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Surface Geophysics Survey Report Subsurface Corrective Action
Unit 447 Project Shoal Area, Nevada

April 2011

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Contents

1.0 Introduction ........................................................................................................................................... 1
  1.1 Background ........................................................................................................................................... 1
2.0 Surface Geophysical Methods .................................................................................................................. 1
  2.1 Seismic Reflection Survey .................................................................................................................. 2
  2.2 Preliminary Electromagnetic Survey .................................................................................................. 2
  2.3 Full-Scale Electromagnetic Survey ..................................................................................................... 2
  2.4 Dike Survey ......................................................................................................................................... 3
3.0 Interpretation of Results .......................................................................................................................... 3
4.0 Conclusions and Recommendations ....................................................................................................... 4
5.0 References ............................................................................................................................................... 4

Appendices

Appendix A Boise State University Seismic Survey Report
Appendix B Hasbrouck Geophysics, Inc. Preliminary EM Survey Report
Appendix C Hasbrouck Geophysics, Inc. EM Full Survey Report
Appendix D Photos from the Dike Survey
1.0 Introduction

This report summarizes the surface geophysics program conducted by the U.S. Department of Energy (DOE) Office of Legacy Management (LM) at the Project Shoal Area Subsurface Corrective Action Unit 447 in Nevada. The program was conducted as part of the revised corrective action/closure strategy that was described in the LM letter to the Nevada Division of Environmental Protection (NDEP) dated November 24, 2009. The objectives of the surface geophysical surveys were to obtain data that would help image the water table and identify faults/major fracture zones that may affect groundwater flow at the site. Two geophysical methods were used to meet these objectives: seismic reflection and electromagnetic (EM), controlled-source audio magnetotellurics/magnetotellurics.

1.1 Background

The original corrective action/closure strategy used a numerical groundwater flow and transport model to assist in the evaluation of data and selection of a corrective action alternative. The model results were also used to determine a contaminant boundary and establish a restricted region surrounding the site. The corrective action alternative for the site consists of monitoring with institutional controls and is presented in the Corrective Action Decision Document/Corrective Action Plan (CADD/CAP; DOE/NNSA 2006). As part of the original strategy, three wells (MV-1, MV-2, and MV-3) were installed in 2006 for the dual purpose of monitoring and evaluating the flow and transport model results. Based on a comparison of monitoring data and modeling results, the groundwater flow and transport model could not be validated (NDEP letter; July 11, 2008). Pursuant to the Federal Facility Agreement and Consent Order (FFACO 1996, as amended March 2010), LM is developing a revised corrective action/closure strategy for the site.

On November 24, 2009, LM submitted a Short-Term Data Acquisition Plan (DOE/LM 2009) to NDEP detailing the proposed data collection and field investigation activities that would support a revised corrective action/closure strategy. Proposed activities included (1) using geophysical methods to image the water table and identify faults and fracture zones with the potential to affect groundwater flow and (2) developing an enhanced monitoring system for collecting hydrologic and geochemical data.

2.0 Surface Geophysical Methods

Geophysical methods can be used to indirectly sample the subsurface and, when used in conjunction with site well data, allow a more complete site conceptual model to be developed. The seismic reflection method uses an energy source (explosives, hammer, or vibroseis) to transmit seismic energy through the subsurface. A portion of the seismic energy is reflected back to geophones that are evenly spaced along the ground surface to record the data. The recorded data are used to identify seismic velocity and/or density contrasts (reflectors) in the subsurface that may be interpreted as faults, shear zones, significant changes in porosity, and/or the water table. The EM method determines the earth’s subsurface electrical resistivity distribution by measuring time-dependent variations of the earth’s natural electric and magnetic fields, as well as the electric and magnetic fields resulting from high-frequency induced waves. Resistivity values in any rock type are directly related to changes in the rock’s porosity, variation of the salinity of the fluids filling the rock, and the presence of some specific minerals that are excellent
conductors of electricity (Northwest Mining Association 1980). The EM method is often used to find structures and subsurface materials that are good producers of groundwater. The following sections provide a summary of the geophysical surveys and the dike survey conducted at the site.

2.1 Seismic Reflection Survey

A 2-dimensional (2D) seismic reflection survey was conducted in June 2010. The survey consisted of three seismic profiles (totaling 3.26 miles) collected along site roads and three vertical seismic profiles (VSP) collected in wells not equipped with dedicated pumps. A trailer-mounted, 200-kilogram accelerated hammer was used as the seismic energy source for the profiles and VSPs. The VSPs were acquired in wells HC-1, HC-2, and HC-6. A VSP is primarily used to convert seismic data, recorded in time, to depth. VSPs also provide velocity information that assists in seismic reflection data processing. A ground-based magnetic survey was also collected as part of a work study project during the seismic survey.

Data from the seismic survey were difficult to interpret because the reflectors on all three profiles were discontinuous, making interpretations subjective. The prominent shear zone in the eastern part of the site and a mounded high-reflectivity zone overlying a core of subdued reflectors west of the shear zone are the most identifiable features. The identification of other features, such as the water table, fractures, and dikes, cannot be made with confidence. Due to the limited quality of the seismic data acquired during the 2D survey, a more comprehensive 3D survey was not warranted. A copy of the geophysical report is provided as Appendix A.

2.2 Preliminary Electromagnetic Survey

A feasibility test was conducted in April 2010 to evaluate if electromagnetic methods could identify subsurface features at the Shoal site. The feasibility test was limited to 25 stations along two lines that cross surface ground zero at the site. The limited survey successfully identified the detonation zone, providing encouragement that it could also identify other subsurface structures that influence water flow. Based on these results, a full-scale EM survey was recommended for the site. Results from the preliminary EM survey are presented in Appendix B.

2.3 Full-Scale Electromagnetic Survey

The full EM survey was performed at the site in August and September 2010. Data were acquired at 312 stations positioned along 24 lines with a 250 ft grid spacing. The survey identified areas of spatially varying resistivities that were attributed to features in the subsurface at the site. The contact between the unsaturated and saturated zones (the water table) was inferred from the depth where observed water levels in site wells approximately coincided with the transition from a relatively continuous band of low-resistivity material to higher-resistivity material below. The lower-resistivity areas in the unsaturated zone are interpreted as zones of increased fracturing, more alteration (possible increased clay content), higher porosity, and areas of increased infiltration. Additionally, the water in the unsaturated zone may have a higher sodium chloride content that is derived from windblown deposits associated with the salt flats within Fourmile Flat west of the site. The alternating low- and high-resistivity zones above the water table align approximately with the N 50–60° W orientation of fractured dikes at the site. A copy of the EM survey report is provided as Appendix C.
2.4 Dike Survey

A field survey of the dikes present in portions of the study area was performed during the full-scale EM survey in September 2010. The Sand Springs batholith is composed of granodiorite and granite, aplite and pegmatite dikes, andesite dikes, rhyolite dikes, and rhyolitic intrusive breccia. Faults, joints, and fractures at the site are vertical to steeply dipping and are distributed along two dominant structural trends that generally strike N 50–60° W (orientation of the majority of dikes at the site) and N 30° E (orientation of the shear zone east of surface ground zero). The hills to the south, southwest, west, and northwest are underlain by erosion-resistant dikes, granite, and granodiorite. The pegmatite and aplite dikes appear fractured in surface outcrops, with the fractures oriented perpendicular to the dike. The andesite dikes appear heavily fractured in surface outcrop, with no preferred fracture orientation, and the quartz veins are shattered. Only a few small dikes are evident in the central portion of the site; however, this area has lower relief than the surrounding hills and has fewer bedrock exposures. In general, the size and number of dikes diminishes from west to east. Photos from the dike survey are provided as Appendix D.

3.0 Interpretation of Results

The following observations and interpretations were made from an evaluation of the data:

**Seismic Results**

- The prominent shear zone in the eastern part of the site was identified on the east-west seismic profile (profile 1).
- A mounded zone of subdued reflectors west of the shear zone was also identified on the east-west seismic profile (profile 1) and is interpreted as a core of more-competent, less-fractured rock.
- Features such as the water table, fractures, and dikes were not identifiable from the seismic data.

**EM Results**

- Data from the EM survey indicated that resistivities in the unsaturated zone are more variable than resistivities in the saturated zone. The lower-resistivity areas in the unsaturated zone are interpreted as areas of increased fracturing, more alteration, higher porosity, and increased infiltration.
- Contrasting high- and low-resistivity areas in the unsaturated zone are further interpreted as areas of lower and higher recharge, respectively. The higher-recharge areas occur along preferential flow paths that appear as zones of lower resistivity.
- The low-resistivity areas observed above the water table are believed to result from the infiltration of more electrically conductive saline water. Windblown salts from the adjacent salt flats are the source of the increased salinity. The older, less saline water in the saturated zone (more uniform higher resistivities than in the unsaturated zone) remains from a time when the climate in the area was much less arid. During the last glacial cycle, the adjacent valleys were filled by lakes to a much higher level than the current salt flats, and infiltration...
rates of fresh water would have been much greater than the current infiltration rates of relatively saline water.

- The zones of contrasting resistivities generally trend N 50–60° W, or parallel to the strike of highly fractured dikes that are visible along the western boundary of the study area. If the fracturing of dikes observed at the surface persists at depth, these dikes would have the potential to impart a hydrogeologic anisotropy that would favor preferential flow of groundwater within them.

### 4.0 Conclusions and Recommendations

Based on recent technical discussions pertaining to the surface geophysical data, the EM results will be evaluated in context with other site data, to resolve uncertainties associated with the site conceptual model. The Short-Term Data Acquisition Plan developed in 2009 outlined a strategy for collecting surface geophysical data, enhancing the monitoring network, and eventually revising the current CADD/CAP. It is recommended that another Short-Term Data Acquisition Plan be developed in late fiscal year 2011 to identify methods that can be used to further resolve uncertainties, verify interpretations, and improve the site conceptual model. The path forward and schedule for revising the CADD/CAP will be submitted to NDEP for review and approval.

### 5.0 References


NDEP (Nevada Division of Environmental Protection), 2008. Draft – Validation Analysis of the Shoal Groundwater Flow and Transport Model, Corrective Action Unit 447, Nevada Division of Environmental Protection, Las Vegas, Nevada, July.

Appendix A

Boise State University Seismic Survey Report
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Geophysical Characterization at the Shoal, Nevada, Site

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# Contents

Executive Summary

Introduction

Seismic Methods

Vertical Seismic Profiling

Well HC-1

Well HC-2

Well HC-6

Seismic Reflection Methods

Seismic Profile 1

Seismic Profile 2

Seismic Profile 3

Summary

Acknowledgements

References
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Executive Summary

This report summarizes results of new geophysical data acquired at the Project Shoal Site, Nevada. Three vertical seismic profiles (VSPs), three seismic reflection profiles, and a set of ground-based magnetic profiles were acquired in wells and on existing roads within the test site. The data were acquired to provide insights into geologic and hydrogeologic controls of groundwater flow in granite related to the underground nuclear test that was conducted at the site. The results from the VSP data show fast seismic velocities and high frequency response in well HC-2 along the western margin of the site typical of a competent granite at the surface and at borehole depths compared to results from wells HC-1 and HC-6. VSP results from wells HC-1 and HC-6 show seismic velocities and frequencies consistent with a weathered layer on the surface, fractured granite at borehole depths, and an increase in seismic velocities at the water table consistent with measurements in well HC-2. The west-east seismic reflection Profile 1 shows reflections to approximately 0.5 km below ground surface (bgs) that suggest kilometer-scale folding within the granite and variable water table depths. The central portion of the profile shows a transparent reflection zone that correlates with a west-dipping shear zone that surfaces near position 1225. The south-north seismic Profiles 2 and 3 show a series of discontinuous reflectors in the upper 0.5 km depth that is consistent with west-east fractures within the granite at and near water table depths. Magnetic results are consistent with seismic measurements in that regional folding represents an approximately 100 nano Tesla (nT) anomaly between anticlinal and synclinal axes of the folding observed along Profile 1. Assuming groundwater flow is controlled by geologic conditions, west-east folding may enhance north-south flow. However, west-east fractures may inhibit or influence north-south flow.

Introduction

The 12-kiloton Project Shoal underground nuclear test, conducted on October 26, 1963, was detonated in granitic rock at a depth of approximately 369 m bgs. The cavity created by the test collapsed shortly after the detonation and formed a rubble chimney that extends upward to a depth of approximately 260 m bgs. The site is located within a granitic batholith in the northern portion of the Sand Springs/Stillwater Range of west-central Nevada. Vertical to steeply dipping normal faults, joints, and fractures at the site generally strike N 50° W and N 30° E. The water table is approximately 300 m bgs. A shear zone, located approximately 500 m east of surface ground zero (sgz), may act as a barrier to lateral fluid flow. Other faults and fractures may also influence groundwater flow. The site is located approximately 50 km east of Fallon, Nevada, and is accessible to the public (Figure 1).
Figure 1. Project Shoal Area, located in western Nevada in the Sand Springs/Stillwater Range.
Seismic Methods

Vertical Seismic Profiling

A VSP involves lowering a geophone down a borehole and transmitting sound waves through the geologic formation from the maximum borehole depth to the surface. A VSP survey is useful to estimate formation seismic velocities, to calibrate reflection travel times measured with surface seismic methods, and to calibrate seismic frequency and amplitude values with depth. I conducted three VSP surveys at Project Shoal. These surveys were conducted in monitoring wells HC-1, HC-2 and HC-6 (Figure 2). The Boise State 200 kg accelerated weight drop source and a Geostuff 3-component 10 Hz borehole seismometer were used to acquire the data. These acquisition parameters match the surface seismic data described below.

![Figure 2. Location map for Shoal showing seismic profiles, boreholes, shear zone, and 1963 blast location.](image-url)
The source was positioned approximately 10 m from each well to avoid interference from air-coupled seismic signals and to provide seismic velocities of the near-surface weathered zone. Seismic measurements were taken at 1-m intervals from maximum depth to the surface. Here, I assume that the first arrival picks represent straight ray path p-wave arrivals. Formation interval velocities are derived from a running average of first arrival picks. Gaps in interval velocity values with depth represent low-confidence pick zones. Data were only acquired in the cased portion of each well.

**Well HC-1**

Well HC-1 is 409 m deep, and the well casing extends to 291 m bgs. The borehole is open from the bottom of the casing to total depth. This well is located along seismic Profile 3, approximately 0.5 km north of the blast well PS-1 (Figure 2). Fractured, coarse-grained granite was logged from top to bottom, and thin, intrusive, andesitic dikes were inferred between 275 and 281 m depths that correlate with fault and/or fracture zones within the granite (DOE, 1998). VSP logging began at the depth of static water level in well HC-1, which was approximately 330 m bgs. The source position was readjusted a number of times to account for soft ground conditions and poor source plate coupling. These soft ground conditions resulted in a lower frequency response compared to VSP measurements in HC-2 and HC-6.

Figure 3. Vertical seismic profile for well HC-1, located between seismic Profiles 2 and 3 along the northern boundary of the Shoal site (Figure 2). Interval seismic velocities are measured from ~3,000 to 6,000 m/s, consistent with fractured to unaltered granite. The water table is at a depth of approximately 330 m, below the VSP measurements.
First arrivals appear from surface to more than 300 m bgs in well HC-1 (Figure 3). At 329 m bgs, first motion from the direct arrival appears at 100.6 ms travel time, or an average formation velocity of 3,272 m/s. Average velocity values for the upper 20 m are approximately 700 m/s, and the average velocity from the 20–329 m depth interval is 4,491 m/s. The near-surface values are consistent with unsaturated, unconsolidated sediments in the upper 20 m and are also consistent with soft surface conditions observed at the source. Seismic velocities below 20 m bgs are consistent with weathered to competent granite. Alternating fast and slow seismic velocity zones are consistent with competent granite/dike locations and fracture zones, respectively.

Well HC-2

The 397-m-deep well HC-2 is cased to 291 m bgs and is located approximately 0.5 km west of central well PS-1 (Figure 2). Fractured, coarse-grained granite was logged from top to bottom with an intrusive aplite dike between 137 and 152 m depths that correlate with fault and/or fracture zones within the granite (Figure 4; DOE, 1998). Additional fault or fracture zones were encountered at 176–192 m, 253–258 m, and 335–341 m depths. Static water level in well HC-2 was approximately 343 m bgs. VSP logging began at approximately 210 m bgs and thus sampled the velocity in unsaturated granite surrounding well HC-2. Ground conditions at the source were solid, and the seismic source was not moved during VSP acquisition.

First-arrival signals appear from surface to approximately 170 m bgs, with poor signal-noise ratio below 170 m bgs (Figure 4). At 178 m bgs, first motion from the direct arrival appears at 55.5 ms travel time, or an average velocity of 3,212 m/s. Velocity values for the upper 20 m average approximately 810 m/s, and the average velocity from the 20–300 m depth interval is 5,663 m/s. The near-surface values are consistent with unsaturated, unconsolidated sediments in the upper 20 m and are also consistent with soft surface conditions observed at the source. Seismic velocities below 20 m bgs are consistent with competent granite. Alternating fast and slow seismic velocity zones are consistent with competent granite/dike locations and fracture zones, respectively. A fast seismic zone centered near 50 m bgs is not noted in lithologic logs but likely represents a zone of highly competent granite. First arrivals were not picked below 178 m depth due to poor signal strength. Poor data quality below 178 m depth may be attributed to a fracture/fault zone (DOE, 1998), where poor formation coupling to the casing may have significantly attenuated seismic energy.
Well HC-6

The 378-m-deep well HC-6 is cased to 376 m bgs and was originally drilled for tracer tests. The well is located along the southern boundary of the Shoal site, west of a prominent northeast-striking shear zone mapped at the site (Figure 2). Fractured, coarse-grained granite was logged from top to bottom with extensive fault and/or fracture zones below 50 m bgs (DOE, 2000). Static water levels in well HC-6 were at approximately 298 m bgs. VSP logging began at approximately 375 m bgs and thus sampled the velocity in both unsaturated and saturated granite in well HC-6.

First-arrival signals appear from surface to approximately 375 m bgs, with a significant change in first-arrival velocity and frequency at approximately 300 m bgs (Figure 5). A neutron log acquired in HC-6 shows a similar change at 300 m bgs that relates to water table depths. At 378 m bgs, first motion from the direct arrival appears at 142.5 ms travel time, or an average velocity of 2,653 m/s. Velocity in the upper 20 m averages approximately 630 m/s, while the average velocity from the 20–300 m depth interval is 2,959 m/s. Average velocity below 300 m bgs is 5,997 m/s. The near-surface values are consistent with unsaturated, unconsolidated sediments in the upper 20 m and are also consistent with soft surface conditions observed at the source. Seismic velocities below 20 m bgs are consistent with competent granite.
Alternating fast and slow seismic velocity zones are consistent with competent granite/dike locations and fracture zones. Fast seismic velocity zones are consistent with low neutron values while slow seismic zones correlate with high neutron values. A large change in seismic velocity below water table depths suggests that this boundary can be mapped with surface seismic methods.

**Seismic Reflection Methods**

Seismic reflection methods are commonly used in exploration for hydrocarbons, coal, geothermal energy, and in shallow applications for engineering, groundwater, and environmental targets. Seismic reflection data acquisition involves a seismic source and an array of sensors or geophones (Figure 6). Seismic sources can include explosives, hammers, and vibroseis sources, all coupled to the ground surface. The seismic source is intended to propagate sound waves through the subsurface. At each seismic velocity or density contrast in the subsurface, the seismic energy is partitioned. A portion of the seismic energy is reflected back to the earth’s surface, while another portion of the seismic energy continues to radiate away from the seismic source. The ground displacement, as the seismic energy returns to the earth’s surface, registers on a geophone (similar to a motion sensor) as a change in voltage, and the analog signal that represents ground displacement is digitally recorded with a seismograph.
Seismic boundaries with large velocity and/or density contrast can include the water table, bedrock surface, and a significant change in porosity or grain size (e.g., clay to sand) within a sedimentary sequence. Once seismic data are recorded, seismic processing steps include removing or attenuating coherent and random signals not related to the reflection energy, a data sort from shot gathers to common midpoint gathers, a seismic velocity analysis and correction, elevation corrections to a common datum, and stacking data at varying ray geometries to produce a section that simulates a geologic cross section (e.g., Yilmaz, 2001).

![Figure 6. (A) Cartoon of acoustic waves transmitting from a hammer source through a subsurface layer and returning to geophone locations at the surface. (B) A Boise State University 500 lb rubber-band-accelerated hammer source. (C) An example shot record showing reflections and other coherent and random signals. Longer travel paths appear on the down side of the fault (on A). These longer travel paths result in delayed reflector travel times (on C).](image)

Seismic reflection data interpretation involves identification of coherent reflectors, offsets in these reflectors, and the strength of the reflected signals. Tied to borehole information, seismic velocities, and geologic and other geophysical data, a geologic interpretation is formed. Reflecting boundaries represent a change in physical properties at a
measured travel time. A tie to borehole and geologic information provides the link between seismic data and a geologic interpretation. Depth estimates from seismic velocities alone are not precise, but they serve as a reasonable first-order estimate of reflector depth. A more accurate correlation of seismic data to depth requires extrapolation from borehole measurements.

Seismic Profile 1

The 2.1-km-long west-east Shoal site Line 1 seismic reflection profile is located along the main access road from Highway 31 (Figure 2). The profile crosses borehole HC-2 near position 1030, Profile 2 near position 1080, the blast zone near position 1150, Profile 3 near position 1205, and a shear zone mapped near position 1230. Elevation along the profile decreased from west to east by approximately 100 m (Figure 7). A ground-based magnetometer profile was acquired along the profile that showed variations of ~200 nT across the profile. An upward continued profile to remove ground-based magnetic effects shows a magnetic low along the western and central portions of the profile. East of the shear zone at position 1230, total magnetic field values remain consistently high.

Seismic reflection results from Profile 1 show reflections to approximately 0.3 s two-way travel time, or approximately 500 m bgs (Figure 7). Reflections vary in character and depth across the profile, and a single reflector is not clearly identified. Because VSP HC-6 shows a large change in seismic velocity at the water table, I interpret the base of the high-reflectivity zone as the water table. This suggests the water table elevation may vary across the Shoal site and may be influenced by geologic structures.

The reflectors along Profile 1 show a pattern of kilometer-scale structures across the profile (Figure 7). The peak elevation of a high-reflectivity zone appears at position 1080 and has the appearance of an anticline. This could be caused by a zone of subhorizontal stress-relief fracturing that overlies a deeper, less fractured core at depth. However, this position is also consistent with a magnetic high observed on the ground-based magnetometer profile, suggesting that the high-reflectivity zone could be the contact of the overlying granite and a deep intrusive core composed of a denser more mafic composition. A zone absent of near-surface reflectors appears near the mapped shear zone. This zone is also coincident with a topographic low (appearance of a syncline) of relatively coherent reflectors at depth. Reflectors at position 1230 suggest the presence of a west-dipping shear zone that truncates reflectors to the east and west. Semicontinuous reflectors east of the shear zone suggest that additional faults may be prominent, but the lack of coherent reflectors make interpretation in this area difficult.
Figure 7. Elevation profile, unmigrated seismic reflection profile, and interpreted, migrated, and depth-converted seismic image from the Shoal site Line 1.
Seismic Profile 2

The 0.75-km Shoal site Line 2 profile was acquired along the west shoulder of the south-north access road from Line 1 (Figure 2). Profile 2 crosses Profile 1 at position 2115 and terminates to the north at a steep topographic slope and vista. Elevation along the profile varies approximately 10 m with a topographic low at position 2115 (Figure 8).

Semicontinuous, relatively flat-lying reflectors and the short length of Profile 2 make interpretation difficult (Figure 8). Diffractions scattered across the profile may result from fractures in the granite that cause large lateral velocity changes. Lateral variations in the ground-based magnetic profile are consistent with considerable fracturing in the granite.

Seismic Profile 3

The 2.4 km Shoal site Line 3 profile was acquired along the east shoulder of the south-north access road from Line 1 (Figure 2). The profile crosses monitoring well MV-1 at position 3085, MV-2 at position 3100, and HC-1 at position 3140. The southern portion of the profile extends along the winding road from positions 3001 to 3150, then extends along a relatively straight profile to the northern termination of the profile. The profile begins at the Profile 1 road where it crosses Profile 1 at position 1205. The elevation rises from 1580 m at position 3001 to 1650 m at position 3200 (Figure 9). North of position 3200, the elevation varies less than 20 m. The profile parallels the interpreted fracture zone (Figure 2). Instrument failure prevented acquisition of ground-based magnetic profiling along this profile.

Semicontinuous reflectors appear along the length of Profile 3 in the upper 300 m bgs (Figure 9). The strongest amplitude reflector is located from the approximately 250 to 350 m depth interval that I interpret as the water table. Diffractions on the unmigrated profile suggest that lateral velocity contrasts are present and may represent faults or fracture zones. At these diffraction boundaries, I identify offset reflectors in the upper 300 m depth.
Figure 8. Elevation profile, unmigrated seismic reflection profile, and interpreted, migrated, and depth-converted seismic image from the Shoal site Profile 2. A ground-based magnetic profile is shown on top.
Figure 9. Elevation profile, unmigrated and migrated seismic reflection profile from the Shoal site Profile 3.
Summary

Seismic data from the Shoal site show that large seismic velocity contrasts are present in the upper 300 m bgs. These velocity contrasts correspond with fractures and water table depths. I interpret the dominant reflector on Profiles 1 and 3 as the water table. This reflector is offset and shows considerable variation in depth. Additional reflectors on the seismic profiles may represent layering within the Shoal site granite. Because only discontinuous reflectors consistently appear across each profile, a detailed velocity analysis of the seismic data is not possible. Because of the uncertainties in stacking velocities, depths inferred from travel times are not precise. Therefore, absolute depths to the water table and geologic boundaries contain some uncertainties. Diffractions that I identify along the profiles represent large lateral velocity contrasts. These large contrasts are interpreted as fracture zones that may be conduits to groundwater flow at the Shoal site.

Acknowledgements

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References

Appendix B

Hasbrouck Geophysics, Inc. Preliminary EM Survey Report
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Final Report

Project Shoal Area
CSAMT/MT Initial Feasibility Test

for

S. M. Stoller Corporation
Grand Junction, Colorado

May 24, 2010
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TABLE OF CONTENTS

INTRODUCTION................................................................................................................................. 1
METHODOLOGY .................................................................................................................................. 1
DATA ACQUISITION AND PROCESSING .............................................................................................. 3
RESULTS ............................................................................................................................................... 4
CONCLUSIONS AND RECOMMENDATIONS ......................................................................................... 7
LIMITATIONS OF INVESTIGATION ...................................................................................................... 8

FIGURES
Figure 1: Typical field setup of Geometrics StrataGem EH4 MT system
Figure 2: CSAMT/MT data example
Figure 3: Station locations map, 1:8000 scale
Figure 4: Line 1 resistivity depth section
Figure 5: Line 2 resistivity depth section
Figure 6: Lines 1 and 2 resistivity depth sections
Figure 7: Horizontal depth slice at ~800 feet relative to surface
Figure 8: Horizontal depth slice at ~1000 feet relative to surface
Figure 9: Horizontal depth slice at ~1200 feet relative to surface
Figure 10: Regional topographic map, 1:24,000 scale, with stations and interpreted structures

MOVIE
Horizontal depth slices from 0 to ~3000 feet, relative to surface, at 50-foot intervals

ADDITIONAL PLOTS ON CD
Horizontal depth slices from 0 to ~3000 feet, relative to surface, at 50-foot intervals
Line 1 resistivity elevation section
Line 2 resistivity elevation section
Lines 1 and 2 resistivity elevation section
INTRODUCTION
This report presents the results of a controlled source audio magnetotellurics/magnetotellurics (CSAMT/MT) geophysical survey conducted in the Project Shoal area, Nevada. The objectives of the survey were to acquire data that will help identify the water table, evaluate the prevailing horizontal groundwater flow direction, identify faults and/or major fracture zones that may affect groundwater flow, and assist in identifying locations for new monitoring wells.

METHODOLOGY
The true resistivity of earth materials is dependent upon several factors, including composition, grain size, water content, and physical characteristics. In general, fine-grained materials such as clays and silts have lower resistivities than coarse-grained materials such as sands and gravels. Unweathered and unfractured hard rocks such as certain sedimentary rocks (e.g., sandstone, chert), volcanic rocks, plutonic rocks, and some metamorphic rocks generally have high resistivities. The presence of fracturing and weathering lowers the resistivity of these rocks. Additionally, the occurrence of groundwater will greatly reduce the resistivity of all rocks and sedimentary materials (through electrolytic conduction). Because of this effect, groundwater is a good target for electromagnetic (EM) geophysical methods that measure resistivity. Clay is also very conductive (low resistivity) as a result of surface-conduction processes, and geological formations with significant amounts of clay in the matrix will generally have limited groundwater production. If appreciable amounts of clay occur in fractures and faults, low-resistivity anomalies that resemble the presence of water may be identified. However, if fractures and faults transmit water at high yields, it is unlikely that clay will form.

CSAMT/MT is an EM geophysical method commonly used in the groundwater industry. It determines the earth’s subsurface electrical resistivity distribution by measuring time-dependent variations of the earth’s natural electric (E) and magnetic (H) fields, as well as the electric and magnetic fields resulting from high-frequency induced waves. The CSAMT/MT method is designed to investigate from depths of approximately 50 to 2500 feet or greater, depending upon resistivities and EM noise. In areas with generally lower subsurface resistivities, the maximum investigation depth will be shallower than 2500 feet. The method is often used to find structures and subsurface materials that are good producers of groundwater or to site high-yield production wells.

Figure 1 shows a graphical representation of the field setup of the CSAMT/MT instrumentation used in this project. In essence, electric dipoles and magnetometers are laid out in perpendicular directions (i.e., Ex, Ey, Hx, and Hy), and both natural and transmitted frequencies are recorded from distant and nonpolarized sources (i.e., the measured EM fields will impinge upon the earth as uniform plane waves). EM waves from sources that are too close will have spherical wave fronts that will not be uniform within a survey area, and waves polarized in one direction will limit the type of measurements that can be made in addition to possibly introducing noise. Distance for EM waves is conveniently specified in terms of wavelength. Where EM waves penetrate conductors, one radian is used as the standard distance and is termed skin depth (also defined as the depth at which the amplitude of a plane wave has been attenuated to 1/e, or 37%). Since wavelength $\lambda = \frac{2\pi}{k}$ (where $k = \text{wave number}$), then one skin depth $\delta = 1/k$. Since $k = (\omega \mu_0 \sigma/2)^{1/2}$, where $\omega = \text{angular frequency}$, $\mu_0 = \text{permeability of free space}$, and $\sigma = \text{conductivity}$, then $\delta = (2/\omega \mu_0 \sigma)^{1/2} = (1/4\pi^2 10^{-7})^{1/2}(\rho f)^{1/2} \approx 503(\rho f)^{1/2}$ in meters, where
ρ = apparent (measured) resistivity in ohm-meters, and $f = \text{signal frequency in hertz (Hz)}$. From both experimental results and numerical simulations, at distances greater than 3 skin depths, the uniform and plane portions of EM waves are dominant, and at 6 to 7 skin depths, the EM waves are completely uniform and plane relative to the precision to which they can be measured. Natural sources will be far removed (greater than 7 skin depths) and therefore will be uniform and plane. However, when sources are measured from artificial transmitters, the distance between the transmitter and receiver must be at least 3 skin depths for EM waves to be uniform and plane.

CSAMT/MT measurements may be made in either the tensor or scalar mode. Tensor measurements use all four components (paired as $E_x/H_y$ and $E_y/H_x$) and are best used in areas where the structure is very complex, when soundings are far apart relative to the size of geologic features under investigation, or where regional anisotropy is strong. Scalar measurements use only one component pair (i.e., $E_x/H_y$ or $E_y/H_x$) and are generally adequate in one-dimensional (1D) layered environments or more complex areas if measurements are dense. If geoelectric strike (which may or may not be the same as geologic strike) is known, then measured resistivities with the $E$ field oriented parallel to strike are referred to as transverse electric (TE) mode measurements, while resistivities with the $E$ field oriented perpendicular to strike are referred to as transverse magnetic (TM) mode measurements. Ideally, the use of tensor measurements is preferred in most areas, especially if the direction of strike is unknown or difficult to determine; however, the presence of polarized noise or low signal amplitude often dictates the use of scalar measurements.

CSAMT/MT measurements are adversely influenced by the presence of EM noise caused by overhead or underground power lines, grounded metal fences, metallic pipelines, other underground utilities, and structures that contain metal (such as reinforced concrete). The influence of these EM noise sources on CSAMT/MT data may be minimized by orienting the $E$ and $H$ field components at approximately 45º to the sources; however, noise may still be present within the data; thus, scalar measurements must be used rather than the preferred tensor mode.

The electric and magnetic data from either tensor or scalar CSAMT/MT measurements are used to assess surface impedance and estimate subsurface resistivity at various frequencies. Surface impedance $Z$ is the ratio of electric to magnetic fields ($Z_{ij} = E_i/H_j$) and is the basis for defining apparent resistivity [$\rho_{ij} = \frac{1}{\omega \mu_0}|Z_{ij}|^2 = \frac{0.2}{f}|Z_{ij}|^2$] and impedance phase {$\phi_{ij} = \tan^{-1}\left(\frac{\text{Im}(Z_{ij})}{\text{Re}(Z_{ij})}\right)$}. CSAMT/MT field data consist of sounding curves that are logarithmic plots of apparent resistivity versus frequency. Apparent resistivities at high frequencies correspond to generally shallow investigation depths, and apparent resistivities at low frequencies correspond to deeper investigations. Apparent resistivities are bulk resistivities with contributions from different heterogeneous materials. Model transformations of the data calculated with forward and inverse computer software are good first-order approximations of the resistivity structure/layering beneath each station or sounding and are presented as cross sections of subsurface resistivity. These cross sections are used for the interpretation of geologic and hydrogeologic conditions. In general, CSAMT/MT data have shown a 10 to 15 percent variation between the actual depths to the anomalies, as verified by test hole drilling, and the depth predicted by the models.
DATA ACQUISITION AND PROCESSING

Data were acquired for this project with a StrataGem EH4 CSAMT/MT system manufactured by Geometrics Inc. of San Jose, California, operating at frequencies ranging from 10 Hz to 92 kHz. The Geometrics StrataGem EH-4 instrument was calibrated at the factory and required no field calibration. With the StrataGem EH-4, time-series of the four components of data (Ex, Ey, Hx, and Hy) were recorded for three overlapping frequency bands: 10 to 1000 Hz, 500 to 3000 Hz, and 750 to 92,000 Hz. For each CSAMT/MT station, or sounding, the magnetic sensors and 50-meter-long electric dipoles were oriented with a compass and prism so that all components in each direction were parallel (i.e., Ex and Hx were parallel as were Ey and Hy). The Ey and Hy components were oriented S25°W to N25°E, which is parallel to assumed regional geologic and geoelectric strike.

The instrument gains were independently set before collecting data at each sounding with identification of possible interference and other quality control procedures assessed before recording the data. After the gains were adjusted, 10 runs of time series data were obtained in the lowest frequency band, and 15 runs were acquired in the middle and highest frequency bands. The lowest frequency band recorded only natural signals, the middle band encompassed both natural and transmitted signals, and the highest band recorded signals from 15 separate transmitted frequencies in addition to any natural signals present. The StrataGem EH-4 is a broadband instrument and as such will record signals with any frequencies within its operating range. The transmitter is used to augment the typically lower-amplitude signals in the middle and highest frequency bands. The data from each sounding were stored on the instrument’s hard drive and downloaded to a laptop PC at the end of each field day.

Figure 2 is an example of raw data acquired with the StrataGem EH-4, although not from this project area. The lower right portion of the figure presents a one-dimensional model, which is labeled as “true” resistivity. This model is generally only useful for simple, layered geologic environments and is only marginally applicable to this project area. The x-axis for each of the three plots within the upper right portion of the figure is logarithmic frequency, and the top plot is scalar resistivity, ranging logarithmically from 1 to 500 ohm-meters, the middle plot is scalar phase from 0° to 90°, and the bottom plot is scalar coherency from 0 to 1.0. On each plot, data from the x direction are shown as diamonds, and the y-direction data are squares. Under ideal circumstances and in areas with no appreciable geologic structures, the x- and y-direction data should fall nearly on top of each other in the resistivity plot, have a phase close to 45°, and have a coherency around 1.0.

A total of 25 separate CSAMT/MT soundings at nominal spacings of 250 feet were acquired along two lines, also nominally separated by 250 feet, as shown in Figure 3. Overall, the CSAMT/MT data were considered good to very good quality with low natural signal amplitudes adversely affecting some of the low- and middle-frequency-band data. Because soil suitable for driving in the electrode stakes a few inches was not present near the Surface Ground Zero location, two stations along line 2 (numbers 16 and 17) were moved off-line to the northeast. It was also necessary to slightly move station number 12 off the axis of line 1 because two of the electrodes would have otherwise been in the excavation waste pile, resulting in high contact resistances and poor data quality. Because of the low natural signal amplitudes, it was necessary to process the data in the scalar mode.
CSAMT/MT data from each station are initially inspected and edited when appropriate. Editing of the data is somewhat subjective but is based upon experience, juxtaposition of $x$ and $y$ direction resistivity data, phase differences from the optimum value of 45°, and coherency. Generally resistivity values above about 40,000 Hz, around 1000 Hz, and below approximately 50 Hz (typical noisy high frequency and low natural signal amplitude frequencies) are often edited out, as are a few other selected frequencies where either the phase or coherency of the data is not considered acceptable. Two-dimensional depth sections are then modeled along profiles. These models are constructed through use of Geometrics’s ElectroMagnetic Array Profile (EMAP) transform software that calculates the Bostick transform resistivities from the CSAMT/MT data. Each depth section consists of logarithmic resistivity versus depth of the Bostick inversion of each CSAMT/MT sounding along a relatively straight line. Subsequently, values for each sounding are converted into a format compatible with the Tecplot Focus 2009 (Release 2, Build 12.1-0-6712) computer program and presented as two- and three-dimensional cross sections in depth or elevation format. Additionally, data from both lines are interpolated into a rectangular cube, and horizontal slices, referenced to the surface, are shown at intervals of 50 feet from the surface to a depth of 3000 feet.

RESULTS
As described in S.M. Stoller Corporation’s (Stoller’s) Request for Proposal (RFP), the Project Shoal Area is in the northern portion of the Sand Springs Range in west-central Nevada’s Churchill County. Specifically, Project Shoal is in Gote Flat within an area that is part of the Cretaceous-age Sand Spring batholith, which is composed of granodiorite and granite, aplite and pegmatite dikes, andesite dikes, rhyolite dikes, and rhyolitic intrusive breccia. Internal deformation of the Sand Springs batholith is mostly by high-angle normal faults that strike northeast and northwest, joints that parallel the northwest-trending faults, and fracture cleavages that generally parallel the northeast-trending faults. The faults, joints, and fractures are distributed between two dominant structural trends that generally strike N50°W and N30°E and are vertical to steeply dipping. Several dikes of varying composition predominantly follow the same two orientations and intrude along these lines of preexisting weakness.

Also from Stoller’s RFP, the water table is considered present beneath the site at depths ranging from approximately 975 to 1090 feet below ground surface (bgs), and groundwater moves primarily through fractures within the batholith. Recharge occurs by infiltration of precipitation on the mountain range, and regional discharge occurs into the adjacent valleys. The groundwater divide along the upland area of the range west of the site separates flow to the east and west. A shear zone, thought to be located about 1500 feet east of the site, is interpreted as a barrier to flow due to disparate groundwater head levels in wells separated by the shear zone.

Figures 4 and 5 are the resistivity depth sections for lines 1 and 2, respectively, and Figure 6 shows both lines with line 2 arbitrarily moved 3000 feet to the north to facilitate interpretation (e.g., make it possible to identify trends between the two lines). Elevation sections are included on the accompanying CD. Several horizontal depth slices, relative to the surface and with the correct distance relationship between the two lines, are included within the main body of this report. Additionally, the depth slices are shown at intervals of 50 feet within a movie and as separate plots on the accompanying CD.
Resistivities to a depth of 3000 feet within the survey area range from approximately 200 to 3000 ohm-meters. It is interpreted that resistivities less than about 300 ohm-meters are indicative of primarily granitic rocks and/or faults and fractures that are water-saturated, while resistivities between approximately 300 and 600 ohm-meters are interpreted as indicating partial water-saturation of the rocks or a lesser degree of saturation because of a decreased presence of faulting and/or fracturing. Resistivities between about 600 and 2000 ohm-meters are interpreted as variably weathered granitic batholithic components or perhaps rhyolitic intrusive breccia in which the lower values represent either more weathering or the rhyolite breccia. Rocks with resistivities greater than about 2000 ohm-meters are interpreted as more competent granite.

A steeply dipping fault or fracture is interpreted along both lines with an extrapolated surface expression between stations 7 and 8 along line 1 and between stations 19 and 20 along line 2, which is consistent with the approximate regional geologic strike of N25°E. This fault or fracture is indicated in the depth sections as large differences in resistivities, with lower values to the southeast. The fault or fracture appears to increase in dip, to almost vertical, at depths greater than about 900 feet and its presence is interpreted to be absent beyond a depth of about 2400 feet. Southeast from this fault or fracture are interpreted water-saturated rocks (resistivities less than about 300 ohm-meters) present at depths along line 1 to around 900 ± 100 feet, with a possible thickness of about 100 to 150 feet, and slightly shallower, by maybe 100 feet or so, along line 2 with a similar thickness. These interpreted water table depths are shallower than the reported 975 to 1090 feet; however, the definition of “water table” can be interpreted differently. For resistivity measurements, “water table” is primarily the depth at which the pore spaces start to become filled with moisture, which may or may not be the same as actual water depth measurements.

Surface elevation differences between the two lines are less than about 20 or 30 feet in the area of interpreted highest water saturation (i.e., lowest resistivities), which is hard to discern on the elevation sections because of the large vertical scale (note that elevations are estimated from topographic maps and have not been surveyed in the field). Thus, because the interpreted water table may be about 100 feet shallower along line 2, there appears to be a difference in elevation of the water table between the two lines in the zone with the interpreted highest water saturation. However, two lines of data and a general EM modeling accuracy of 10% to 15% of actual depth are insufficient to ascribe a dip on the water table with much certainty. If data are acquired regionally over the area, and similar differences in elevation of the interpreted water table are shown on numerous profiles, then an interpretation of water table dip would have greater certainty, although it would be better to supplement the EM data with current water depth measurements from nearby wells and/or other geophysical data to constrain the modeling. Also, no geophysical results are absolute, and interpreting slight dips, particularly of the water table, in reflection seismic data can be difficult. Certainty of the interpretation depends upon how well-defined the refraction statics are and the accuracy of the interpreted stacking velocities and intervals.

Northwest of the interpreted fault or fracture there are differences in the resistivity of the subsurface material along the two lines, particularly to a depth of about 1000 feet bgs. Resistivities along line 1 exceed 2000 ohm-meters, and those along line 2 are between about 1000 and 1500 ohm-meters. The material along line 1 in this area is interpreted as relatively competent granite, and along line 2 it is interpreted as weathered granitic batholithic components.
or perhaps rhyolitic intrusive breccia. This relatively higher resistivity material along both lines occurs within 50 or 100 feet of the surface near the extrapolated surface expression of the interpreted fault or fracture, while farther to the northwest, the higher-resistivity material appears to be absent for about the upper 600 feet along both lines and is present to a depth less than 800 feet along line 2. Given that the two lines are only about 250 feet apart, the relatively large differences in resistivities (1000 or 1500 ohm-meters along line 2 to greater than 2000 ohm-meters along line 1) could be attributed either to structure or to influences from the detonation. Re-entry drilling at Surface Ground Zero indicated that a rubble chimney extended approximately 356 feet above the shot point, which may account for a portion of the resistivity differences, since the test was conducted at approximately 1211 feet bgs, and its effects may extend in different directions from the actual shot point. Microfracturing will be present around large, subsurface cavities and related rubble zones created either by explosions or mining. These microfractures, which may form in preferential directions, will have effects of essentially increasing the pore size, and consequently, if these pores are filled with air (i.e., there is no water saturation), then the resistivity will increase. Another possibility for the differences in resistivity between the two lines in the area northwest of the interpreted fault or fracture is the presence of a west-northwest-trending structure that separates relatively competent granite from granitic batholithic components or rhyolitic intrusive breccia. This structure might trend approximately parallel to the base of the hill northeast of the EM stations, and it could be an extension of a structure that formed the small canyon to the east in which the main access road is located. Additional lines of data will either prove or disprove these possibilities.

The shear zone that is thought to be located about 1500 feet east of the site and is interpreted as a barrier to flow may be indicated by slightly higher resistivities within the upper few hundred feet along the southeasternmost 500 to 750 feet of both lines and also by the absence of low resistivities (i.e., less than 300 ohm-meters and interpreted as water saturated) at a depth of about 1000 feet in that area. However, the possible shear zone does not appear to have similar significant resistivity contrasts, as seen in the interpreted fault or fracture to the northwest, particularly along line 1. Nevertheless, a possible interpreted shear zone may be present with an extrapolated surface location between stations 3 and 4 along line 1 and between stations 23 and 24 along line 2, which is again consistent with the approximate regional geologic strike of N25°E. This possible shear zone appears to have a steep dip along line 1, but it is hard to discern dip along line 2.

Figures 7 through 9 are selected horizontal depth slices, relative to the surface, at depths of 800, 1000, and 1200 feet. The depth slices show the much higher resistivity material northwest of the interpreted fault or fracture and the more modest resistivities southeast of the possible interpreted shear zone. The interpreted water-saturated, primarily granitic rocks are indicated between these two structures as lower resistivities, less that about 300 ohm-meters. At a depth slice of 800 feet, the interpreted northwest fault or fracture is located between stations 8 and 9 along line 1 and between stations 18 and 19 along line 2, which is a similar strike as that extrapolated on the surface but indicates a dip to the northwest, since the surface extrapolation of the structure is farther to the southeast (i.e., between stations 7 and 8 along line 1 and between stations 19 and 20 along line 2). The interpreted location of the northwest fault or fracture appears to vary in strike direction with depth, as seen on the slices at depths of 1000 and 1200 feet.
Figure 10 is a 1:24000-scale topographic map of the general area around Project Shoal with the EM station locations and extrapolated surface expression of the northwest fault or fracture and southeast shear zone highlighted. From this map an approximate regional geologic strike based on the higher topography, or outcrop, can be estimated as N25°E west of Gote Flat, but farther to the north, near the middle of Section 34, the geologic strike on the west side may become more northerly. It is more difficult to see on the topographic map the possible regional geologic strike on the east side of Gote Flat, but it appears somewhat similar to the west side for the area north of the EM stations, but perhaps more easterly for the area south of the EM stations. Field measurements of the outcrops would be necessary to actually confirm the strike directions.

Although it is difficult with only two lines of data to make any areal interpretations, variations of strike at depth of the interpreted northwest fault or fracture and also to a certain extent for the interpreted possible shear zone to the southeast may indicate that the assumed different directions of faulting, fracturing, or jointing may be present (i.e., two dominant structural trends that generally strike N50°W and N30°E). Also, differences in resistivity between the two lines in the area northwest of the interpreted fault or fracture could indicate the presence of a west-northwest-trending structure, perhaps separating relatively competent granite from granitic batholithic components or rhyolitic intrusive breccia that somewhat parallels the base of the hill northeast of the EM stations, and it is perhaps an extension of a structure that formed the small canyon to the east in which the main access road is located. Additionally, the interpreted location of the northwest fault or fracture is farther to the southeast than expected (it was originally thought to be northwest of Surface Ground Zero). Additional EM data covering a larger area would help resolve the complex nature of the subsurface structure.

**CONCLUSIONS AND RECOMMENDATIONS**

The objectives of the survey have been met by identifying the approximate depth and thickness of the water table, and locating faults and/or major fracture zones that may affect groundwater flow. The two lines of data acquired are insufficient at this point to ascribe a dip on the water table with much certainty, although there are differences in elevation of lower resistivity material between the two lines, which is interpreted as indicating the water table. If EM data are acquired regionally over the area, and similar differences in elevation of the interpreted water table are shown on numerous profiles, then an interpretation of water table dip or prevailing horizontal groundwater flow direction would be more certain. The locations for new monitoring wells cannot be determined until completion of the optional full survey.

A steeply dipping fault or fracture is interpreted along both lines towards the northwest with an extrapolated surface expression consistent with the approximate regional geologic strike of N25°E. This fault or fracture appears to increase in dip, to almost vertical, at depths greater than about 900 feet, and its presence is interpreted to be absent below a depth of about 2400 feet. Southeast from this fault or fracture are interpreted water-saturated rocks present at depths somewhat shallower that the reported 975 to 1090 feet. However, the definition of “water table” can be interpreted differently. For resistivity it is primarily where the pore spaces start to become filled with moisture, which may or may not be the same as actual water depth measurements. If EM data are acquired near a well that has been logged for water depth at about the same time as the geophysical survey, then a factor can be determined and applied between the physical and geophysical measurements for what is considered water table depth.
Northwest of the interpreted fault or fracture there are relatively large differences in the resistivity of the subsurface material along the two lines (1000 or 1500 along line 2 to greater than 2000 ohm-meters along line 1) particularly to about a 1000-foot depth. The two geophysical survey lines are only about 250 feet apart, and the relatively large differences in resistivities in this area could be attributable either to structure or to influences from the detonation. Microfracturing will be present around large, subsurface cavities and related rubble zones created by explosions or mining. These microfractures, which may form in preferential directions, will have the effect of essentially increasing the pore size, and if the pores are filled with air (i.e., there is no water saturation), the resistivity will be increased. Another possibility for the differences in resistivity between the two lines in the area northwest of the interpreted fault or fracture could be the presence of a west-northwest-trending structure, perhaps separating relatively competent granite from granitic batholithic components or rhyolitic intrusive breccia that somewhat parallels the base of the hill northeast of the EM stations and perhaps is an extension of a structure that formed the small canyon to the east in which the main access road is located. Additional lines of data will either prove or disprove these theories.

The shear zone that is thought to be located about 1500 feet east of the site and is interpreted as a barrier to groundwater flow is seen in the resistivity data although it does not appear to have resistivity contrasts as large as at the interpreted fault or fracture to the northwest. The approximate regional geologic strike of the interpreted shear zone is N25°E, which is similar to that seen along the interpreted structure to the northwest.

Although it is hard with only two lines of data to make any areal interpretations, inspection of the depth slices reveals variations of strike at depth of the interpreted northwest fault or fracture and also to a certain extent for the interpreted possible shear zone to the southeast which may indicate that assumed different directions of faulting, fracturing or jointing are present (i.e., two dominant structural trends that generally strike N50°W and N30°E). Also, differences in resistivity between the two lines in the area northwest of the interpreted fault or fracture could indicate the presence of a west-northwest trending structure perhaps related to the small canyon to the east in which the main access road is located. Additionally, the interpreted location of the northwest fault or fracture is further to the southeast than anticipated (it was originally thought to be perhaps northwest of Surface Ground Zero).

Additional data covering a larger area will help resolve the complex nature of the subsurface structure. Therefore, it is recommended that a larger area be surveyed with the CSAMT/MT technique. The survey area should extend both northeast and southwest from the original two lines, but it also should be extended farther to the southeast along the original two lines to see if higher resistivities, similar to those seen in the northwest, are present.

**LIMITATIONS OF INVESTIGATION**
This investigation was performed using the degree of care and skill ordinarily exercised under similar circumstances by an experienced and licensed geophysicist practicing in this or similar locations. No warranty, express or implied, is made as to the conclusions and professional advice included within this report.
The findings of this report are valid as of the date of the geophysical survey. However, changes in the conditions of a property can occur with the passage of time, whether they are due to natural processes or the work of people on this or adjacent properties. Accordingly, the findings of this report may be invalidated wholly or partially by changes outside of our control. Therefore, this report is subject to review and revision as changed conditions are identified.
Typical field setup of Geometrics StrataGem EH4 CSAMT/MT System

Figure 1
CSAMT/MT Survey
Raw Data Example

Figure 2
Figure 3
Project Shoal CSAMT/MT Survey
Resistivity Depth Sections
Lines 1 and 2

Figure 6

Note: Line 2 arbitrarily moved 3000 feet north to facilitate interpretation
Project Shoal CSAMT/MT Survey
Horizontal Depth Slices Relative to Surface

Depth = -800 feet

Figure 7
Hasbrouck Geophysics, Inc.
Project Shoal CSAMT/MT Survey
Horizontal Depth Slices Relative to Surface

Depth = -1200 feet

Figure 9

Hasbrouck Geophysics, Inc.
Appendix C

Hasbrouck Geophysics, Inc. EM Full Survey Report
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Project Shoal Area
CSAMT/MT Full Survey

for

S. M. Stoller Corporation
Grand Junction, Colorado

December 20, 2010
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>METHODOLOGY SUMMARY</td>
<td>1</td>
</tr>
<tr>
<td>DATA ACQUISITION AND PROCESSING</td>
<td>1</td>
</tr>
<tr>
<td>SUMMARY OF RESULTS</td>
<td>10</td>
</tr>
<tr>
<td>LIMITATIONS OF INVESTIGATION</td>
<td>12</td>
</tr>
<tr>
<td>APPENDIX A: DETAILED METHODOLOGY</td>
<td>16</td>
</tr>
</tbody>
</table>

## TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1: Water Level Depths, Elevations, and Screen Intervals</td>
<td>4</td>
</tr>
<tr>
<td>Table 2: Station Names and Numbers</td>
<td>14</td>
</tr>
</tbody>
</table>

## FIGURES

- Figure 1: Typical field setup of Geometrics *StrataGem EH4 MT* system
- Figure 2: CSAMT/MT raw data and quality control examples
- Figure 3: Station, well and NW to SE profile locations
- Figure 4: Station, well and SW to NE profile locations
- Figure 5: Station and well locations superimposed on topographic map
- Figure 6: Profile I resistivity elevation section
- Figure 7: Profile AQ resistivity elevation section
- Figure 8: Profile AL resistivity elevation section
- Figure 9: Profile AK resistivity elevation section
- Figure 10: 2D view of horizontal elevation slice at 4400 ft
- Figure 11: 2D view of horizontal elevation slice at 4500 ft
- Figure 12: 2D view of horizontal elevation slice at 4300 ft

## MOVIES ON CD

- Feasibility Data Movie – Horizontal Depth Slices (avi format)
- NW to SE profiles A to X 3D resistivity depth sections (avi and rm formats)
- NW to SE profiles A to X 3D resistivity elevation sections (avi and rm formats)
- SW to NE profiles AA to AW 3D resistivity depth sections (avi and rm formats)
- SW to NE profiles AA to AW 3D resistivity elevation sections (avi and rm formats)
- NW to SE and SW to NE profiles A to X and AA to AW, respectively, 3D resistivity elevation sections viewed from the SE (avi and rm formats)
- NW to SE and SW to NE profiles A to X and AA to AW, respectively, 3D resistivity elevation sections viewed from the SW (avi and rm formats)
- Horizontal depth slices from 0 to -3000 ft, relative to surface, at 50 ft intervals (avi and rm formats)
- Horizontal elevation slices from 5450 to 2200 ft at 50 ft intervals (avi and rm formats)
- Cut-away of elevation based rectangular resistivity cube viewed from the SE (avi and rm formats)
ADDITIONAL PLOTS ON CD
Feasibility Data Plots, Horizontal Depth Slices and Line Elevation Sections – 64 Plots
NW to SE profiles A to X 2D resistivity depth sections – 24 Plots (A through X)
NW to SE profiles A to X 2D resistivity elevation sections – 24 Plots (A through X)
SW to NE profiles AA to AW 2D resistivity depth sections – 23 Plots (AA through AW)
SW to NE profiles AA to AW 2D resistivity elevation sections – 23 Plots (AA through AW)
INTRODUCTION
This report presents the results of a controlled-source audio magnetotellurics/magnetotellurics (CSAMT/MT) geophysical survey conducted at the Shoal, Nevada, site. The objectives of the survey were to acquire data that will help identify areas of relatively high hydraulic conductivity, including faults and major fracture zones, identify the water table, evaluate the prevailing horizontal groundwater flow direction, and identify locations for new monitoring wells.

METHODOLOGY SUMMARY
The true resistivity of earth materials is dependent upon several factors, including composition, grain size, water content, and physical characteristics. The occurrence of groundwater greatly reduces the resistivity of all rocks and sedimentary materials; thus, it is a good target for electromagnetic (EM) geophysical methods that measure resistivity. CSAMT/MT is an EM geophysical method commonly used in the groundwater industry to determine the earth’s subsurface electrical resistivity distribution by measuring time-dependent variations of the earth’s natural electric (E) and magnetic (H) fields, as well as the electric and magnetic fields resulting from high-frequency induced waves. Figure 1 shows a graphical representation of the field setup of the CSAMT/MT instrumentation used in this project. In essence, electric dipoles and magnetometers are laid out in perpendicular directions (i.e., Ex, Ey, Hx and Hy), and both natural and transmitted frequencies are recorded from distant and nonpolarized sources (i.e., the measured EM fields will impinge upon the earth as uniform plane waves). If geoelectric strike (which may or may not be the same as geologic strike) is known, then measured resistivities with the E field oriented parallel to strike are referred to as transverse electric (TE) mode measurements, and resistivities with the E field oriented perpendicular to strike are referred to as transverse magnetic (TM) mode measurements.

CSAMT/MT field data consist of sounding curves that are logarithmic plots of apparent resistivity versus frequency. Apparent resistivities at high frequencies correspond to generally shallow investigation depths, and apparent resistivities at low frequencies correspond to investigations at greater depths. Apparent resistivities are bulk resistivities with contributions from different heterogeneous materials. Model transformations of the data calculated with forward and inverse computer software are good first-order approximations of the resistivity structure/layering beneath each station or sounding and are presented as cross sections of subsurface resistivity. These cross sections are used for the interpretation of geologic and hydrogeologic conditions. In general, CSAMT/MT data have shown a 10 to 15 % variation between the actual depths to the anomalies, as verified by test hole drilling, and the depth predicted by the models. A detailed description of the methodology is provided as Appendix A.

DATA ACQUISITION AND PROCESSING
Data were acquired for this project with a leased StrataGem EH4 CSAMT/MT system, manufactured by Geometrics Inc. of San Jose, California, operating at frequencies ranging from 10 Hz to 92 kHz. The system was calibrated at the factory and required no field calibration. With the StrataGem EH-4, time-series of the four components of data (Ex, Ey, Hx, and Hy) were recorded for three overlapping frequency bands: 10 to 1000 Hz, 500 to 3000 Hz, and 750 to 92,000 Hz. For each CSAMT/MT station, or sounding, the magnetic sensors and 50-meter-long electric dipoles were oriented with a compass and prism, or by other means, so that all components in each direction were parallel (i.e., Ex and Hx were parallel as were Ey and Hy). The Ey and Hy components were oriented S 25° W to N 25° E, which was closely parallel to assumed regional geologic and geoelectric strike.
The instrument gains were independently set before data collecting began at each station, and possible interference and other quality control procedures were assessed before data recording began. After the gains were adjusted, 10 runs of time series data were obtained in the lowest frequency band, and 15 runs were acquired in the middle and highest frequency bands. The lowest frequency band recorded only natural signals, the middle band encompassed both natural and transmitted signals, and the highest band recorded signals from 15 separate transmitted frequencies in addition to any natural signals present. The StrataGem EH-4 is a broadband instrument and will record signals with any frequencies within its operating range. The transmitter is used to augment the typically lower-amplitude signals in the middle and highest frequency bands. The data from each sounding were stored on the instrument’s hard drive and downloaded to a laptop PC at the end of each field day.

Figure 2 shows an example of raw quality control data acquired for this project. The lower right portion of each station presents a one-dimensional model, which is labeled as “true” resistivity. This model is generally only useful for simple, layered geologic environments and is only marginally applicable to this project area. The x-axis for each of the three plots within the upper right portion of each station is logarithmic frequency; the top plot is scalar resistivity ranging logarithmically from 1 to 5000 ohm-meters, the middle plot is scalar phase from 0º to 90º, and the bottom plot is scalar coherency from 0 to 1.0. On each plot, data from the x direction are shown as diamonds, and the y direction data are squares. Under ideal circumstances and in areas with no appreciable geologic structures, the x and y direction data should fall nearly on top of each other in the resistivity plot, have a phase close to 45º, and a coherency around 1.0.

A total of 312 separate CSAMT/MT stations, on a nominal grid of 250 ft, were acquired as shown in Figures 3 and 4. Figure 5 shows all the stations superimposed on a topographic map. Table 2, located at the end of the report, indicates the relationship between station names and numbers. The station numbers shown in Table 2 are used in all of the figures, movies, and plots in this report. Because an initial survey consisting of 25 soundings was conducted near the middle of the grid, most of those soundings were not repeated. However, for quality control, two stations were essentially repeated (stations 243 and 244 from the full survey are close to stations 1016 and 1017 from the initial survey) with examples shown in Figure 2. Generally, resistivity values above about 70,000 Hz, between about 1000 to 3000 Hz, and below approximately 30 Hz (typical noisy high frequency and low natural signal amplitude frequencies) are often edited out, as are a few other selected frequencies where either the phase or coherency of the data is not considered acceptable. Stations 244 and 1016 are within about 80 ft of each other, and there is reasonable agreement between the two data sets. Variations between data sets that are close to each other are expected, to some degree, because of the nature of CSAMT/MT data.

The sources of natural MT variations are ionospheric and magnetospheric currents arising from the interaction of solar and near-earth plasma with the constant geomagnetic field. These variations are from pulsations, polar substorms, solar daily variations, worldwide magnetospheric storms and atmospheric disturbances. Pulsations are presumably a resonant phenomenon arising from the injection of solar plasma into the earth’s magnetosphere, while polar substorms are associated with an increase in the pressure of solar wind and injection of plasma into the auroral ionosphere. Solar daily variations are generated by the rotation of the earth in the magnetic field of ionospheric current vortices (related to the dynamo effect or the flow of ionospheric gases in a constant geomagnetic field) and worldwide magnetospheric
storms that occur after solar flares. Atmospheric disturbances are caused by worldwide thunderstorm discharges and propagate within the earth-ionosphere waveguide. The intensity of these MT variations depends upon solar and thunderstorm activity, time of the year and day, geoelectric structure of the survey area, and geomagnetic latitude. For variations of cosmic origin, the maximum intensity occurs in the years of enhanced solar activity. Variational intensity is stronger during the summer than during the winter. Because of all these variables, data from nearby quality control stations will not be exact but will be similar, as Figure 2 shows.

Over a two-dimensional earth, the TE and TM modes give different apparent resistivity values and are sensitive to different aspects of the subsurface structure. The TE mode is most sensitive to conductors, whereas the TM mode is most sensitive to resistors and shallow structure. The TE mode is purely inductive, while the TM mode additionally has a galvanic component inherent in its response. This makes the TM mode higher resolution with respect to defining lateral contacts. When searching for vertical conductors the TM mode is only weakly excited, while the TE mode can show a very strong response with large spatial extent. Therefore, the interpretation weight of each mode depends on the orientation (vertical, horizontal), the nature of the target (resistive, conductive), and the quality of the data. Because conductive targets (although with perhaps both vertical and horizontal structure) are the primary targets for this project, the data have been processed and interpreted in the scalar TE mode.

Overall, the CSAMT/MT data were considered good to very good quality with low natural signal amplitudes adversely affecting some of the low and middle frequency band data. The data shown in Figure 2 are considered to be in the “good” category. Because of the low natural signal amplitudes, it was necessary to process the data in the scalar mode. CSAMT/MT data from each station are initially inspected and edited when appropriate. Editing of the data is somewhat subjective but is based upon experience, juxtaposition of \( x \) and \( y \) direction resistivity data, phase differences from the optimum value of 45°, and coherency. Two-dimensional depth sections are then modeled along profiles. These models are constructed through use of Geometrics’ ElectroMagnetic Array Profile (EMAP) transform software that calculates the Bostick transform\(^1\) resistivities from the CSAMT/MT data. Each depth section consists of logarithmic resistivity versus depth of the Bostick inversion of each CSAMT/MT sounding along a relatively straight line. Subsequently, values for each sounding are converted into a format compatible with the Tecplot Focus 2010 (Release 1, Build 12.2.0.9077) computer program and presented as two- and three-dimensional cross-sections in depth or elevation format. Additionally, all data are interpolated into a rectangular cube and constant, horizontal depth and elevation slices are shown at intervals of 50 ft from the surface to a depth of 3000 ft. In general, CSAMT/MT data have shown a 10 to 15 % variation (based on field experience) between the actual depths to anomalies, as verified by test hole drilling, and the depths predicted by the models.

**BACKGROUND**

As described in Stoller’s Request for Proposal, the Shoal site area is in the northern portion of the Sand Springs Range in west-central Nevada’s Churchill County. Specifically, Project Shoal is in Gote Flat within an area that is part of the Cretaceous-age Sand Springs batholith, which is composed of granite and granodiorite, aplite and pegmatite dikes, andesite dikes, rhyolite dikes, and other igneous rock types.

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and rhyolitic intrusive breccia. Internal deformation of the Sand Springs batholith is mostly by high-angle normal faults that strike northeast and northwest, joints that parallel the northwest-trending faults, and fracture cleavages that generally parallel the northeast-trending faults. The faults, joints, and fractures are distributed between two dominant structural trends that generally strike about N 50° W and N 30° E and are vertical to steeply dipping.

During a field survey of the dikes, Stoller personnel noted that granite, granodiorite, and large numbers of more erosion-resistant pegmatite dike swarms compose the hills to the south, southwest, west, and northwest of Gote Flat, while the higher hills to the north and east are underlain by fewer but larger and erosion-resistant andesite and rhyolite dikes. The pegmatite dikes are generally 3 to 4 ft wide and in places up to 6 ft wide, hundreds of ft long, and are often surrounded by subsidiary en echelon dikes usually less than 12 inches wide. To the north a few andesite dikes are thought to be hundreds or even thousands of feet long and range from 5 to 20 ft in width. Rhyolite dikes to the east and north are the largest within the project area and reach widths of up to 25 ft. All the dikes are considered to be more transmissive than the granite or granodiorite because they contain more fractures per unit volume than the intrusives. The dikes all strike between N 75° W to N 50° W and are fractured in ways that are postulated to promote preferential west-northwest to east-southeast-oriented groundwater flow.

Measured water levels beneath the site range from approximately 970 to 1370 feet (ft) below ground surface (bgs), or about 3880 to 4285 ft above mean sea level (amsl), as shown in Table 1. The groundwater is thought to move primarily through fractures within the batholith; recharge occurs by infiltration of precipitation on the mountain range and regional discharge into the adjacent valleys. As inferred by Desert Research Institute (DRI), a possible groundwater divide may be present along the upland area of the range west of the site separating flow to the east and west. A shear zone, thought to be located about 1500 ft east of ground zero, has been interpreted by DRI as a barrier to flow due to disparate groundwater head levels in wells separated by the shear zone.

### Table 1: Water Level Depths, Elevations, and Screened Intervals

<table>
<thead>
<tr>
<th>Well</th>
<th>Water Depth (ft bgs)</th>
<th>Water Elevation (ft amsl)</th>
<th>Top of Screen Elevation (ft amsl)</th>
<th>Bottom of Screen Elevation (ft amsl)</th>
<th>Screen Length (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV-1</td>
<td>992.51</td>
<td>4265.03</td>
<td>3,684.81</td>
<td>3,531.00</td>
<td>153.81</td>
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<td>1001.90</td>
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<td>3,275.98</td>
<td>170.77</td>
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<td>MV-3</td>
<td>975.68</td>
<td>4285.82</td>
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<td>3,626.75</td>
<td>171.16</td>
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<td>HC-1</td>
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<td>4,236.01</td>
<td>3,997.12</td>
<td>238.89</td>
</tr>
<tr>
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<tr>
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<td>4,247.90</td>
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<td>HC-5</td>
<td>1368.32</td>
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<tr>
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<td>3,919.30</td>
<td>3,762.30</td>
<td>157.00</td>
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</table>

**RESULTS**

EM data are initially modeled along northwest to southeast profiles, as shown in Figure 3, and those results are then transferred onto southwest to northeast profiles as shown in Figure 4. All
of these data have been transmitted to Stoller for independent presentations and analyses. Depth
and elevation sections for each of the 24 northwest to southeast profiles (A to X) and for each of
the 23 southwest to northeast profiles (AA to AW) are included on the compact disk (CD) that
accompanies this report, and some of the plots are included within the body of the report. For
interpretation purposes, several movies have been made of the data (with and without contoured
water levels from the wells), including resistivity depth and elevation sections of all the profiles,
horizontal depth and elevation slices from the surface to 3000 feet depth, and cutaways of a
rectangular cube generated from the resistivity data. The color scale used for all of the resistivity
plots (blue for low resistivity and red for high resistivity) is reversed from the standard
geophysical convention but is as requested by Stoller.

Resistivities to a depth of 3000 ft within the survey area range from less than 100 to greater than
2000 ohm-meters, although for interpretation purposes the resistivity range is limited on the plots
from 200 to 1000 ohm-meters. Assignment of resistivity value ranges to geology is somewhat
subjective, and far from absolute, because the true resistivity of earth materials is dependent
upon several factors, including composition, grain size, water content, and physical
characteristics. The resistivity-geology assignment is slightly different in this full survey report
from those used during the initial feasibility test because a larger and more representative area
was covered by the full survey.

Resistivity values less than about 250 to 300 ohm-meters are seen along many of the profiles at
depths near the measured water level depths observed in site monitoring wells. These relatively
lower resistivity values also extend several hundred feet upward toward the surface from
observed water levels in the wells. Water level elevations in wells are a function of the elevation
of the screened interval and the pressure at that depth (hydraulic head). Water levels from wells
screened at and possibly even a few hundred feet below the water table should be fairly
representative of the water table depth and can be used with the geophysical data to interpret a
“geophysical water table” for the site. Except for wells HC-5 and HC-8, wells at the site are
screened at or within a few hundred feet below the water table; wells HC-5 and HC-8 are both
screened more than 1000 ft below the water table (Figure 6). The screen zone in HC-5 is below
the bottom of the figure. The observed water levels in these two wells are more likely to be
affected by vertical hydraulic gradients and/or structures that separate their screen zones from
water table depths at the same location. Consequently, measured water levels in these wells may
not directly correlate to water levels interpreted from resistivities at these well locations.
Nevertheless, resistivities less than about 250 to 300 ohm-meters (shown as blue to dark-green
colors on the figures, other plots, and movies) at depths greater than a few hundred feet are
interpreted as indicating groundwater saturation or moisture. Pyrite has been reported at different
depths in some of the older wells and could lower resistivities if the occurrences are relatively
thick (i.e., massive). If the pyrite occurrences are thin, they may show more induced polarization
rather than EM effects.

Along portions of the profiles, resistivity values generally less than 200 ohm-meters are present
in the first 100 ft or so and would usually be interpreted as soils with some clay constituents or
moisture content. However, in this area these low resistivities near surface zones are interpreted
as erosional remnants of dikes (possible mafic pegmatite and andesite) combined perhaps with
silts. Given the general geology of the survey area, it is unlikely that much, if any, clay is
present, although it takes only a small amount to substantially lower resistivities. Near-surface
areas with higher resistivities are probably composed more of grus (angular, coarse-grained fragments from the decomposition of granite).

The higher hills to the north and east are thought to be underlain by large, erosion-resistant andesite and rhyolite dikes, but stations near them have anomalously low resistivities that are unusual for felsic, rhyolitic rocks but could be related to andesite, which is an intermediate type rock between basalt and dacite. Basalts often erode to clays with consequent low resistivities, but it is considered odd for erosion-resistant andesite to have such low resistivities. The presence of large dikes could induce a considerable amount of fractures within the host rocks. These induced fractures may allow for increased infiltration resulting in higher moisture content and thus lower resistivities. Infiltration in the area may be rather high, because groundwater levels appear to be rising about 2 ft per year.

Resistivities from about 300 to 400 ohm-meters are interpreted as indicating partial water saturation of the rocks or a lesser degree of saturation because of a decreased presence of faulting and/or fracturing. Consequently, colors shown on the figures and other plots or movies that range from dark to light green are interpreted as indicating groundwater saturation or moisture but to a smaller degree than the blue to dark-green colors corresponding to resistivities less than about 250 to 300 ohm-meters. Resistivities from about 400 to above 1000 ohm-meters are interpreted as variably weathered to competent granitic batholithic components, or perhaps rhyolitic intrusive breccia, with the lower values representing either more weathering or the rhyolite breccia. The pegmatite dikes, although generally small in width, also have relatively high resistivities and have some influence on bulk resistivity values if the dikes are sufficient in number in an area. Anomalously high resistivities well above 1000 ohm-meters are present at and surrounding surface ground zero and are interpreted as effects of the detonation.

All the depth and elevation resistivity sections in this report have been constructed from raw data that are interpolated, using a kriging function, onto a rectangle that encompasses the data (i.e., the raw data are entered into the Tecplot Focus 2010 program, a rectangle is constructed that covers all the data, and then the raw data are interpolated using a kriging function onto the rectangle). The rectangle of the depth sections is suitable for presentation purposes, but the elevation sections contain interpolated data beyond the surface (i.e., data are interpolated to the edges of the rectangle, which goes above the surface of the earth), and thus those values must be blanked for presentation purposes. The resistivity value of 50,000 ohm-meters shown in the contour legend of the elevation sections is not real and is used to blank above the surface. With most software programs, unreal values used to blank plots can be overridden with a white box, which makes those values invisible, but this is not currently possible with the Tecplot Focus 2010 program. The elevation section movies are labeled as “Work Copy” because a solution to blank the portions of the rectangles above the ground surface has not been found. Similarly, horizontal slice movies in a non-2D format are also labeled “Work Copy” because values are included beyond the station limits and are not blanked. Stoller personnel have proposed a solution to this problem, but the proposed solution was not applied to the plots in this report.

Figure 6 shows the elevation section of the resistivity values along the northwest to southeast-oriented profile I, and a depth section of the same profile is included on the CD (note that there is little difference between the two sections). As described above, the first few hundred feet along portions of the profile have low resistivity values—generally less than 200 ohm-meters—that are interpreted as erosional remnants of dikes combined perhaps with silts, and near-surface areas
with higher resistivities are probably composed more of grus. Beneath the near-surface layer, resistivities are remarkably different on the northwest and southeast ends of profile I. From its northwestern beginning, the first 700 or 800 ft of the profile at elevations from approximately 4900 to 4400 ft (about 500 to 1000 ft depth) has resistivities above about 500 ohm-meters, which is interpreted as more competent granitic batholith components with possible influences from pegmatite dikes. Toward the southeast end of profile I, the anomalously lower resistivities near the northeastern higher hills are present in the resistivity section. This portion of the profile from about station 331 to the southeast end could be a southwest extension of the material that composes the hill to the northeast or possibly related to dike-induced fractures within the host rock. These induced fractures may allow for increased infiltration, resulting in higher moisture content and, thus, lower resistivities.

Resistivities less than about 250 to 300 ohm-meters are seen at depths approximately correlating with measured water levels for wells HC-2, HC-4 and HC-7 along profile I. These lower resistivity values, which are interpreted as indicating groundwater saturation or moisture, extend a few hundred feet or so toward the surface from the water levels measured in the wells. The lower values could be the result of some capillary action, although such action is generally unlikely in fractured granite formations; more likely they are caused by increased moisture associated with infiltration and preferential flow along fractures. As described above, groundwater will lower the resistivity of subsurface material, but even small amounts of moisture in the pores will also have a decreasing effect on the resistivity values, even though such moisture is not able to be measured as a water level. The presence of groundwater, possible moisture from infiltration and preferential flow along fractures above the groundwater, the 10 to 15 % variation of EM modeling, and water levels from deeper screened intervals that may or may not correlate with levels from wells screened higher in the section are factors that together preclude complete agreement between water level measurements and groundwater presence interpreted from the resistivity data. For purposes of identifying the presence of groundwater and prevailing groundwater flow direction, resistivity values less than about 250 to 300 ohm-meters (shown as blue to dark-green colors on the figures, other plots, and movies) and extending from measured water levels upward a few hundred feet, such as those seen in Figure 6, are used. Resistivities from about 300 to 400 ohm-meters (ranging from dark to light-green colors) are also used as an indication of partial water saturation, primarily beneath the lower resistivities. Along profile I there appears to be a slight dip to the northwest (from at least the southeastern end of the profile to about station 341 or 342) on the interpreted groundwater levels from the resistivity data. From just northwest of well HC-2 to about stations 341 or 342, the dip is to the southeast.

The procedure outlined above produces poor agreement along profile I in Figure 6 between measured water levels and groundwater presence interpreted from the resistivity data for wells HC-5 and HC-8. However, as seen in the movies and Figure 7, which is the elevation section along profile AQ, although the agreement is still relatively poor, there appears to be a structure to the southwest of well HC-8 that is manifested as an area with much lower interpreted groundwater levels (i.e., lower resistivities at a greater depth). Why this anomalous area does not extend farther to the northeast and remain evident in the resistivity data at well HC-8 is unknown. As indicated in Table 1, wells HC-5 and HC-8 are screened at intervals much deeper than other wells within the area, and the water level data from these wells are representative of these deeper intervals. As previously noted, the observed water level for a screened interval is a function of both the elevation at the screened interval and the pressure at that depth. Therefore,
water levels from deeper screened intervals may or may not correlate with water levels from wells screened higher in the section, and consequently, there may be differences between the measured water levels and the levels interpreted from the resistivity data. From the northeast end of profile AQ to about its middle, which is near the lowest surface elevations, the apparent dip of the water table is slightly to the southwest, as interpreted from the resistivity data.

Profile AL (Figure 8) passes near wells HC-4 and MV-3 and is also about 190 ft southeast of surface ground zero. Measured water levels in the two wells correlate with the lower resistivity values seen at those depths. A slight dip to the southwest on the interpreted groundwater levels is evident from near the northeastern end of the profile toward lower surface elevations some 1500 ft from that end. Beyond that point the groundwater levels interpreted from the resistivity data appear relatively flat. Similar to profile AQ, the interpreted groundwater level depth increases significantly near the southwestern end of the line. Near the northeastern end of profile AL, there is a large decrease in resistivity values, and these lower resistivities also extend to a depth of at least 3000 ft. This end of profile AL is just beyond a small ridge and almost into another valley, and although it is unlikely that these lower resistivity values at depth are caused by groundwater itself, they could be the result of slightly increased moisture content perhaps related to structure.

The elevation of the detonation is taken as 3953 ft amsl (1212 ft bgs), and the effects of it are significantly present along profile AK, as seen in Figure 9. Resistivities at the detonation elevation and above it are much higher than seen anywhere else in the project area and appear to disrupt the somewhat continuous groundwater near the detonation. Re-entry drilling at surface ground zero indicates that a rubble chimney extends approximately 356 ft above the detonation point, which may account for a portion of the resistivity differences above and beyond the detonation location. Additionally, microfracturing, due in part to tension release, will be present around large, subsurface cavities and related rubble zones created either by explosions or mining. These microfractures, which may form in preferential directions such as zones of weakness created by the presence of dikes, will have the effect of essentially increasing the pore size, and consequently, if these pores are filled with air (i.e., there is no water saturation or moisture), the resistivity will increase.

Figures 6 through 9 are used as interpretation guides, because they are near wells with water levels, and if an elevation of 4400 ft is considered as representative of the middle of interpreted groundwater or moisture levels with resistivity values less than about 250 to 300 ohm-meters, then as seen in Figure 10 there is a rather large area with groundwater saturation or moisture is indicated (see Figure 10). A definite northwest to southeast trend is evident, which Stoller personnel have hypothesized to be a preferential groundwater flow orientation related to the strike of dikes that are more transmissive than the granite or granodiorite because they contain more fractures per unit volume than the intrusives. On the northwestern side of the survey area, higher resistivities are predominant, except around profile G (and extending from about profile F to H) and at profile P. There, resistivities less than about 250 to 300 ohm-meters are present and are interpreted as indicating groundwater saturation or moisture. Resistivities from about 300 to 400 ohm-meters, which are interpreted as an indication of partial water saturation, are also present at the northwestern ends of profiles J, K, S and W.

The northwestern end of profile G is near a large drainage, as seen on Figure 5, and profile P at its northwestern end is on a small ridge just up from another large drainage. These two drainages
appear to be the largest on the northwestern side of the survey area and may have some structural influence on groundwater presence and/or flow. If it is assumed that groundwater may follow the possible structures that have, in part, caused these large drainages, then wells on the extreme eastern edge of Salt Wells Basin near the mouths of these drainages might be used to detect potential contaminant transport from the detonation zone. However, as seen along profile I (Figure 6), the other elevation sections on the CD, and in the movies, there appears to be little or no dip in the groundwater or moisture level interpreted from the resistivity data near the northwestern side of the survey area. If this absence of dip continues to the northwest, then mobile contaminants such as tritium from the detonation may not travel toward Salt Wells Basin.

Wells H-2 and H-3 are within the Salt Wells Basin and are approximately 3.5 and 2.1 miles, respectively, northwest of surface ground zero of the Shoal test. Water level elevations in both wells are about 3907 ft amsl, indicating a flat water table in that portion of the basin, although screen lengths are significantly different in the two wells, which could have an effect on measured water levels. The eastern edge of the Salt Wells Basin can reasonably be taken as being at an elevation of about 4700 ft amsl, and wells H-2 and H-3 are approximately 2.6 and 1.2 miles, respectively, northwest of the edge. The geophysically interpreted representative groundwater or moisture elevation of 4400 ft within the Shoal site survey area, as explained above, is some 500 ft higher than measured groundwater levels in the Salt Wells Basin to the west. This is likely the result of increased recharge on the Sand Springs Range relative to the adjacent basins and to water level differences across faults that separate the mountain range from the Salt Wells Basin.

From the northeastern ends of profiles AQ, AL, and AK (Figures 7 through 9), there appears to be slight southwestern dips on the groundwater levels interpreted from the resistivity data to about the middle of the survey area, after which an area with lower resistivities to a significantly greater depth is evident. This zone of deeper, low resistivity material is generally in the range of 300 to 400 ohm-meters and is interpreted as an indication of possible partial water saturation. As seen on Figure 10, this lower resistivity, deeper zone is essentially bounded by profiles F or G to the northeast, AI to the northwest, and the survey extent to the southeast. Within this anomalous area, interpreted elevations of partial water saturation extend to approximately 3400 ft amsl, and no dikes are mapped in this area. It is likely that this anomalous zone has a slightly different geology and a greater porosity than other areas. As interpreted from resistivity data, groundwater levels appear to dip slightly to the southwest from the northeast end of profile AQ to about its middle, which is near the lowest surface elevations. Wells HC-5 and HC-8, which have much lower measured water levels than the other wells (other than well HC-3), are near the interpreted boundary of this anomalous area, and their lower water levels may be related to the possible structure. However, as noted, wells HC-5 and HC-8 are screened at much greater depths than other wells within the area, and their water levels may or may not correlate with levels from wells screened higher in the section.

Figure 11 is a 2D view at an elevation of 4500 ft, which is 100 ft higher but similar in appearance to the view shown in Figure 10. Northwest to southeast-trending interpreted groundwater or moisture levels are again apparent; the anomaly at the northwestern end of profile G is still evident, and the anomaly at the northwestern end of profile P is less predominant. Well HC-3, which is just east of the southeastern end of profile L, has a measured water level of 3921 ft, but as seen in both Figures 10 and 11, very low resistivities are present at elevations of 4400 and 4500 ft. While increased moisture associated with infiltration and
preferential flow along fractures could account for interpreted groundwater or moisture levels that are a few hundred feet above the measured levels, levels of 500 to 600 ft higher in elevation would require a significant increase in the abundance of fractures, possibly associated with more dikes and increased faulting, or a change in lithology. Dikes within the project area are considered to be more transmissive than the host rocks because they contain more fractures per unit volume than the intrusives, and en echelon rhyolite dikes to the east and north are the largest within the project area. These large, en echelon rhyolite dikes are only mapped in the eastern and northern portions of the survey area; they are thousands of feet long and densely fractured, and they could account for increased infiltration at much shallower depths than in other areas. This interpretation is a possible explanation for the lower resistivities at shallower depths and the disparity between interpreted and measured water levels in well HC-3.

Figure 12, which is a 2D view at 4300 ft elevation, continues to indicate predominant northwest to southeast-trending interpreted groundwater or moisture levels. The significantly higher resistivities seen around and beyond surface ground zero at this elevation, and many others as seen on the plots on the CD and in the movies, appears to influence the presence of interpreted groundwater or moisture. For example, if no detonation had taken place, it is possible that the lower resistivities interpreted as indications of groundwater or moisture levels that extend northwest along profile M beyond surface ground zero would also extend farther northwest along profiles J through L. A small, possible groundwater divide is apparent along profile AR that appears to inhibit continuous interpreted groundwater or moisture levels from the northwest and could be related to a shear zone. However, this possible shear zone is much smaller and farther to the east than hypothesized by DRI. Substantial evidence of a large shear zone that might inhibit groundwater flow to the southeast is not readily apparent within the resistivity data, as can be seen in Figures 6, 10, 11, and 12 and in the movies.2

SUMMARY OF RESULTS

The objectives of the survey have been met by identifying the approximate depth of the water table, evaluating the groundwater flow direction, and locating faults and/or major fracture zones that may affect groundwater flow. Recent geological surveys in the project area have led to the hypothesis of a preferential west-northwest to east-southeast-oriented groundwater flow related to the strike of dikes that are considered to be more transmissive than the host granite or granodiorite because they contain more fractures per unit volume than the intrusives. A definite northwest to southeast trend is evident within the resistivity data at depths associated with water saturation or moisture content.

On the basis of modeled resistivity data from profiles that are near wells with measured water levels, an elevation of 4400 ft was chosen to be representative of the middle of interpreted groundwater or moisture levels. Lower resistivity values extend a few hundred feet toward the surface from the water levels measured in the wells and could be the result of capillary action, although such action is generally unlikely in fractured granite formations. The lower values are more likely caused by increased moisture associated with infiltration and preferential flow along fractures. Groundwater lowers the resistivity of subsurface material, but even small amounts of moisture in the pores also have a decreasing effect on resistivity values, even though such moisture is not able to be measured as a water level.

2 The movies provide the most information if they are played in raster mode using a program such as Framer, which enables viewing of a sequential display of individual elevations.
The measured water levels from the site monitoring wells are representative of a well’s screened interval and in some cases that interval is several hundred feet below the reported water level. The observed water level (hydraulic head) for a screened interval is a function of both the elevation at the screened interval and the pressure at that depth. Thus, wells located near each other but screened at different depths may display different water level elevations. Taking into account the presence of groundwater, possible moisture from infiltration along preferential fractures above the groundwater, the 10% to 15% accuracy of EM modeling, and water levels from deeper screened intervals that may or may not correlate with levels from wells screened higher in the section, there will not be absolute agreement between water level measurements and interpreted groundwater occurrences from the resistivity data.

Assignment of resistivity value ranges to geology is somewhat subjective and far from absolute, because the true resistivity of earth materials is dependent upon several factors, including composition, grain size, water content and physical characteristics. For interpretation purposes, resistivities less than about 250 to 300 ohm-meters (shown as blue to dark-green colors on the figures, other plots, and movies) at depths greater than a few hundred feet are interpreted as indicating groundwater saturation or moisture, and resistivities from about 300 to 400 ohm-meters (ranging from dark to light-green colors) are used as an indication of partial water saturation, primarily beneath the lower resistivities. Consequently, colors shown on the figures and other plots or movies that range from blue to light green are interpreted as indicating groundwater saturation or moisture to varying degrees.

Higher resistivities are predominant on the northwestern side of the survey area, except around profiles G and P where resistivities less than about 250 to 300 ohm-meters are present and are interpreted as indicating groundwater saturation or moisture. The northwestern ends of these profiles are near large drainages that may have some structural influence on groundwater presence and/or flow. If it is assumed that groundwater may follow the possible structures that have, in part, caused these large drainages, then wells on the extreme eastern edge of Salt Wells Basin to the west near the mouths of these drainages might be able to detect potential contaminant transport from the detonation zone. However, as seen along many of the northwest to southeast-oriented profiles, there appears to be little or no dip in the groundwater or moisture levels interpreted from the resistivity data near the northwestern side of the survey area. If this absence of dip continues to the northwest, then mobile contaminants such as tritium from the Shoal site may not travel toward Salt Wells Basin.

From the northeastern ends of the southwest to northeast-oriented profiles there appears to be slight southwestern dips in the groundwater levels interpreted from the resistivity data to about the middle of the survey area, after which an area with lower resistivites to a significantly greater depth is evident. Within this anomalous area in the southeast portion of the survey area, interpreted partial water saturation levels extend down to approximately 3400 ft elevation, and no dikes are mapped. It is likely that, at depth, the geology is slightly different in this anomalous zone compared to other areas (maybe rhyolitic intrusive breccia instead of granite or granodiorite?) with perhaps increased porosity. Wells HC-5 and HC-8, that have much lower measured water levels than the other wells (other than well HC-3), are near the interpreted boundary of this anomalous area and their lower water levels may be related to the possible structure. However, wells HC-5 and HC-8 are screened at levels much deeper than other wells.
within the area, and their water levels may or may not correlate with levels from wells screened higher in the section.

Well HC-3 which is just east of the southeastern end of profile L has a measured water level of 3921 ft, but very low resistivities are present at elevations of 4400 and 4500 ft in the geophysical data. While increased moisture associated with infiltration and preferential flow along fractures could possibly account for geophysically interpreted groundwater or moisture levels that are a few hundred feet above the measured levels, for levels some 500 to 600 ft higher in elevation there needs to be, as related to other portions of the survey area, a significant increase in fractures associated with dikes or a change in geology. Dikes within the project area are considered to be more transmissive than the host rocks because they contain more fractures per unit volume than the intrusives and en echelon rhyolite dikes to the east and north are the largest within the project area. These large, en echelon rhyolite dikes are only mapped in the eastern and northern portions of the survey area, are thousands of feet long, are densely fractured and could account for increased infiltration at much higher elevations, or shallower depths, than in other areas thus offering a possible explanation for the shallower lower resistivities as related to measured water levels in well HC-3.

A small, possible groundwater divide is apparent along profile AR that appears to inhibit continuous interpreted groundwater or moisture levels from the northwest and could be related to a shear zone. However, this possible shear zone is much smaller and further to the east than hypothesized by DRI. Substantial evidence of a large shear zone that might inhibit groundwater flow to the southeast is not readily apparent within the resistivity data.

The subsurface effects of the detonation are significantly present within the EM data. Resistivities at the detonation elevation and above it are much higher than seen anywhere else in the project area and appear to disrupt the nature of somewhat continuous groundwater in the vicinity of the detonation. For example, if no detonation had taken place then it is possible that the lower resistivities interpreted as indications of groundwater or moisture levels that extend northwest along profile M beyond SGZ would also extend further northwest along profiles J through L. Micro-fracturing, due in part to tension releases, will be present around large, subsurface cavities and related rubble zones created either by explosions or mining. These micro-fractures, which may form in preferential directions, such as zones of weakness created by the presence of dikes, will have effects of essentially increasing the pore size and consequently if these pores are filled with air (i.e., there is no water saturation or moisture) then the resistivity will be increased.

**LIMITATIONS OF INVESTIGATION**

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

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

The true resistivity of earth materials is dependent upon several factors, including composition, grain size, water content, and physical characteristics. In general, fine-grained materials such as clays and silts have lower resistivities than coarse-grained materials such as sands and gravels. Unweathered and unfractured hard rocks such as sedimentary rocks (e.g., sandstone, chert), volcanic rocks, plutonic rocks, and some metamorphic rocks generally have high resistivities. The presence of fracturing and weathering lowers the resistivity of these rocks. Additionally, the occurrence of groundwater will greatly reduce the resistivity of all rocks and sedimentary materials (through electrolytic conduction). Because of this effect, groundwater is a good target for electromagnetic (EM) geophysical methods that measure resistivity. Clay is also very conductive (low resistivity) as a result of surface-conduction processes, and geological formations with significant amounts of clay in the matrix will generally have limited groundwater production. If appreciable amounts of clay occur in fractures and faults, low-resistivity anomalies that resemble the presence of water may be identified. However, if fractures and faults transmit water at high yields, it is unlikely that clay will form.

CSAMT/MT is an EM geophysical method commonly used in the groundwater industry. It determines the earth’s subsurface electrical resistivity distribution by measuring time-dependent variations of the earth’s natural electric (E) and magnetic (H) fields, as well as the electric and magnetic fields resulting from high-frequency induced waves. The CSAMT/MT method is designed to investigate from depths of approximately 50 to 2500 ft or greater, depending upon resistivities and EM noise. In areas with generally lower subsurface resistivities, the maximum investigation depth will be shallower than 2500 ft. The method is often used to find structures and subsurface materials that are good producers of groundwater or to site high-yield production wells.

Figure 1 shows a graphical representation of the field setup of the CSAMT/MT instrumentation used in this project. In essence, electric dipoles and magnetometers are laid out in perpendicular directions (i.e., Ex, Ey, Hx and Hy), and both natural and transmitted frequencies are recorded from distant and nonpolarized sources (i.e., the measured EM fields will impinge upon the earth as uniform plane waves). EM waves from sources that are too close will have spherical wave fronts that will not be uniform within a survey area, and waves polarized in one direction will limit the type of measurements that can be made and will possibly introduce noise. Distance for EM waves is conveniently specified in terms of wavelength. Where EM waves penetrate conductors, one radian is used as the standard distance and is termed skin depth (also defined as the depth at which the amplitude of a plane wave has been attenuated to 1/e, or 37%). Since wavelength \( \lambda = 2\pi/k \) (where \( k = \text{wave number} \)), then one skin depth \( \delta = 1/k \). Since \( k = [\omega\mu_0\sigma/2]^{1/2} \), where \( \omega = \text{angular frequency} \), \( \mu_0 = \text{permeability of free space} \), and \( \sigma = \text{conductivity} \), then \( \delta = [2/\omega\mu_0\sigma]^{1/2} = [1/4\pi^2 10^{-7}]^{1/2}[\rho/f]^{1/2} \approx 503[\rho/f]^{1/2} \) in meters, where \( \rho = \text{apparent (measured) resistivity in ohm-meters and} \ f = \text{signal frequency in Hz.} \) From both experimental results and numerical simulations, at distances greater than three skin depths, the uniform and plane portion of EM waves are dominant, and at six to seven skin depths, the EM waves are completely uniform and plane relative to the precision to which they can be measured. Natural sources will be far removed (greater than seven skin depths) and therefore will be uniform and plane. However, when sources are measured from artificial transmitters, the distance between the transmitter and receiver must be at least three skin depths for EM waves to be uniform and plane.
CSAMT/MT measurements may be made in either the tensor or scalar mode. Tensor measurements use all four components (paired as Ex/Hy and Ey/Hx) and are best used in areas where the structure is very complex, when soundings are far apart relative to the size of geologic features under investigation, or where regional anisotropy is strong. Scalar measurements use only one component pair (i.e., Ex/Hy or Ey/Hx) and are generally adequate in one-dimensional (1D) layered environments or more complex areas if measurements are dense. If geoelectric strike (which may or may not be the same as geologic strike) is known, then measured resistivities with the E field oriented parallel to strike are referred to as transverse electric (TE) mode measurements, and resistivities with the E field oriented perpendicular to strike are referred to as transverse magnetic (TM) mode measurements. Ideally, tensor measurements are preferred in most areas, especially if the direction of strike is unknown or difficult to determine; however, the presence of polarized noise or low signal amplitude often dictates the use of scalar measurements.

CSAMT/MT measurements are adversely influenced by the presence of EM noise caused by overhead or underground power lines, grounded metal fences, metallic pipelines, other underground utilities, and structures that contain metal (such as reinforced concrete). The influence of these EM noise sources on CSAMT/MT data may be minimized by orienting the E and H field components at approximately 45º to the sources; however, noise may still be present within the data, and scalar measurements must be used rather than the preferred tensor mode.

The electric and magnetic data from either tensor or scalar CSAMT/MT measurements are used to assess surface impedance and estimate subsurface resistivity at various frequencies. Surface impedance $Z$ is the ratio of electric to magnetic fields ($Z_{ij} = E_i/H_j$) and is the basis for defining apparent resistivity $\rho_{ij} = [1/\omega \mu_0]|Z_{ij}|^2 = [0.2/f]|Z_{ij}|^2$ and impedance phase $\phi_{ij} = \tan^{-1}\{\text{Im}(Z_{ij})/\text{Re}(Z_{ij})\}$. CSAMT/MT field data consist of sounding curves that are logarithmic plots of apparent resistivity versus frequency. Apparent resistivities at high frequencies correspond to generally shallow investigation depths, and apparent resistivities at low frequencies correspond to investigations at greater depths. Apparent resistivities are bulk resistivities with contributions from different heterogeneous materials. Model transformations of the data calculated with forward and inverse computer software are good first-order approximations of the resistivity structure/layering beneath each station or sounding and are presented as cross sections of subsurface resistivity. These cross sections are used for the interpretation of geologic and hydrogeologic conditions. In general, CSAMT/MT data have shown a 10 to 15 % variation (based on field experience) between the actual depths to the anomalies, as verified by test hole drilling, and the depth predicted by the models.
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Typical field setup of Geometrics StrataGem EH4 CSAMT/MT System

Figure 1
Figure 2
Project Shoal CSAMT/MT Full Survey
Resistivity Elevation Section
Profile AQ

Figure 7

Hasbrouck Geophysics, Inc.
Project Shoal CSAMT/MT Full Survey
Resistivity Elevation Section
Profile AL

Figure 8
Project Shoal CSAMT/MT Full Survey
Resistivity Elevation Slice
2D View

Elevation = 4400 feet

Figure 10

Note: All station and profile names on Figures 3 and 4

Hasbrouck Geophysics, Inc.
Project Shoal CSAMT/MT Full Survey
Resistivity Elevation Slice
2D View

Elevation = 4500 feet

Figure 11
Project Shoal CSAMT/MT Full Survey
Resistivity Elevation Slice
2D View

Elevation = 4300 feet
Figure 12

Ground Zero
Well

Note: All station and profile names on Figures 3 and 4

Hasbrouck Geophysics, Inc.
Appendix D

Photos from the Dike Survey
Photo 1: View looking west shows dikes in the northwest portion of the study area.

Photo 2: View looking east shows dikes in the northwest portion of the study area.
Photo 3: View from the northwest portion of the study area looking north shows pegmatite dike in the foreground and andesite dike in the background.

Photo 4: View looking north shows fractured pegmatite dike in northwest portion of the study area.
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