Seismic Reflection and Magnetotelluric Imaging of Southwestern Dixie Valley Basin, Nevada

Jeff Unruh[1], Brian Gray[1], Karen Christopherson[2], Satish Pullammanappallil[3], Steve Alm[4], and Kelly Blake[5]

[1]Lettis Consultants International, Inc., Walnut Creek CA
[2]Chinook Geoconsulting, Inc., Evergreen, CO
[3]Optim Software, Reno NV
[4]Dept. of Geology, University of Kansas, Lawrence KS
[5]Navy Geothermal Program Office, China Lake CA

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ABSTRACT

Seismic reflection and magnetotelluric (MT) data acquired in southern Dixie Valley provide a unique opportunity to evaluate stratigraphy and conductivity structure associated with the seismically active, east-southeast-dipping Dixie Valley fault and related structures. Based on analysis of 2-D seismic reflection profiles and lithological data from deep borehole 66-16 in southern Dixie Valley, we recognize four major subsurface lithologic units in Dixie Valley (youngest to oldest): (1) Late Cenozoic fluvial basin fill deposits (approximately 122 m to 183 m thick); (2) Older Basin Fill deposits (244 m to 305 m thick); (3) a Volcanic Tuff and Porphyry unit (about 360 m thick); and (4) a Lower Volcanic unit (about 1190 m thick) resting on crystalline basement (approximately 1933 m depth). All units are offset by one or more strands of the Dixie Valley fault. The 3-D MT data reveal a conductive anomaly or anomalies in southwestern Dixie Valley adjacent to the Stillwater Range front at a depth of about 2000 ft to 3600 ft (700 to 1300 m). Locally, the range-front conductive anomaly is spatially associated with the Elevenmile Canyon temperature anomaly at the southwestern margin of the study area. The anomaly is primarily located within the Volcanic Tuff and Porphyry and Lower Volcanic units in the hanging wall of the Dixie Valley fault, and appears be capped above by the Dixie Valley basin fill deposits. We interpret the conductive zone to be associated with the presence of fluids and/or hydrothermal alteration. A more laterally extensive conductive anomaly is present in the upper 2800 ft (850 m) of south-central Dixie Valley at the very northern end of the Navy seismic array and is spatially associated with the Pirouette Mountain high-temperature anomaly. Assuming that this MT anomaly is associated with geothermal fluids and/or alternation, and not simply conductive

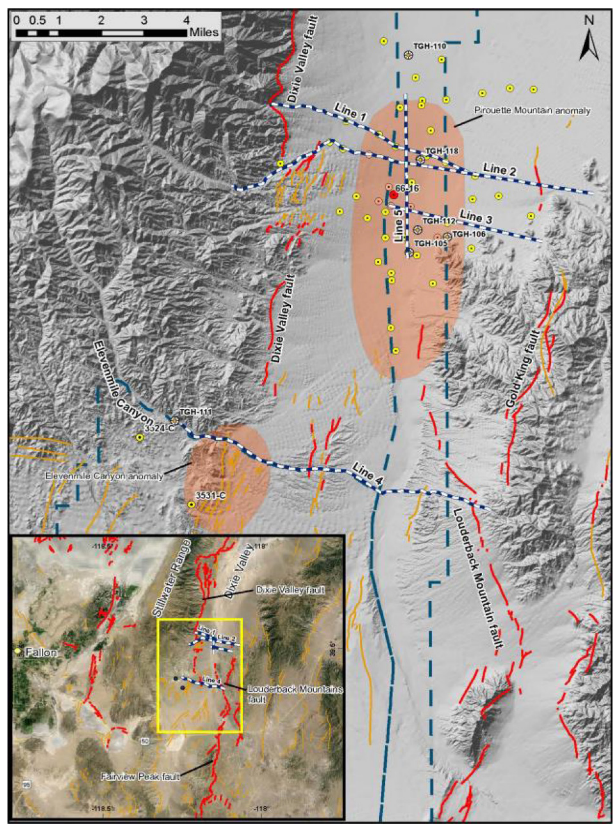

Figure 1. Location map of the Navy study area in southern Dixie Valley, with locations of 2-D seismic lines. Faults shown are from the U.S. Geological Survey Quaternary fault and fold database. Orange indicates late Quaternary activity; red indicates locations of surface rupture during the 1954 earthquake sequence.

clays within the fluvial basin deposits, the source of the fluids may be a deeper reservoir north of the reflection array in Dixie Valley basin. If this is correct, the fluids may have migrated up the Louderback Mountains fault or other structures east of the Dixie Valley fault.

Introduction

This paper summarizes an analysis of 2-D seismic reflection lines and a 3-D magnetotelluric (MT) dataset acquired by the US Navy Geothermal Program Office in 2013 to evaluate geothermal potential on military lands in southern Dixie Valley, Nevada (Figure 1). In addition to providing subsurface imaging of Dixie Valley basin southwest of the better-characterized Dixie Valley geothermal field, the new Navy datasets permit an integrated evaluation of fault structure, stratigraphy, and conductivity structure in the vicinity of the blind Elevenmile Canyon and Pirouette Mountain geothermal systems (Figure 1; Williams and Blackwell, 2012).

Geologic Setting

Dixie Valley is a NNE-SSW-trending late Cenozoic structural basin that has developed in the hanging wall of the Dixie Valley fault, an east-southeast-dipping normal fault along the eastern margin of the Stillwater Range (Figure 1). Development of the modern basin may have begun with the onset of Basin and Range extension in this region about 14-12 Ma (Dilles and Gans, 1995; see discussion in Alm, 2016). The Dixie Valley fault can be traced at least 65 km north of the current study area to northern Dixie Valley, where the fault and ancillary structures are interpreted to be conduits for upwelling fluids and contribute to reservoir fracture permeability for a 62 MW dual-flash geothermal field that produces >285° C fluid from depths of about 2.5 to 3.5 km (Blackwell et al., 2007).

The Dixie Valley fault ruptured on 16 December 1954 as part of a complex earthquake sequence that began with rupture on an east-dipping fault bounding the eastern margin of Fairview Peak south of the study area, followed by a second earthquake several minutes later on the Dixie Valley fault (Caskey et al., 1996). The 1954 Fairview Peak and Dixie Valley ruptures exhibit an *en echelon* relationship with an approximately 10-km-wide left step located between the two faults. Mankhemthong (2008) referred to this 10 km *en echelon* step between the Dixie Valley and Fairview Peak faults as the "Inter Basin Transition Zone" (IBTZ). The Navy seismic reflection array is located at the southern end of the Dixie Valley fault and partially within the IBTZ. Based on detailed mapping and analysis of potential field data, Alm (2016) interpreted that a key structure within this zone is the Louderback Mountains fault, which accommodates partial transfer of slip from the Fairview Peak fault to the Dixie Valley fault. The Louderback Mountains fault strikes north-northwest, dips steeply west, and bounds the eastern margin of the southern Dixie Valley basin (Figure 1). The fault is approximately 9 miles (14.5 km) long and is nearly contiguous with the east-dipping Fairview Peak fault to the south. The Louderback Mountains fault strikes into the Holocene alluvium of Dixie Valley north of its northernmost mapped extent (Figure 1), and aeromagnetic, gravity (Alm, 2016) and MT data (Christopherson, 2013) suggest the presence of a complex structure where slip is transferred west across the basin to the Dixie Valley fault (Alm et al., 2016).

Surficial geologic units within Dixie Valley primarily consist of Quaternary alluvial fan and fluvial deposits derived from the Stillwater Range to the west, and the Louderback and Clan Alpine Mountains to the east (Figure 1). The pre-Quaternary stratigraphy encountered in a deep borehole drilled in the approximate center of the Navy seismic reflection array (Hunt Energy Corporation borehole 66-16; Figure 1) is characterized by about 5,000 ft (1,524 m) of Tertiary pyroclastic and volcanic rocks resting nonconformably on crystalline basement rocks. Probable equivalents of the volcanic rocks in borehole 66-16 are exposed in the Stillwater Range, the Louderback Mountains, and the Clan Alpine mountains bounding the modern basin (John, 1993; 1995; 1997; John and Silberling, 1994; Alm, 2016). The lower part of the Tertiary volcanic section was derived from the Stillwater caldera complex and is late Oligocene to early Miocene in age (John, 1993). Younger Miocene volcanic rocks intrude and unconformably overlie deformed remnants of the Stillwater caldera rocks (Alm, 2016). Basement rocks reported at the bottom of borehole 66-16 include meta-quartz arenite and granodiorite (Table 1). Crystalline basement rocks exposed in the Stillwater Range and Clan Alpine Mountains are dominantly Jurassic and Triassic metasedimentary rocks (John and Silberling, 1994).

Interpretation of Seismic Lines

A) Seismic Stratigraphy

We recognize several distinct seismic stratigraphic units in the subsurface of southern Dixie Valley based on differences in reflector character and correlation with lithologic units reported in borehole (BH) 66-16 drilled by the Hunt Energy Coorporation in the late 1970's (Table 1). From youngest (shallowest) to oldest, the units include:

1) *Late Cenozoic Basin Fill Deposits*: We interpret closely-spaced layered reflectors in the upper 400 ft to 600 ft (122 m to 183 m) as late Cenozoic alluvial fan and fluvial deposits that have accumulated in the hanging wall of the Dixie Valley fault. The reflectors associated with these deposits dip gently westward and are locally offset by the fault. This reflector package also thickens westward across the basin, consistent with syn-depositional subsidence and west-down tilting of the hanging wall of the Dixie Valley fault.

2) *Older Basin Fill Deposits:* The late Cenozoic fluvial deposits are underlain by a relatively more massive package that is about 800 ft to 1000 ft (244 m to 305 m) thick in the central part of the basin near BH 66-16, and thickens westward in the hanging wall of the Dixie Valley fault. Following Alm (2016), we interpret these reflectors to be associated with older fluvial and lacustrine (?) deposits that date back to the formation of the present Dixie Valley structural basin in the late Miocene. Reflective fabric in the Older Basin Fill deposits slopes gently westward toward the western margin of the basin and the surface trace of the Dixie Valley fault, and the unit thickens westward as well. The overlying Late Cenozoic fluvial deposits appear to be generally conformable, and the combined thickness of the Late Cenozoic and Older basin fill deposits in the vicinity of BH 66-16 (as interpreted in the reflection data) is about 1200 ft to 1400 ft (366 m to 427 m).

3) *Tuff and Volcanic Porphyry Unit:* An approximately 1180 ft (360 m) thick package of rocks beneath the Older Basin Fill deposits corresponds to a section of "tuff and volcanic porphyry" noted in the 1265 ft -2445 ft depth interval in BH 66-16 (Table 1). The upper and lower contacts of this unit are interpreted in seismic lines 1, 2, and 5 in the northern part of the seismic array closest to BH 66-16 (Figure 1). We cannot confidently identify or distinguish this unit in line 1 at the southern end of the array. Based on patterns of reflector truncations and dip discordances, the contact between the Tuff and Volcanic Porphyry Unit and the overlying basin fill deposits is at least locally an angular unconformity.

4) *Lower Volcanic Unit:* An approximately 3900 ft thick (1189 m) package of layered, moderately dipping, and highly reflective rocks underlies the Volcanic Tuff and Porphyry unit. These layered rocks generally correspond to a thick section of alternating rhyodacite and dacite reported in the 2445 ft – 6345 ft depth range (745 m – 1934 m) in BH 66-16 (Table 1), and are likely associated with the Oligocene-early Miocene Stillwater Caldera Complex (Alm, 2016).

5) *Crystalline Basement:* BH 66-16 encountered meta quartz arenite below the Lower Volcanic Unit rocks at 6345 ft (1934 m) depth, and then granodiorite at 7115 ft depth (about 2168 m; Table 1). In general, reflector quality and imaging are poor at these depths, and the contact between the Lower Volcanic Unit and crystalline basement is not readily discernable.

Table 1. Lithologic Units Encountered in Borehole 66-16.

Unit (from log)	Depth (ft)	Elevation (ft)	Comments
Dixie Valley basin deposits (inferred)	0	3860	Upper 1265 ft of well not logged. Base of alluvial deposits not noted.
Tuff and volcanic porphyry	1265	2595	Log starts in this unit at 1265 ft depth.
Rhyodacite	2445	1415	
Dacite	3230	630	
Rhyodacite	5115	-1255	
Meta quartz arenite	6345	-2485	Assumed to be top of crystalline basement
Granodiorite	7115	-3255	

Notes: (1) Ground surface elevation of well is 3860 ft; K.B. is 22 ft above ground level. (2) Depths shown in table assume that the zero datum for depths reported in log is -465 ft below K.B. (i.e., 3417 ft elevation).

John (1995) notes that two episodes of deformation are recorded in Oligocene to early Miocene tuffs deposited in the Dixie Valley region. An initial early Miocene deformation episode resulted in as much as 50 to 90 degrees of eastward tilting of the Oligocene-Miocene silicic volcanic and volcaniclastic rocks (John, 1993). Given the 12 to 14 Ma onset of Basin and Range extension in this region (Dilles and Gans, 1995), deformation represented by the steep reflector dips in the Lower Volcanic Unit, and the angular unconformity between the Tuff and Volcanic porphyry and basin fill deposits, pre-dates subsidence of the present Dixie Valley basin recorded in the shallow fluvial package, and thus reflects the earlier Miocene deformation events (Alm, 2016).

B) Fault Interpretation

For this paper, we focus primarily on interpreting the down-dip geometry of faults that ruptured during the 1954 earthquake sequence, and which appear to offset the late Cenozoic fluvial deposits in some of the reflection profiles. These structures include the Dixie Valley and Louderback Mountains faults (Figure 1). Given their activity, these faults are most likely to form permeable pathways for geothermal fluid migration in the modern seismotectonic setting. See Alm (2016) for a more detailed structural geologic interpretation of the seismic reflection data, including faults that primarily deform the volcanic rocks beneath the basin fill deposits.

As part of our structural analysis, we considered interpretations of the Dixie Valley fault as either a low-angle fault, or a moderately to steeply dipping fault. As discussed in Lettis Consultants International (2013), a subsurface trajectory for the fault with an average dip of 25° to 40° can be interpreted on the approximately east-west-trending 2-D lines through a series of low-angle east-dipping reflectors and reflector truncations. In this low-angle interpretation, the contact between the Lower Volcanic Unit and underlying crystalline basement encountered in BH 66-16 at 5,880 ft depth (1803 m; Table 1) is the Dixie Valley fault rather than a nonconformity. This low-angle interpretation is similar to observations reported in Dixie Valley approximately 20 km north of the Navy seismic array near a prominent re-entrant in the Stillwater Range front that is informally known as "the Bend". In this region, Caskey et al. (1996) documented field relations indicating that the Dixie Valley fault dips about 25° at the surface and in the shallow subsurface. Based on analysis of shallow high-resolution seismic reflection survey in the vicinity of "the Bend" and modeling of gravity data, Abbott et al. (2001) interpreted that the Dixie Valley fault dips 25° to 30° to a depth of about 2.7 km, and has a downward-flattening (listric) geometry.

In contrast, Hodgkinson et al. (1996) inferred that the Dixie Valley fault dips about 55° in the upper 6 km of the crust based on joint inversion of leveling and triangulation data from the 1954 earthquake sequence, and Alm (2016) interpreted that the fault dips moderately to steeply east based on analysis of the same 2-D seismic reflection data presented here.

In this paper we follow the general interpretation of Hodgkinson et al. (1996) and Alm (2016) that the Dixie Valley fault is a moderately to steeply dipping structure in the Navy study area. This interpretation is more consistent with the epicenter of the 1954 Dixie Valley earthquake, the location of which implies that the fault dips moderately to steeply east to connect the surface rupture along the Stillwater range front to the earthquake focus at depth. It is possible that the fault has a relatively shallow dip beneath the western margin of southern Dixie Valley, but ramps abruptly down to the east beneath eastern Dixie Valley to the depth and location of the 1954 earthquake focus. However, this model predicts that a large, deep syncline should be associated with the postulated flat-ramp transition, which is not observed in the topography or potential field data east of the seismic array.

Association of Conductive MT Anomalies With Stratigraphy and Geologic Structure

Based on analysis of a 3-D inversion of MT data (CGG, 2013) acquired by the Navy within the seismic array, Christopherson (2013) identified distinct conductive zones beneath the late Cenozoic fluvial deposits (Figures 2-5):

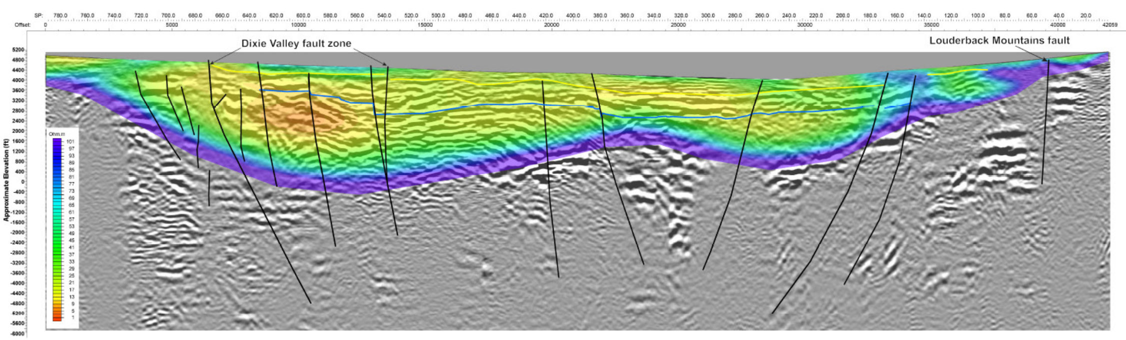

Figure 2. Seismic line 4 at the southern end of the Navy 2-D array (see Figure 1 for location). Interpreted faults are indicated by black lines. Warmer colors indicate relatively higher conductivity. Stratigraphic horizons: (1) base of late Cenozoic fluvial deposits, yellow; and (2) base of Older Basin Fill deposits, blue.

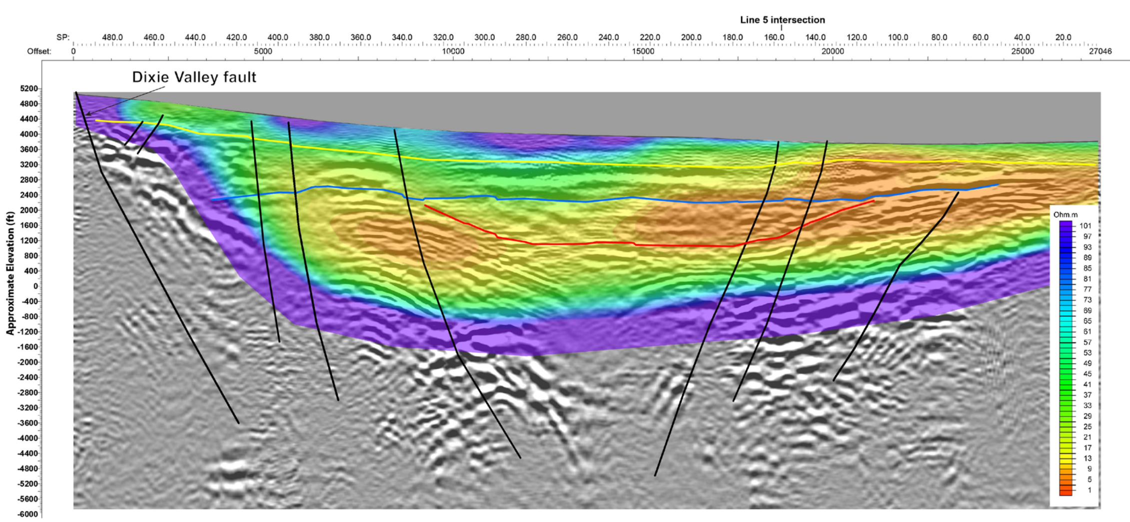

Figure 3. Seismic line 1 at the northern end of the Navy 2-D array (see Figure 1 for location). Warmer colors indicate relatively higher conductivity. Stratigraphic horizons: (1) base of late Cenozoic fluvial deposits, yellow; (2) base of Older Basin Fill deposits, blue; (3) base of Volcanic Tuff and Porphyry; red.

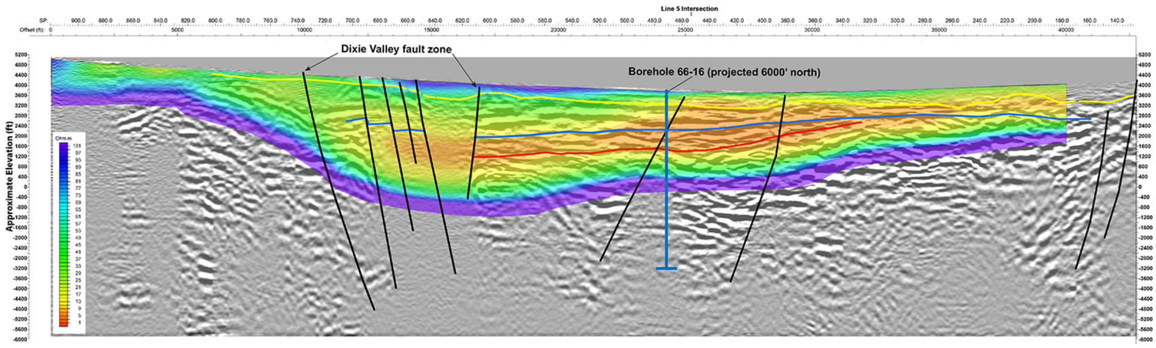

Figure 4. Seismic line 2 at the northern end of the Navy 2-D array (see Figure 1 for location). See Figure 3 for explanation of annotations.

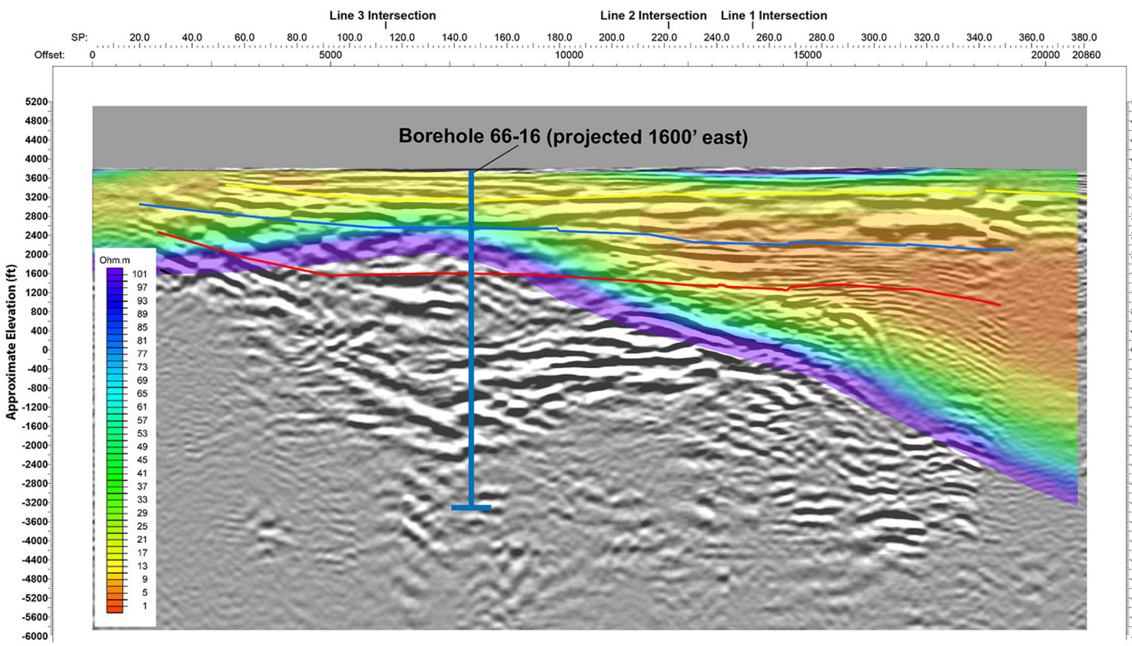

Figure 5. Seismic line 5 at the northern end of the Navy 2-D array (see Figure 1 for location). See Figure 3 for explanation of annotations.

1) *A conductive zone or zones in southwestern Dixie Valley adjacent to the Stillwater Range front.* This conductive anomaly or anomalies is imaged in seismic lines 1, 2 and 4 (Figure 1), and locally is associated with the Elevenmile Canyon geothermal system at the southern end of Dixie Valley (line 4; Figure 2). On lines 1 and 2 (Figures 3 and 4), the conductive zone is at a depth of about 2000 ft to 3600 ft (610 – 1100 m). On line 4 (Figure 2) the conductive zone lies in the depth range of 1100 ft to 2700 ft (340 – 820 m). At present, we do not know if the range-front anomaly is laterally continuous along the entire N-S extent of the study area. The conductive zone is elliptical in the plane of the 2-D seismic lines (elongated in the east-west direction). In lines 1 and 2 (Figures 3 and 4, respectively), the conductive zone appears to be associated with steeply dipping synthetic faults, which likely sole into or terminate against the main Dixie Valley range-front fault at depth. In Lines 1, 2 and 4 (Figures 3, 4 and 2, respectively) the conductive zone is located within volcanic rocks and appears to be capped by the basin fill deposits.

2) *A conductive zone or zones in south-central Dixie Valley*. A relatively broad conductive zone is present in the 500 ft to 2600 ft depth range (152 – 792 m) beneath south-central Dixie Valley in the northern part of the Navy study area (Figure 3). The conductive anomaly is spatially associated with the Pirouette Mountain temperature anomaly (Williams and Blackwell, 2012) (Figure 1). As imaged by the MT data and seismic lines 1 and 2 (Figures 3 and 4), the conductive anomaly is generally associated with the Older Basin fill and Volcanic Tuff and Porphyry units. However, a relatively shallow upward continuation of the anomaly in the late Cenozoic fluvial deposits appears to be associated with strands of a west-dipping fault zone in the central part of the valley that may be related to the northern extension of the Louderback Mountains fault (Alm, 2016; Figures 3 and 4). In the plane of north-south-trending seismic line 5 (Figure 5), the conductive anomaly thickens and deepens north of line 1, and tapers out abruptly to the south in the vicinity of line 2. The northward increase in thickness and depth is associated with a north-facing homocline in reflective rocks at depth that we associate

primarily with the volcanic rocks beneath the basin fill deposits. The homocline is located along the southern margin of the gravity low associated with deepening of Dixie Valley to the north (Alm, 2016). At the northern end of line 5, loss of fold limits resolution of the structural and stratigraphic relationships at depth.

Interpretation

We interpret the range front conductive anomaly or anomalies to be due to the presence of fluids and/or alteration along the Dixie Valley fault and ancillary hanging wall structures. The anomaly may image an active or relict geothermal reservoir in the volcanic rocks (with fracture permeability?) that has been charged with geothermal fluids circulating upward along the Dixie Valley fault. In lines 1 and 2 (Figures 3 and 4), the anomaly is specifically associated with a steeply-dipping piedmont fault zone located basinward of the range-front trace of the Dixie Valley fault. The basin fill deposits may be acting as a cap or seal for the system.

As imaged in line 1 (Figure 3), the more laterally-extensive conductive anomaly beneath the axis of the basin is approximately centered in depth along the contact between the Older Basin Fill and underlying volcanic rocks. A shallow and more spatially-limited upward continuation of the anomaly is associated with the younger Late Cenozoic alluvium in the center of the basin (Figure 3). It is possible that the anomaly is associated with conductive clays in the basin deposits. Alternatively, it may be due to hot fluids migrating up one or more antithetic faults in the hanging wall of the Dixie Valley fault, such as the Louderback Mountains fault (Figure 1). Another potential migratory pathway for fluids to charge a reservoir in the Older Basin Fill and Volcanic Tuff and Porphyry units would be updip from a source in the deeper parts of Dixie Valley basin to the north of the seismic array. This model could explain the northward deepening and expansion of the conductive anomaly in seismic Line 5 (Figure 5). See Alm (2016) and Alm et al. (2016) for further analysis of the structure of this region.

The imaging of geologic and conductivity structure by these data sets provides further context for evaluating temperature gradient data for the Elevenmile Canyon and Pirouette Mountain anomalies summarized by Williams and Blackwell (2012). Two intermediate-depth temperature gradient holes (3524-C and 3531-C, Figure 1) drilled on the Elevenmile Canyon anomaly were located in the footwall of the range-front fault, showed no temperature overturns, and appeared to approach isothermal conditions of about 80°C (Williams and Blackwell, 2012). Temperature gradient hole drilling to 150 meters in 2013 in this area by the Navy Geothermal Program Office (GPO) produced similar results (Figures 6 and 7). Both TGH-104 and 111 (Figure 6) were drilled on the same well pad within Eleven Mile Canyon and the temperature profiles of both were roughly the same with steady increases in temperature to a maximum of ~35˚C (Figure 7). These holes, and the previous data cited by Williams and Blackwell (2012), may record conductive heat flow from the deeper source located in the hanging wall to the east.

In the center of Dixie Valley to the north, two older temperature gradient holes along the western margin of the Pirouette Mountain anomaly (3349 and 3316-C; Williams and Blackwell, 2012) show shallow temperature overturns in the 100 m to 150 m

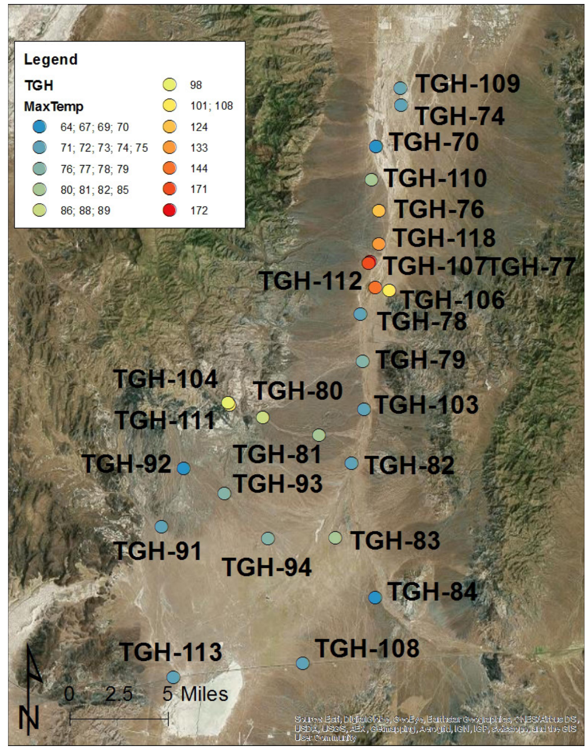

Figure 6. Map of the southern Dixie Valley study area showing locations of temperature gradient holes drilled by the Navy Geothermal Program Office.

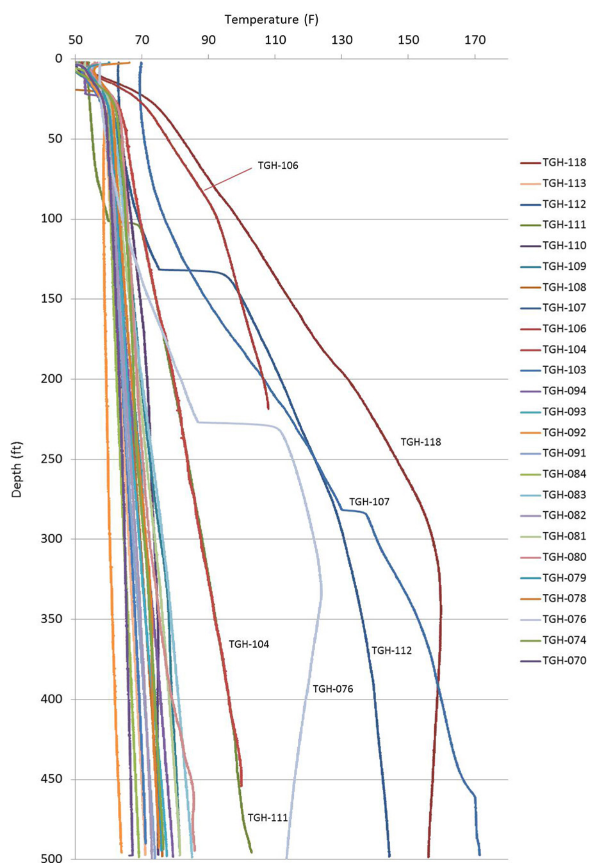

Figure 7. Temperature-depth profiles for holes shown in Figure 6.

depth range. Recent temperature gradient hole drilling in this region by the GPO (Figures 6 and 7) demonstrates similar overturns within 150 meters. However, as the basin fill depth decreases with proximity to Pirouette Mountain, temperature gradient hole profiles show a steady increase in temperature to 150 meters depth, with the highest temperature (~75˚C) in TGH-107 at the bottom of the hole with no overturn. The variation of these bottom hole temperatures may reflect shallow lateral flow of thermal waters from the northwest that migrated upward along strands of the Dixie Valley fault from the deeper range-front conductive anomaly.

Several intermediate holes drilled in the central and northern parts of the Pirouette anomaly cited by Williams and Blackwell (2012) exhibited steep shallow gradients with rapid transitions to isothermal or near-isothermal sections below about 100 m to 150 m depth; these holes likely intercepted the northward thickening and deepening conductive anomaly imaged at the north end of seismic line 5. The isothermal conditions in the upper 150 - 600 m recorded by the wells suggests the source for the geothermal fluids may be at greater depth to the north.

Summary and Conclusions

An array of 2-D seismic reflection lines and 3-D MT data acquired by the Navy in southern Dixie Valley provides complementary imaging of spatially-varying conductivity, geologic structure, and stratigraphy. Conductive anomalies are associated with the hanging wall of the east-dipping Dixie Valley fault along the Stillwater Range front, and a west-dipping fault zone in the south-central Dixie Valley that may be the on-strike extension of the Louderback Mountains fault. The seismic reflection and MT data provide additional geologic context for evaluating temperature gradient data from the Elevenmile Canyon and Pirouette Mountain geothermal anomalies in southern Dixie Valley.

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