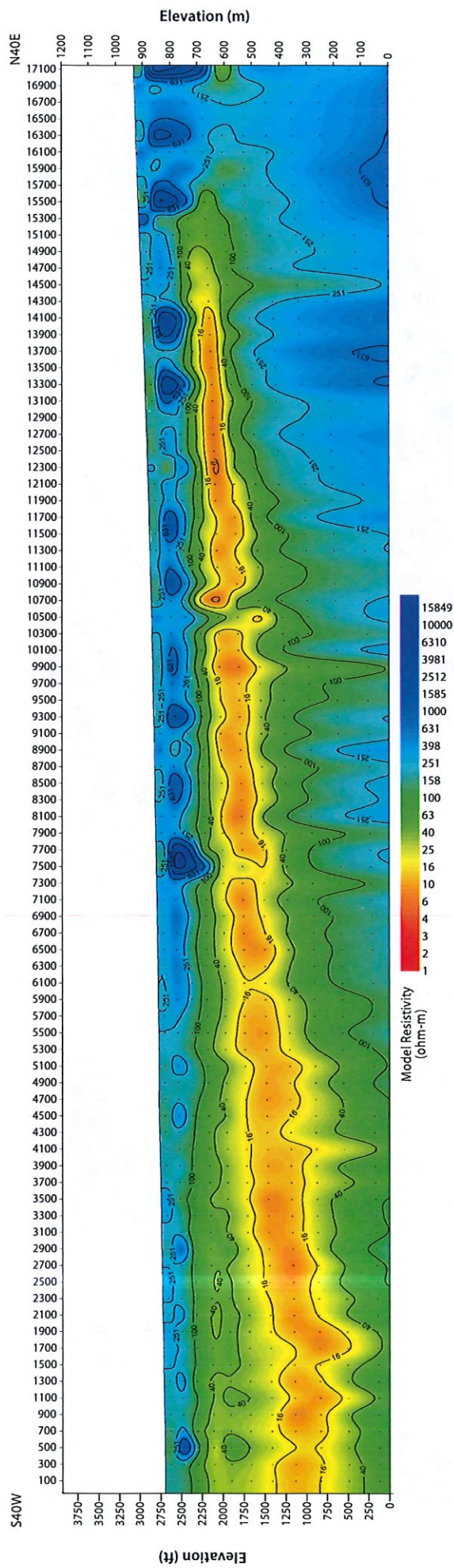
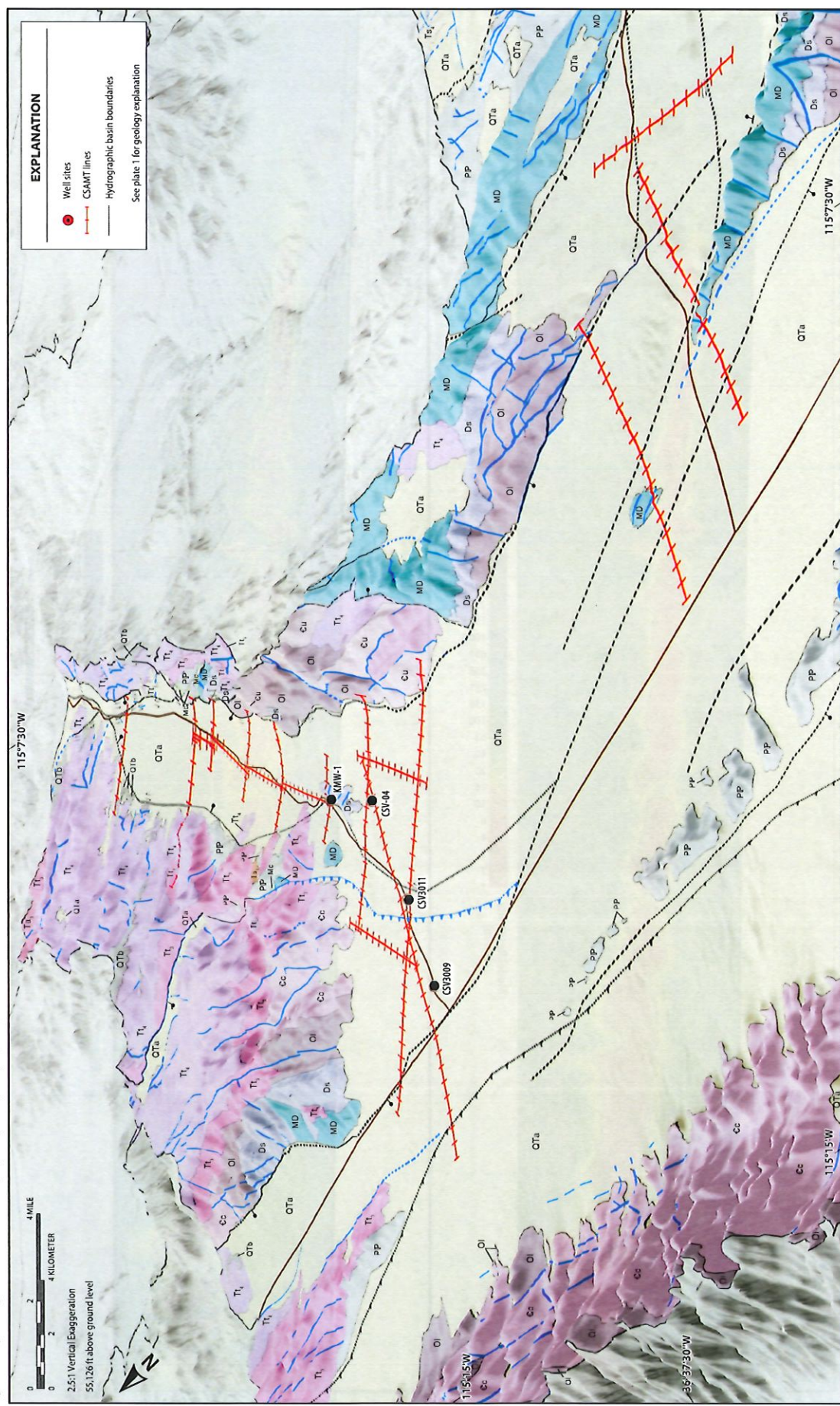


Figure 26. CSAMT transect of line 14 perpendicular to and located on the southeast end of CSAMT line 10 and Line 11 in northern Coyote Spring Valley

Figure 27. Map showing CSAMT transects in Kane Springs Valley and Coyote Springs Valley



2012 and 2021 Kane Springs Valley High Resistivity Blocks and Faults

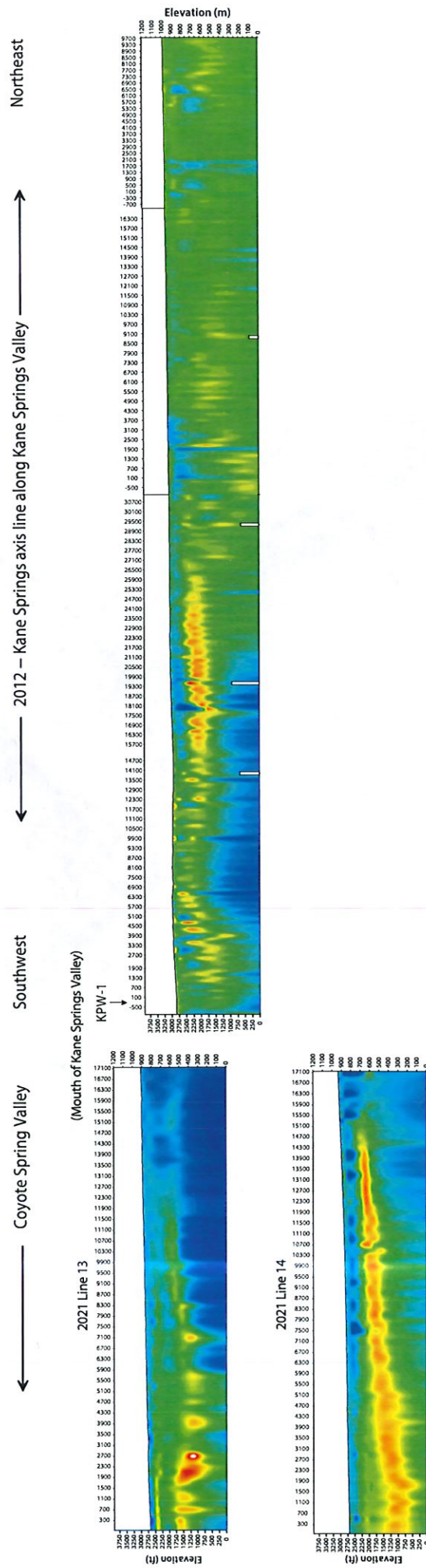


Figure 28. CSAMT transect of lines 13 and 14 with NSAMT transect of the Kane Springs Valley axial line. This figure shows the high resistivity block and faults at the southwest end of Kane Springs Valley. This high resistivity block is interpreted to be shallow and moderately shallow Paleozoic carbonates.

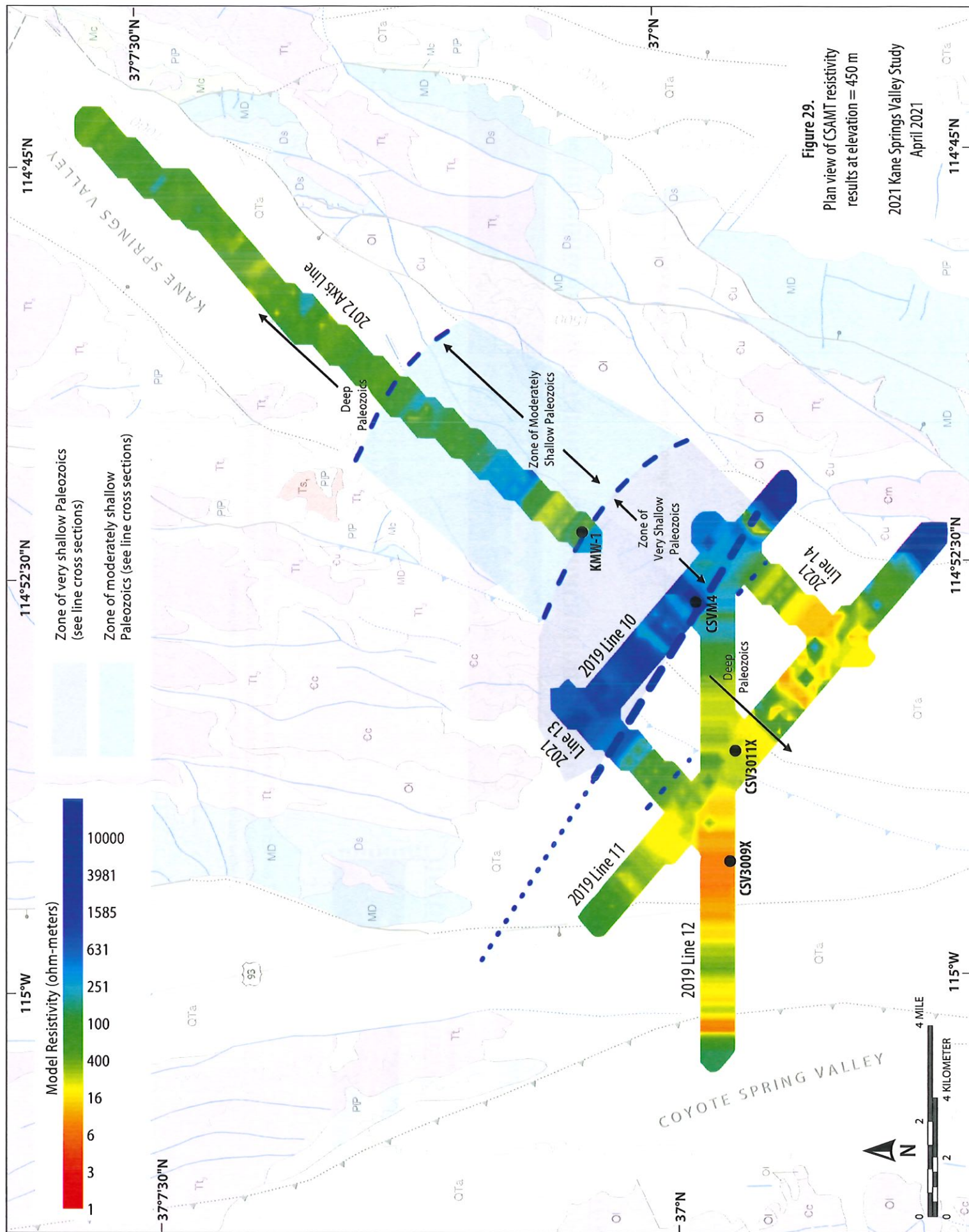


Figure 29.

Plan view of CSAMT resistivity
results at elevation = 450 m

2021 Kane Springs Valley Study
April 2021

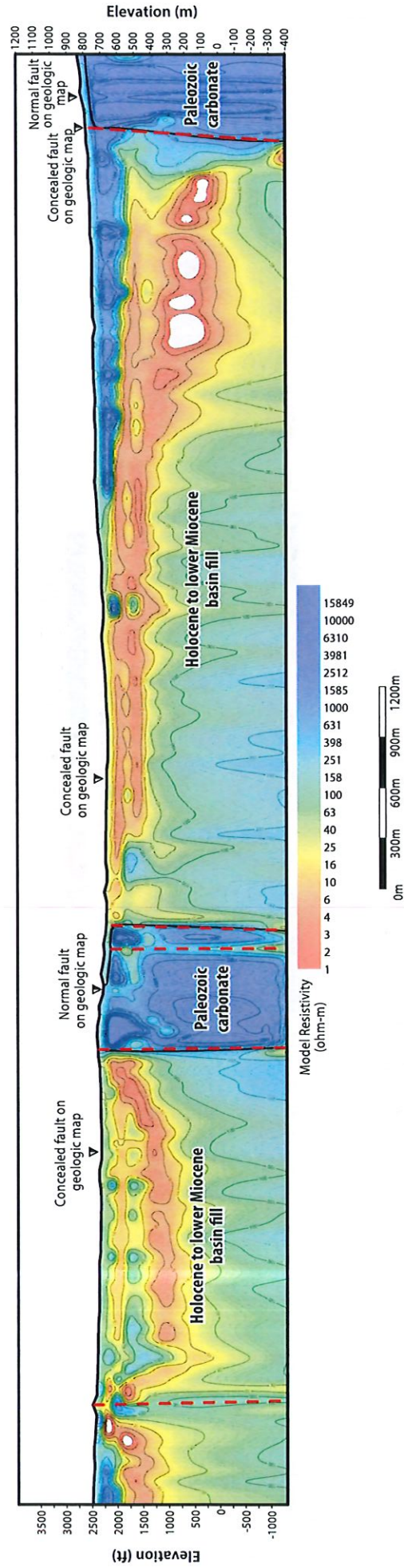
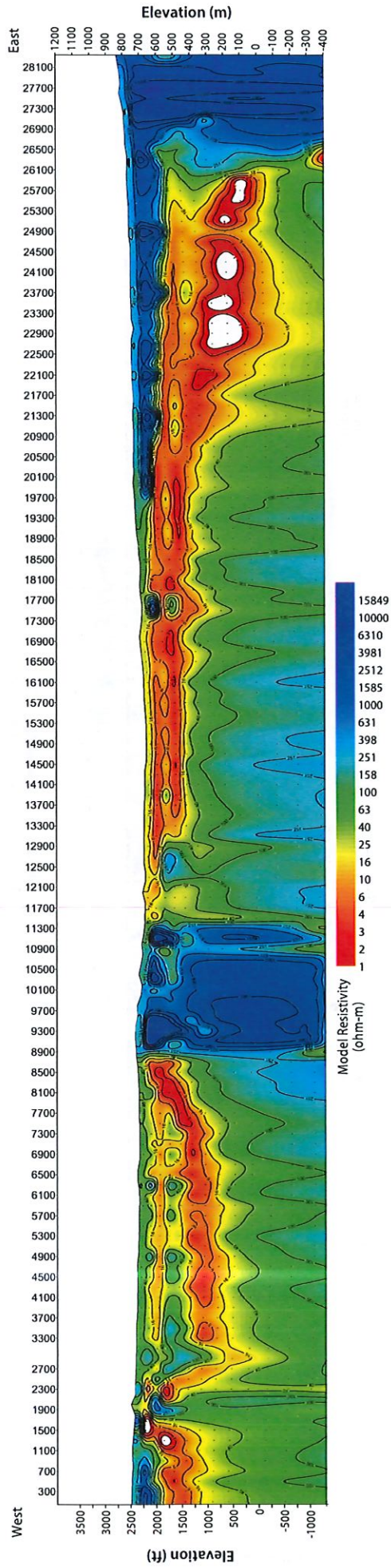


Figure 30. CSAMT transect line A through southern Coyote Spring Valley

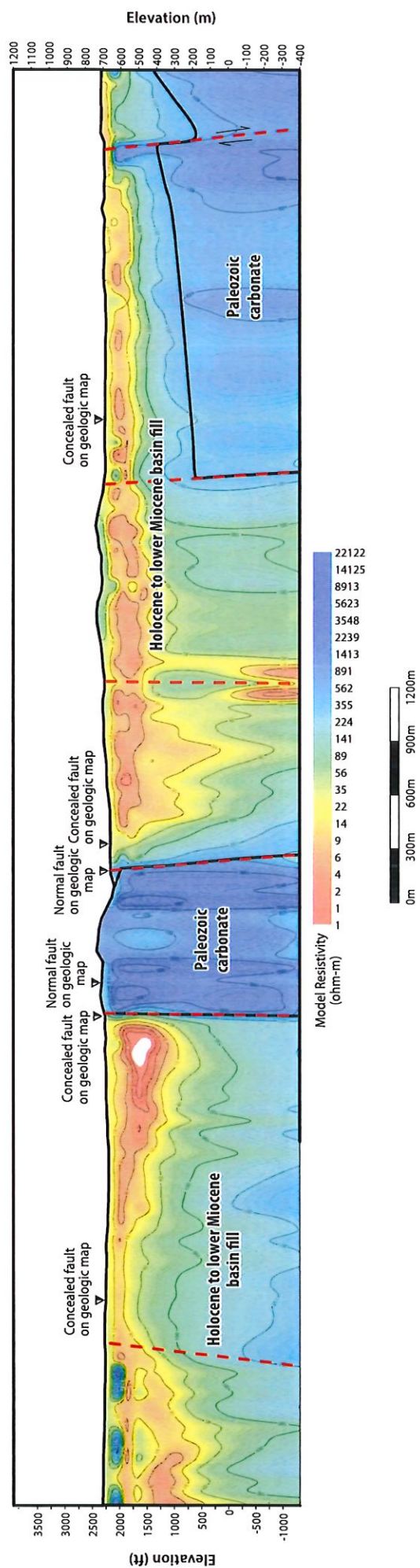
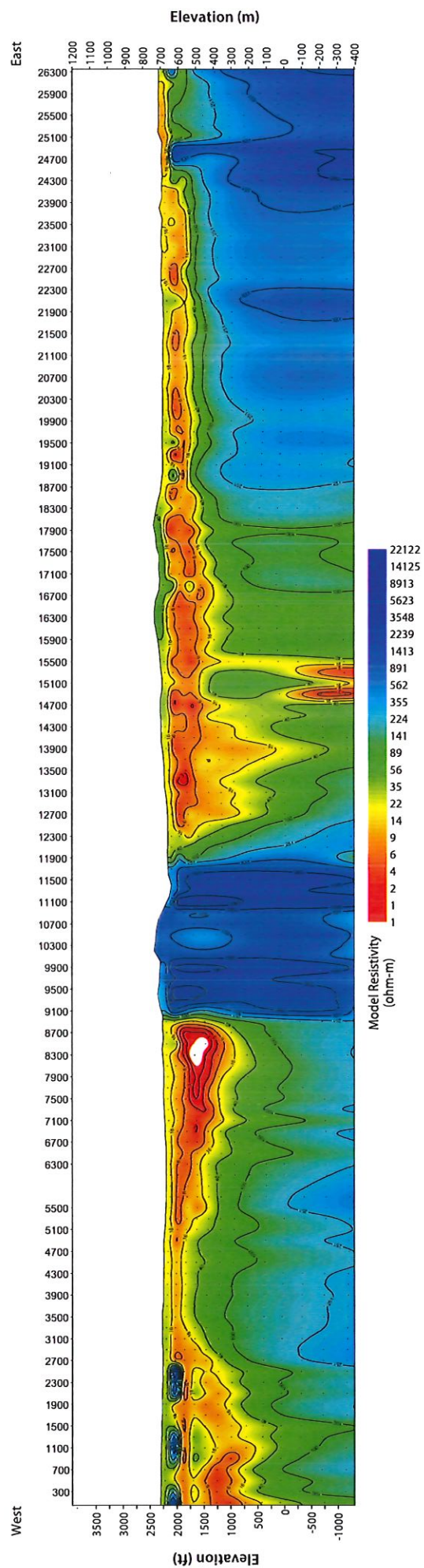


Figure 31. CSAMT transect line B through southern Coyote Spring Valley and the Muddy River Springs area

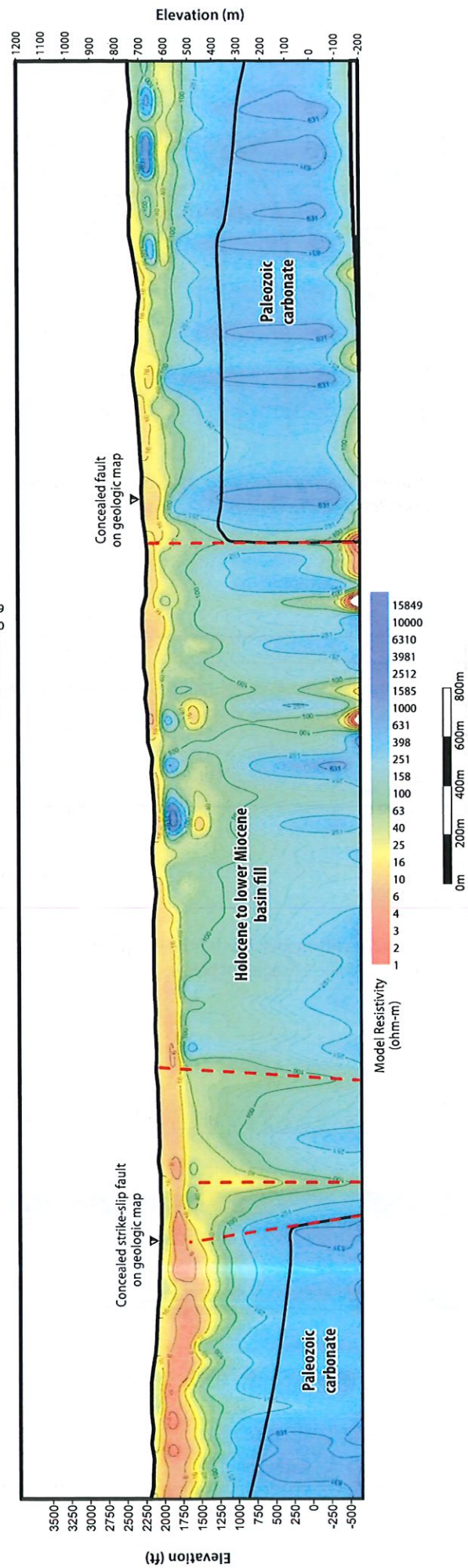
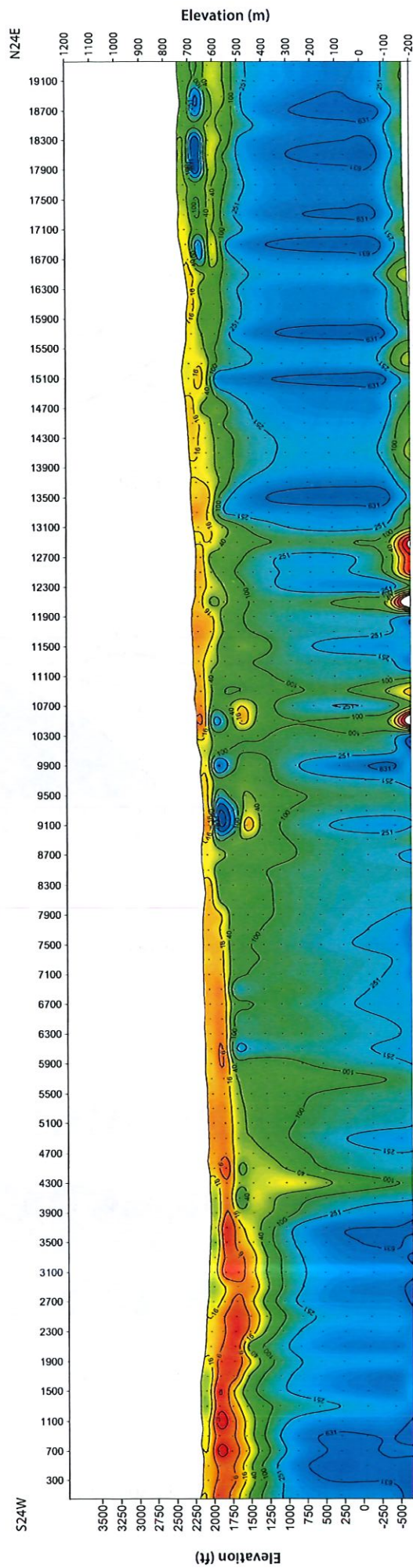
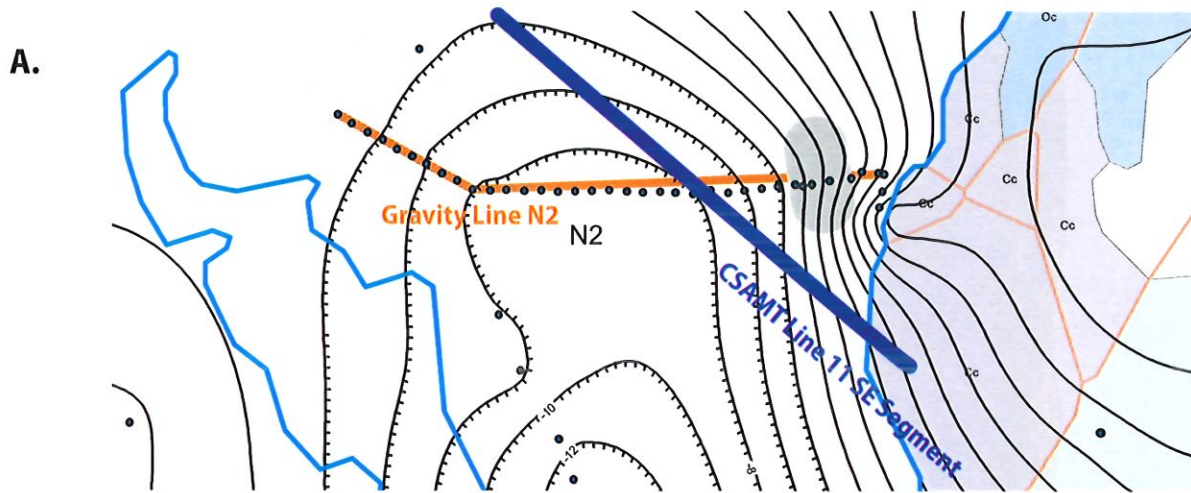
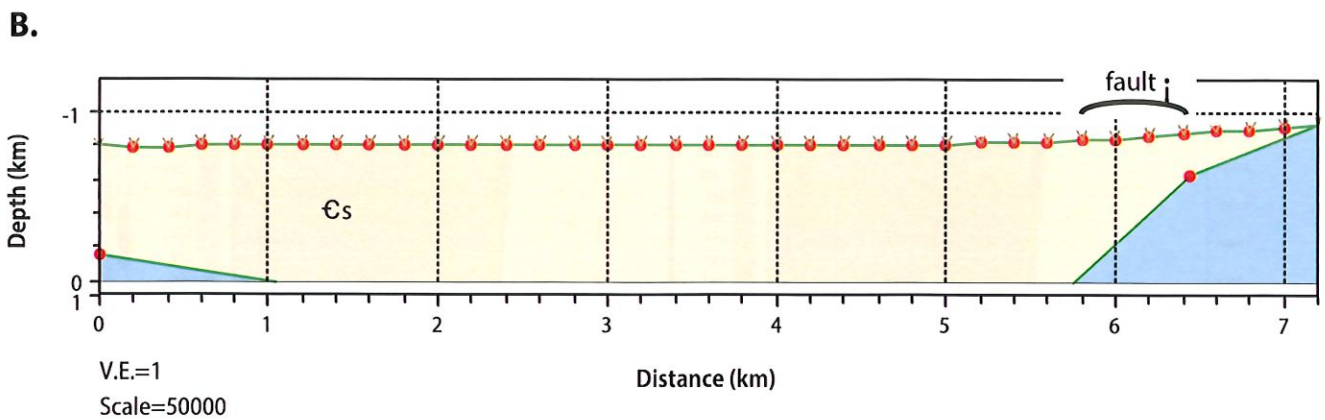


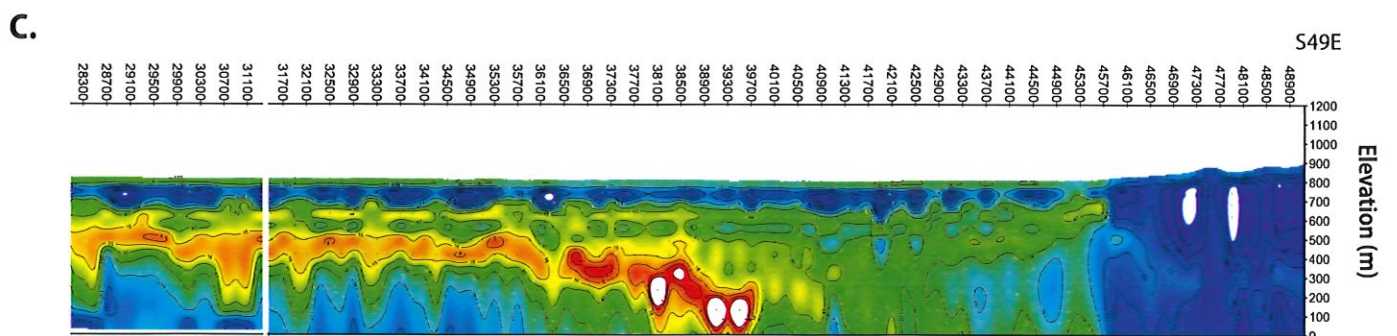
Figure 32. CSAMT transect of line C through the Muddy River Springs Area



Plan view map location of the USGS gravity line N2 relative to the SE segment of CSMAT line 11 on plate 1 from Phelps, et. al. (2000).



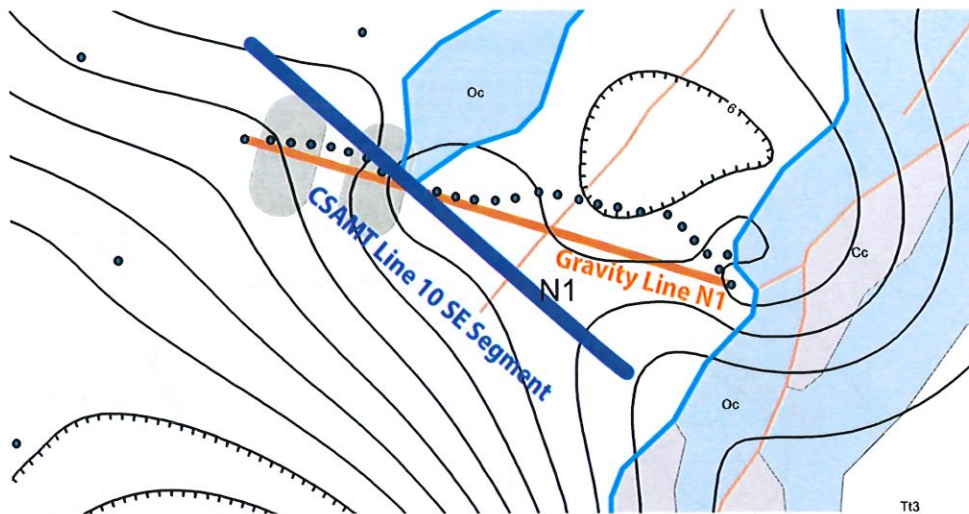
Line N2 gravity model results from Phelps, et. al. (2000), showing surface to sea level at the same scale as the CSMAT line 11 segment below.



The SE segment of CSMAT line 11 from surface to sea level at the same scale as the gravity results in "B" above.

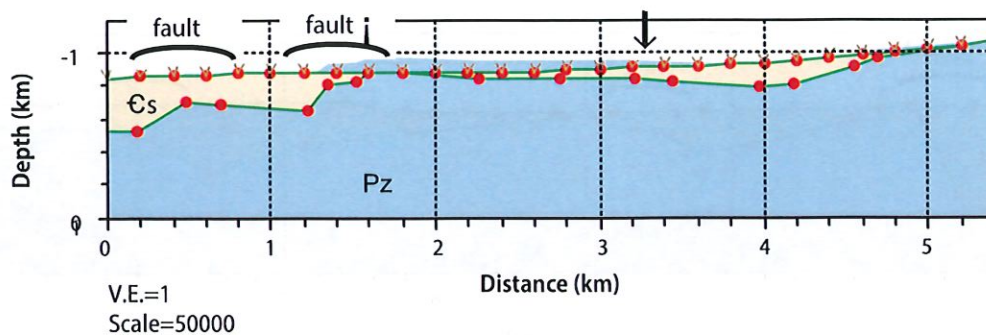
Figure 33. U.S. Geological Survey gravity line N2 and CSMAT line 11 in northern Coyote Spring Valley

A.



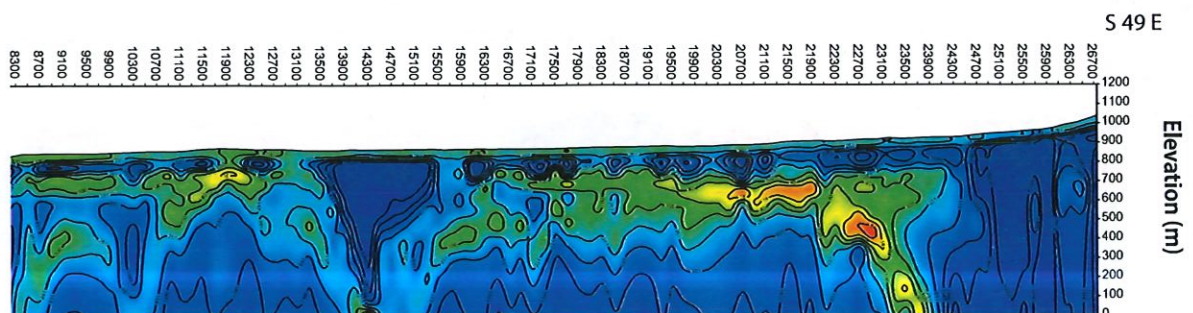
Plan map location of the USGS gravity line N1 relative to the SE segment of CSAMT line 10 on plate 1 from Phelps, et. al., 2000.

B.



Line N1 gravity model results from Phelps, et. al. (2000), showing surface to sea level at the same scale as the CSAMT line 10 segment below.

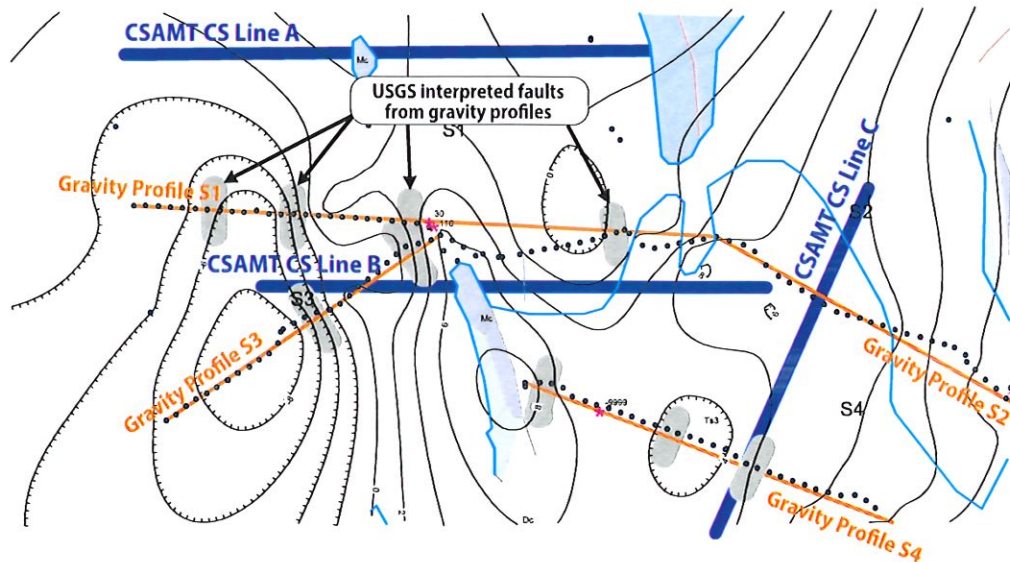
C.



The SE segment of CSAMT line 10 from surface to sea level at the same scale as the gravity results in "B" above.

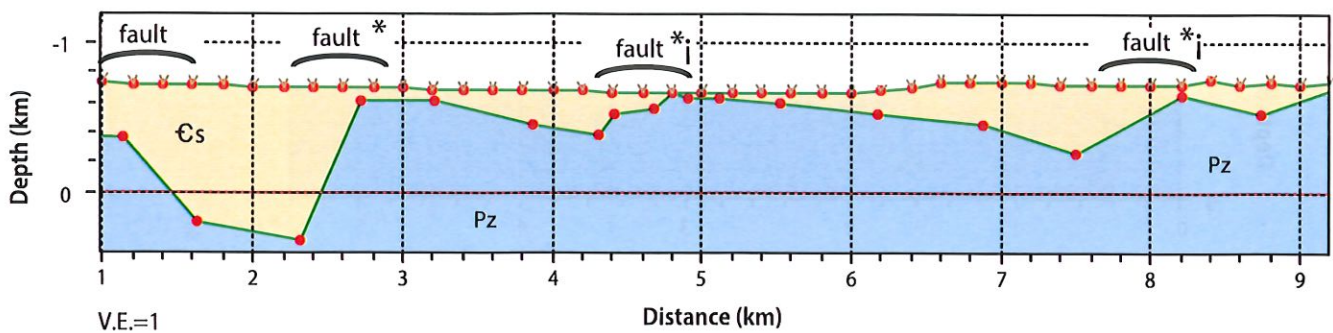
Figure 34. U.S. Geological Survey gravity line N1 and CSAMT line 10 in northern Coyote Spring Valley

A.



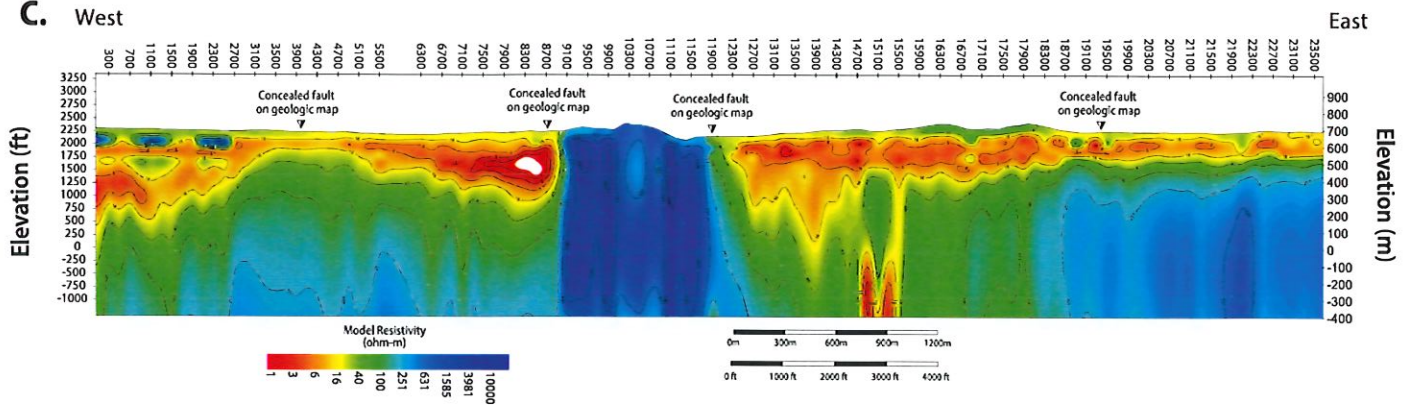
Plan view map location of the USGS gravity line S1 relative to the segment of CSAMT line CS B on plate 1 from Phelps, et. al. (2000).

B.



The eastern 8 km of line S1 gravity model results from Phelps, et. al. (2000), showing surface to an elevation of -400 m at the same scale as the CSAMT line CS B segment below.

C. West



The segment of CSAMT line CS B from surface to elevation -400 m at the same scale as the gravity results in "B" above for gravity line S1.

Figure 35. U.S. Geological Survey gravity line S1 and CSAMT Coyote Spring line B in Coyote Spring Valley

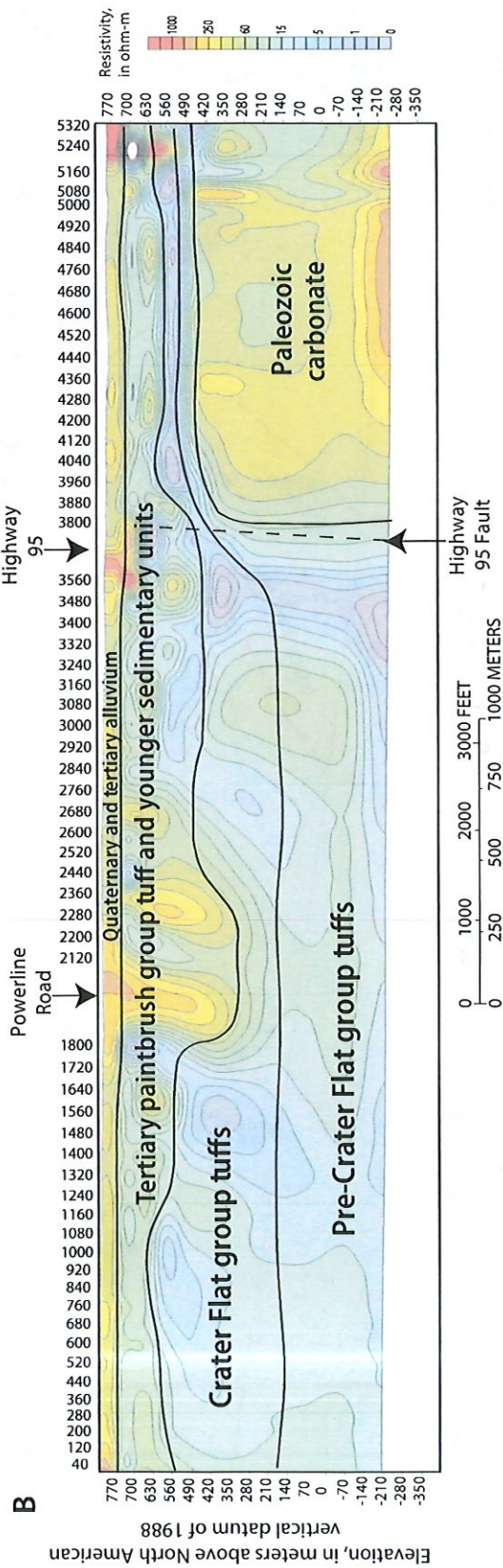
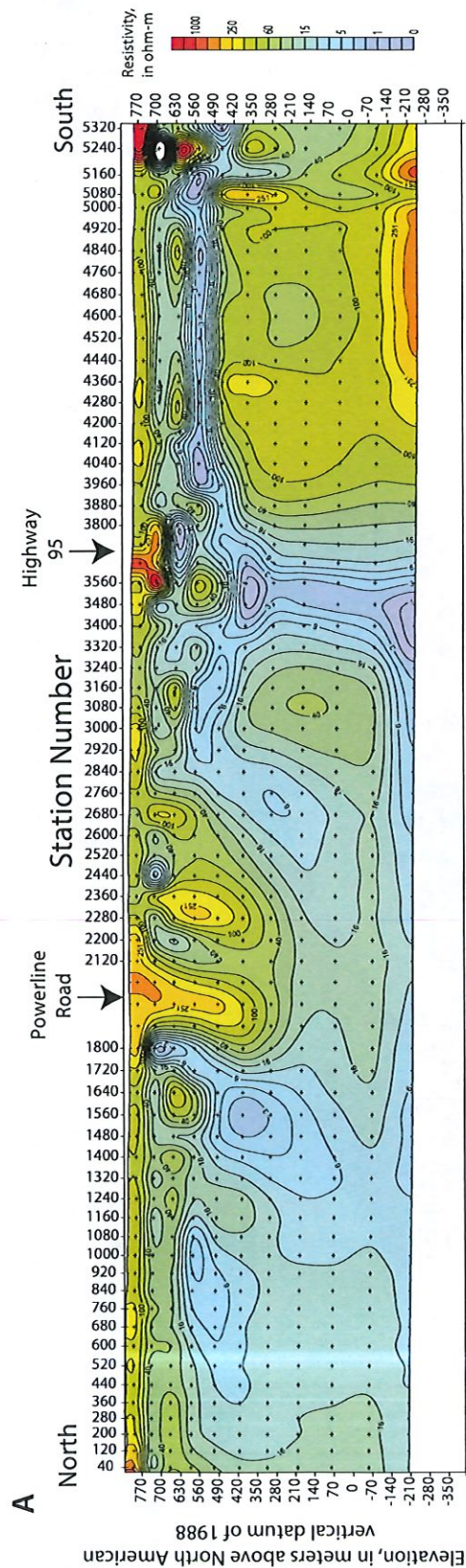


Figure 36. Smooth model inversion cross section of line A taken from characterization of the Highway 95 fault in Lower Fortymile Wash using electrical and electromagnetic methods, Nye County, Nevada. USGS Scientific Investigations Report 2012-5060.

Figure 37. Local groundwater elevation map of southern Kane Springs Valley, a portion of Coyote Spring Valley and a portion of the Muddy River Springs Area

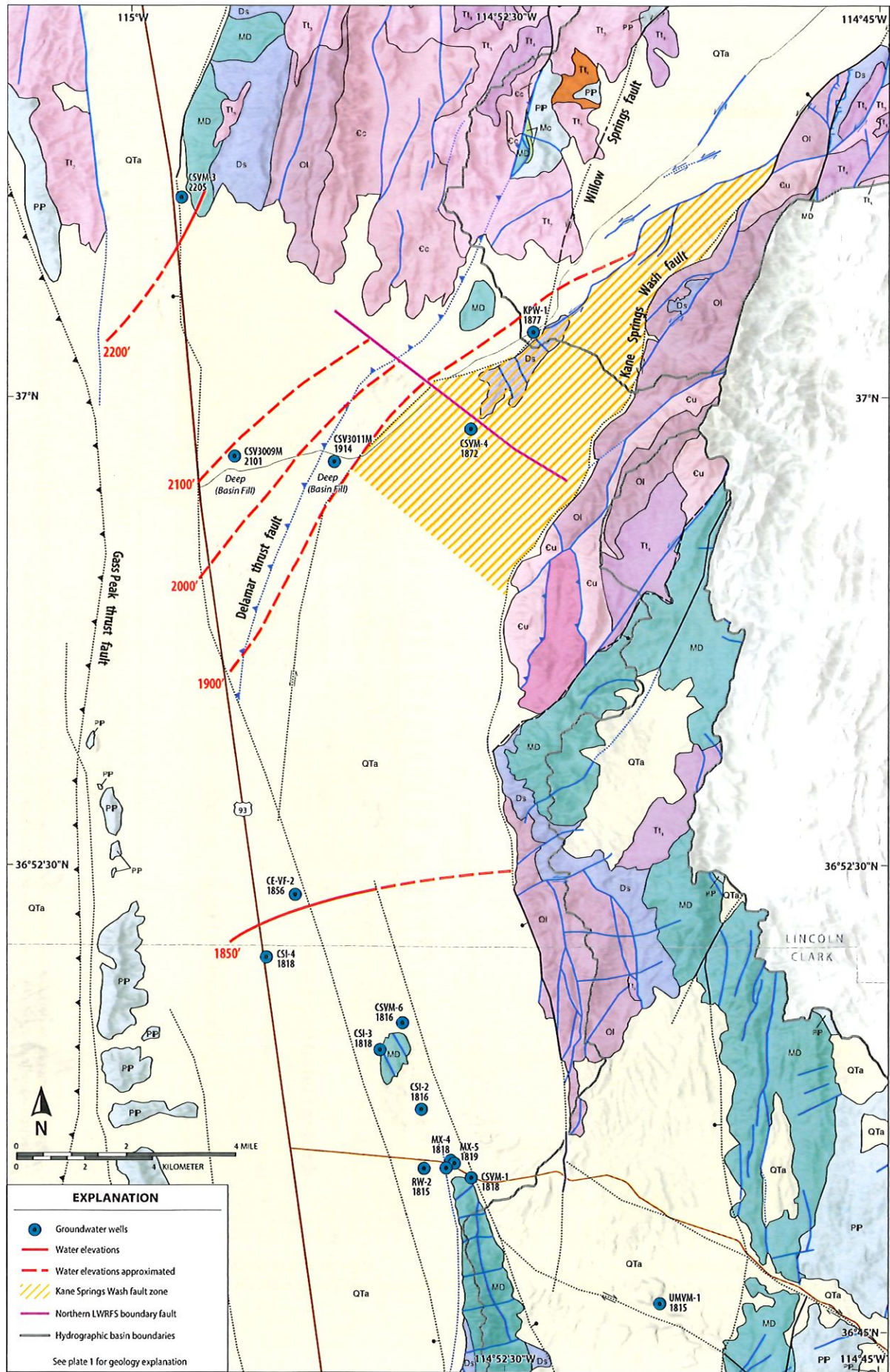


Plate 1 of 2

¹Retired (work completed while with Zonge International, Inc.)
²Vidler Water Company, a Division of DR Horton Homes

2025



CSAMT AND NSAMT RESULTS OF SOUTHERN KANE SPRINGS VALLEY, COYOTE SPRING VALLEY, AND THE MUDDY RIVER SPRINGS AREA

Plate 2 of 2

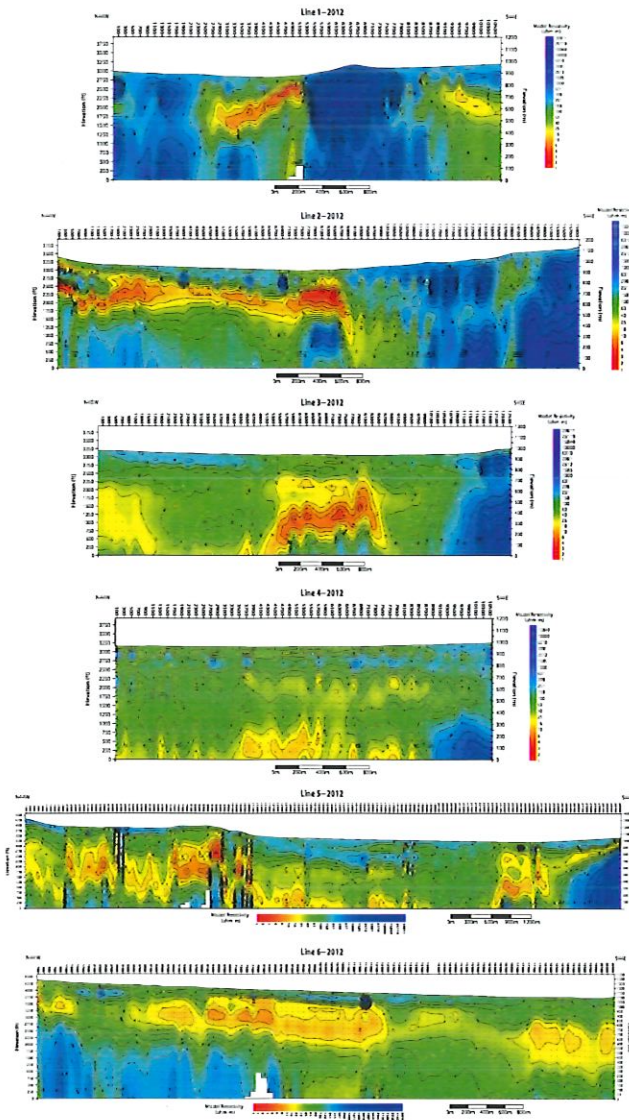
Norman R. Carlson¹, Greg L. Bushner², Ryan Hoerth³

¹Retired work completed while with Zonge International, Inc.

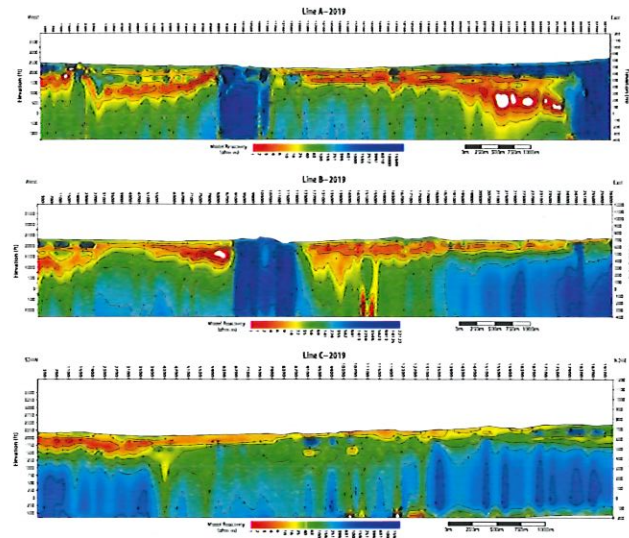
²Vador Water Company, a Division of Olin Nutrition

2025

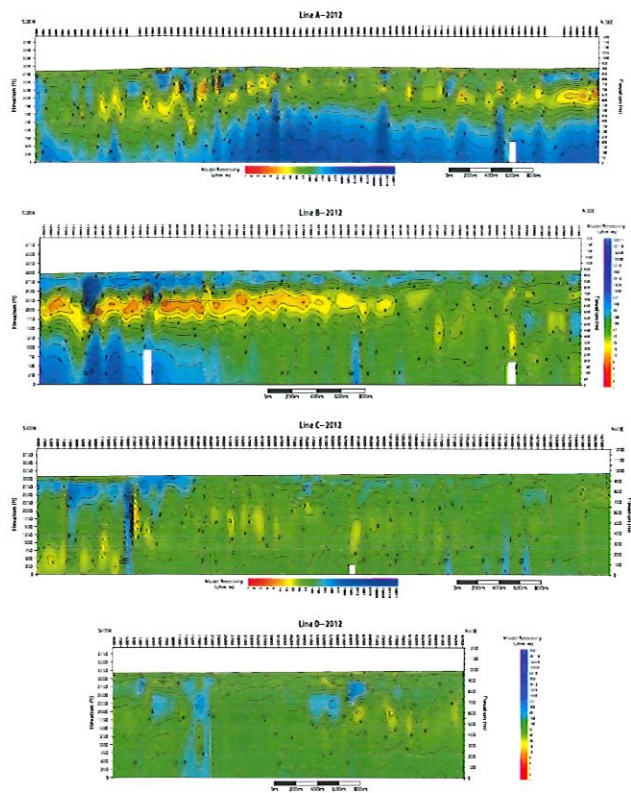
Kane Springs Valley CSAMT and NSAMT Results Resistivity Cross Sections 2012 Lines 1, 2, 3, 4, 5, and 6



Coyote Spring Valley and the Muddy River Spring Area CSAMT Results 2019 Resistivity Cross Sections Lines A, B, and C



Kane Springs Valley CSAMT and NSAMT Results Resistivity Cross Sections 2012 Lines A, B, C, and D



Northern Coyote Spring Valley CSAMT Results 2019 and 2021 Resistivity Cross Sections Lines 10, 11, 12, 13, and 14

