Targeting Geothermal Resources in the Lahontan Valley, Nevada; Analysis of Neogene Faulting Through 2D Seismic, Topographic, and Satellite Imagery Analysis

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ABSTRACT

We analyze and interpret seven depth-migrated 2D seismic reflection profiles at Naval Air Station Fallon (NASF), in conjunction with topographic and air photo analysis, to better understand the location, geometry, and sense of slip of Neogene faults within and adjacent to the Lahontan Valley near Fallon, Nevada. Our analysis reveals a zone of northeast-striking normal faults in eastern Lahontan Valley, informally referred to as the Lahontan fault zone (LFZ), beneath the NASF Mainside facilities. The LFZ structures consistently displace Tertiary basalts and an overlying section of Neogene (?) to Quaternary lacustrine and fluvial deposits down to the west. North of NASF Mainside we identify several northwest-striking faults intersecting LFZ faults at near right angles. These northwest-trending structures comprise the southern margin of the Sagouse fault zone, which has Quaternary geomorphic expression within the Lahontan Valley. East of NASF Mainside, northeast-dipping traces of the Rainbow Mountain fault zone are imaged in the 2D seismic reflection data and exhibit Quaternary geomorphic expression at the surface. Relatively high temperatures encountered in exploratory boreholes southeast of the Mainside airfield are spatially associated with the LFZ, and specifically may be localized along a change in structural trend from NNW-striking faults south of NASF to the NNE-strike of the LFZ. At least some of the LFZ faults appear to intersect and/or terminate against strands of the NNW-striking Sagouse fault zone in the northern part of the seismic array. The structural complexity associated with slip transfer from the LFZ to the Sagouse fault zone may be associated with locally increased fracture density and permeability, and thus be prospective for further geothermal exploration.

Regional Tectonic Setting

The NASF project area is located in west-central Nevada roughly straddling the boundary between the Walker Lane belt and the Basin and Range tectonic province. The Walker Lane belt is an approximately 100-km-wide zone of active faulting bordering the eastern margin of the Sierra Nevada block or microplate. Patterns of mixed strike-slip and normal faulting within the Walker Lane belt primarily accommodate northwest translation of the Sierran microplate with respect to stable North America (Unruh et al., 2003). In general, strike-slip faults in the Walker Lane are oriented NW-SE, subparallel to Sierran-North American motion. Normal faults in the Walker Lane generally strike north to northeast, oblique to Sierran-North American motion and at a high angle to the orientation of the maximum extensional strain associated with NW dextral shear (Unruh et al., 2003). Normal faults in the Walker Lane belt typically exhibit left-stepping en echelon geometry characteristic of transtensional deformation. In contrast to the sinuous, curvlinear, and laterally continuous faults of San Andreas transform system, the distributed and discontinuous faulting in the Walker Lane belt is likely a function of lower slip rate, transtensensional style, and modest cumulative displacement (Wesnousky, 2005).

The northwest-trending structural fabric of the Walker Lane belt, largely reflecting the influence of strike-slip faulting, abruptly changes to a northeast-trending fabric in the Basin and Range province to the east, where the dominant structures are northeast-striking normal faults that bound prominent tilted fault blocks. The northeast-striking Rainbow Mountain fault in the eastern part of the study area ruptured during the 1954 Rainbow Mountain earthquake and produced normal surface fault scarps.

Geologic Units/Seismic Reflectors

Geologic mapping by the Nevada Bureau of Mines and Geology (NBMG) and Morrison (1964) indicate that much of the seismic survey area is underlain by Tertiary volcanics and late Tertiary- to Quaternary-age lacustrine, fluvial, and aeolian doposits. For the purpose of characterizing seismic reflectors within the Lahontan Valley, we use mudlogs from deep boreholes located several miles southeast of the NASF airstrip (Figure 1), and from those, identify five distinct lithostratigraphic assemblages.

The shallowest and most conspicuous of the assemblages is the Neogene Lahontan basin fill sequence composed of lacustrine and fluvial deposts intercalated with volcaniclastics, which become more abundant with depth. The bedded nature of the Neogene sediments is well imaged in the seismic data, aiding in the definition of small-scale faults with minimal displacements. Underlying the Neogene basin lacustrine/fluvial assemblage is a section of volcaniclstic deposits (dominantly high-silica tuffs), the upper contact of which results in relatively high amplitude reflector mappable throughout most of the NASF section of the survey area. Underlying the volcaniclastic sequence is an ~2000 ft thick section of Tertiary basalts that dip gently westward towards the presumed center of the Neogene basin within the Lahontan Valley. These basalts are similar in composition and stratigraphic thickness to the Tertiary Bunejug Formation east and southeast of NASF (Katzenstein and Bjornstad, 1987). Underlying the basalts is an ~3000 ft thick section of Tertiary andesitic, dacitic, and basaltic lavas. Below 7000 ft depth, a thick sequence (≥ 1500 ft) of silicic volcanics, primarily rhyolites and tuffs, were encountered within multiple boreholes. The basal crystalline basement assemblages encountered in the deepest borehole are Jurassic-Creataceous age metamorphic rocks.

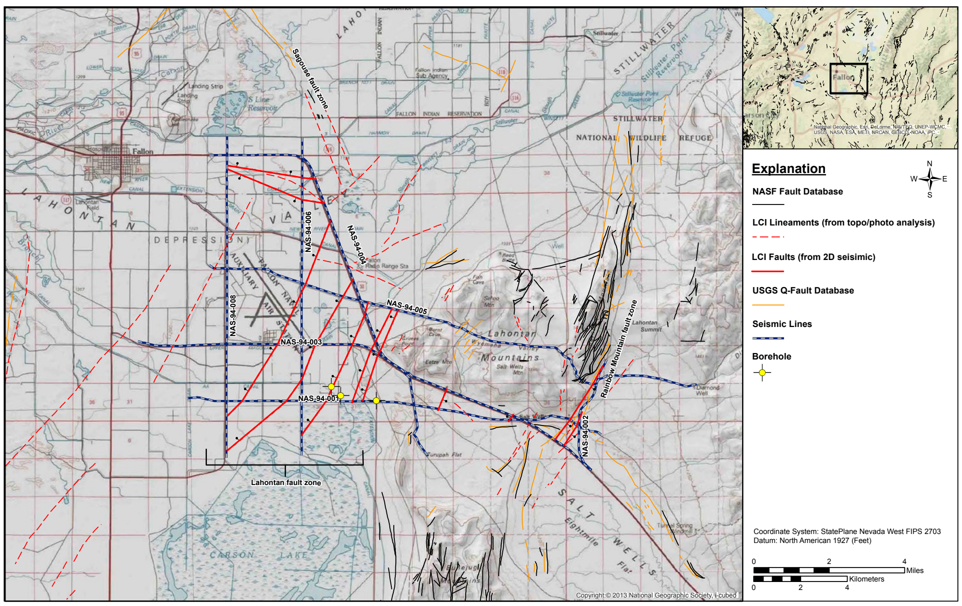

Figure 1. Location map with lineaments and subsurface faults from this study and faults compiled from NBMG geologic maps and the USGS Quaternary fault and fold database. Faults projected in subsurface to 3500′ elevation. Not all assigned faults intersect the 3500′ datum.

Data and Analytical Methods

I) Development of the NASF Geologic and Geophysical Database

Prior to analysis of the seismic reflection data, LCI developed a comprehensive GIS (Geographic Information System) database of pre-existing geologic, geophysical, topographic, and photographic data provided by the US Navy Geothermal Program Office (GPO), the Nevada Bureau of Mines and Geology (NBMG), the United States Geologic Survey, and the United States Department of Agriculture. The GIS database included: recently-published geologic maps; fault mapping; borehole locations; gravity maps, magnetic maps, 1/3 arc second NED digital elevation models (DEMs) and hillshade images; National Agricultural Imagery Program (NAIP) air photos; and locations of seismic surveys.

II) Office-Based Air Photo and DEM Lineament Mapping

We performed a lineament analysis utilizing the USGS NED 1/3 arc-second DEMs, 1-m-resolution LiDAR-based DEM collected on NASF property, 2006 NAIP imagery, and 2011 Google Earth imagery. Lineament analysis was used to supplement fault mapping compiled by the NBMG and USGS. Lineaments were mapped primarily along linear topographic breaks, tonal contrasts, drainage deflections, and discontinuities observed in recessional shorelines of paleo Lake Lahontan.

III) Interpretation of Reprocessed 2D Seismic Reflection Data

Reprocessed 2D seismic reflection lines (in sgy format) were loaded into IHS Kingdom Suite 2D/3D Pack seismic interpretation software. In addition, geologic maps, the USGS Quaternary Fault Database (Q-fault), LCI lineament mapping, gravity, and borehole data were imported into Kingdom Suite for use during seismic interpretation. Mapped faults were grouped into two categories: (1) "assigned" and (2) "unassigned". Assigned faults are those correlated across two or more seismic lines and whose multiple mapped traces define three-dimensional fault surfaces. Unassigned faults are those that could not be correlated between multiple seismic lines.

Assigned faults were also given a letter grade to indicate our relative level of confidence in the fault interpretation and its location. Confidence grades are A, B, and C, corresponding to "almost certain", "probable", and "possible", respectively. Grading was based on seismic signature (i.e. is the fault well defined by linear breaks in seismic reflectors, dip discordances, clear displacement of reflectors, etc?), lateral continuity (linearity of the feature through multiple seismic profiles), and consistency in orientation and sense of displacement.

IV) 3D Fault Model Development

The 3D NASF model was developed using OpendTect version 4.4 seismic interpretation and visualization software to display fault surfaces, stratigraphic horizons, and fault traces identified and mapped in Kingdom Suite. Assigned fault surface grids were generated in Kingdom Suite and exported as ascii grid files. Unassigned faults were also exported using an xyz format. Three-dimensional stratigraphic horizon grids were generated in Kingdom Suite using a protocol that generates a horizon surface with vertical separation across assigned faults.

2D Seismic Reflection Surveys

The seismic array encompasses an area of approximately 60 square miles (Figure 1). Seismic lines NAS-94-001 and NAS-94-003 (Figure 2) are oriented east-west and extend from the Lahontan Valley in the west to approximately ½ mile east of the 1954 rupture trace(s) of the Rainbow Mountain fault (RMF), crossing the Salt Wells basin along the way. Seismic line NAS-94-005 also runs east-west from the Lahontan Valley to just beyond the RMF, crossing the intervening Lahontan Mountains. Seismic Line NAS-94-004 extends east-west along the northern margin of the study area from ~ 1 mile southeast of Rattlesnake hill, turns south passing just west of Grimes Point, and eventually terminates at Star Flat. NAS-94-005 is another east-west orientated line located north of NAS-94-003, crossing the Lahontan Mountains via Wyemaha Valley, and terminating just east of the 1954 rupture trace of the RMF. Three north-south seismic reflection lines are included with the NASF seismic survey: NAS-94-006 and NAS-94-008 in the Lahontan Valley; and NAS-94-02, which roughly parallels the 1954 RMF rupture trace along the eastern piedmont of the Rainbow Mountains.

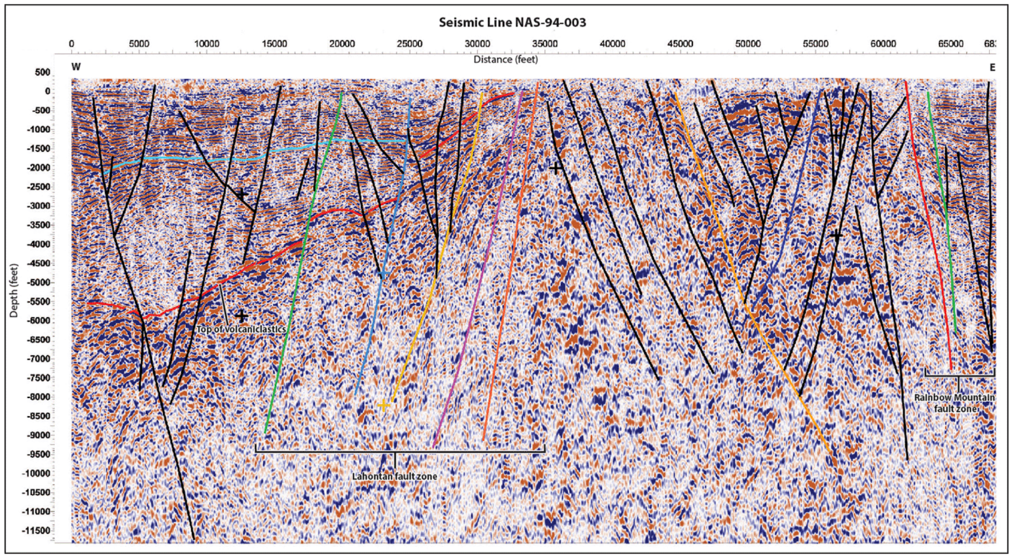

Figure 2. Seismic Line NAS-94-003 crossing the Lahontan Basin (west), the southern margin of the Lahontan Mountains, and terminating at Salt Flat in the east. Sub-horizontal Neogene sediment reflectors in both Lahontan and Salt Flat basin provide the best opportunities to evaluate Neogene faulting. Colored faults are those which correlate to one or more adjacent seismic lines. Faults outlined in black are unrecognized on adjacent seismic lines.

Seismic Data Limitations

An examination of nearby faults on NBMG geologic maps and within the Quaternary Fault and Fold Database (Q-fault database) shows that individual bedrock fault traces in the area are typically shorter (commonly much shorter) than the 1.5-mile spacing between seismic lines. As noted previously, short discontinuous lengths are characteristic of many faults in the Walker Lane and Basin and Range. Many of the individual assigned fault traces mapped on the seismic lines may be shorter than the line spacing and therefore many of the assigned fault surfaces may actually be composite surfaces comprised of multiple linked traces sharing similar spatial orientations and structural characteristics. Additionally, the interpretation of small-scale faulting beyond and below the extent of basin-fill sediments is inhibited by the lack of distinct laterally-continuous seismic reflectors. Thus, small-scale faults are be difficult to identify within the Tertiary volcanic sequence. The level of detail to which small-scale faults have been mapped during this study attempts to reflect this uncertainty. As mapped, small-scale fault density is greater within the basin fill sediments, primarily because offsets of the layered reflectors are easier to recognize. It is possible, however, that fracture density is similar or even greater within the Tertiary volcanic sequence.

Fault Domains

The seismic survey area is herein divided into three tectonically distinct domains: (1) the Lahontan Valley; (2) the Lahontan Mountains; and (3) the Rainbow Mountain fault domain (Figure 1).

I) Lahontan Valley

Quaternary fault mapping by the NBMG and USGS, supplemented by lineament mapping for this project, indicate that two, and possibly three, primary sets of faults are present in the Lahontan Valley. The first set strikes north to north-northwest and is observed within and along the margins of Bunejug Mountain immediately east of Carson Lake. These faults offset the Tertiary basalts and are mapped across lacustrine/fluvial deposits along regressive shorelines of paleo Lake Lahontan. Their ages are presently unclassified in the Q-fault database, however, they are latest Pleistocene to Holocene in age if they offset regressive Lake Lahontan shorelines. Faults along the western margin of Bunejug Mountain strike north-northwest into modern Carson Lake and are not recognized to the north. Faults within the core of Bunejug Mountain strike north and are not recognized to the north within Turupah Flat. Faults along the eastern margin of Bunejug Mountain strike north to north-northeast, projecting into and along strike with the Rainbow Mountain fault zone. As Figure 1 illustrates, this zone of distributed faulting appears to diverge near the northern margin of Bunejug Mountain, bifurcating into separate northwest and northeast striking fault zones. Through lineament mapping, we recognize a zone of possible northwest-striking faults emanating from the southwest margin of the Lahontan Valley, expressed as laterally-extensive topographic and tonal lineaments. These lineaments cross cut Quaternary sediments and strike roughly parallel with the primary zone of faults recognized in the seismic reflection data. The Sagouse fault zone, compiled by Adams and Sawyer (1999) in the Q-fault database, defines a series of northwest-striking faults crossing the Lahontan Valley on the northern margin of the study area. These faults are recognized as topographic and strong tonal lineaments and disrupt the trends of several modern fluvial channels. Our lineament analysis suggests the fault zone reported by Adams and Sawyer (1999) should be extended several kilometers to the southeast.

The Lahontan Valley domain lies entirely within the physiographic Lahontan Valley and is dominated by a series of west-dipping normal faults (Figure 3) that displace both the top of volcaniclastics and the overlying section of Neogene (?) to Quaternary basin-fill lacustrine, fluvial, and possible eolian deposits. Six of these faults have been correlated across multiple seismic lines and all strike toward the northeast, between N25E and N32E. These faults strike about 5-10 degrees more easterly than the 1954 traces of the Rainbow Mountain Fault. For convenience, these west-dipping faults, along with second-order postulated structures to the west, are referred to herein as the "Lahontan fault zone" (LFZ). The structure of the basin is expressed by relief on the top of the Tertiary volcanic sequence, which defines the base of a broad, possibly asymmetric, synform within the Lahontan Valley, deepening westward to a depth of approximately 6000 ft. The deepest part of the basin within the seismic array lies just north of the intersection of seismic lines NAS-94-005 and NAS-94-008. Individually, down-to-the-west displacement on the top of Tertiary volcanics ranges from less than 200 to up to 700 feet. Near the northern margin of the survey, several west-northwest-striking faults are observed to offset basin reflectors. Collectively, these faults define a horst block oriented nearly perpendicular to the predominant NE-SW LFZ faults. We interpret these north-northwest-striking faults to be structurally related to the Sagouse fault zone north of the survey area. The western and southern basin margins were not imaged by the seismic data (Figures 1 and 2). Numerous east-dipping antithetic faults are mapped throughout the survey area; however, only those on the western margin of the survey area appear to be deeply rooted, including one fault correlated between seismic lines (Figure 3). Gravity data support the presence of a deep basin bounded by structural highs to the north and east. Interestingly, the total depth of the basin (~6000' on the top Tertiary volcanics) cannot be accounted for solely by faults imaged in the seismic data, suggesting that additional faults, perhaps normal faults northwest of the seismic survey area, have played a significant role in the development of the Lahontan Basin.

II) Lahontan Mountains

East of the Lahontan Valley, the Lahontan Mountains domain is an eroded low-relief horst block between the LFZ and RMF (Figure 1). This domain also includes the area of Salt Flat, directly south of the Lahontan Mountains. Geologic maps and the Q-fault database show relatively few faults mapped within and through the Tertiary volcanic sequences present in the Eetz, Seehoo, and Salt Wells Mountains. Rainbow Mountain is included within the RMF domain. We identified several discontinuous geomorphic lineaments through the mountains; however, none of them have significant length or are particularly compelling geomorphic features as active, high slip-rate faults. The Q-fault database includes discontinuous Holocene-age fault traces within Wyemaha Valley between Eetz and Seehoo Mountains; however, these faults do not extend more than several hundred meters into the margins of Eetz and Seehoo Mountains. Their classified age is likely based on geomorphic expression within latest Pleistocene Lake Lahontan deposits (USGS, 2010). In the subsurface, numerous east-dipping faults are observed on seismic line NAS-94-005, which crosses the mountains, and on seismic lines NAS-94-001 and NAS-94-003, which traverse the southern margin of the mountains. The majority of these faults cannot be correlated between seismic lines, suggesting the short, discontinuous pattern of mapped faults at the surface is likely representative of faults in the subsurface. Only two faults were correlated in this domain and both span the short distance between seismic lines NAS-94-001 and NAS-94-003. The primary fault is an east-dipping, northeast-striking normal fault mapped in Salt Flat (Figure 3). The fault is imaged in the Tertiary volcanic sequence as an angular discordance where footwall reflectors exhibit down-to-the-east-drag folding and the dip of hanging wall reflectors increases towards the fault, forming an apparent roll-over anticline. The second fault is antithetic to the primary east-dipping fault. In general, faults within the Lahontan Mountains domain are discontinuous, lack prominent surficial geomorphic expression, and, with a couple of exceptions, cannot be correlated between seismic lines.

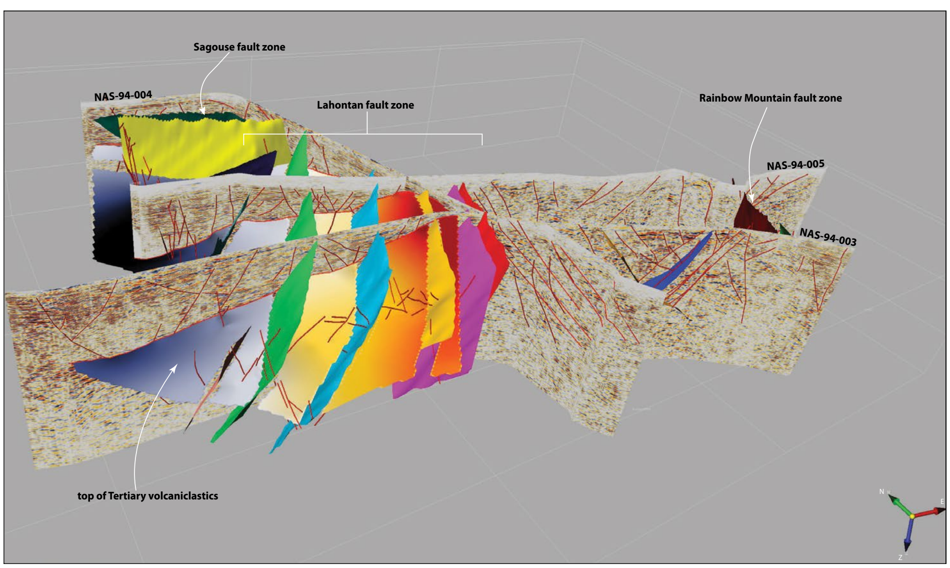

Figure 3. Example view of the three-dimensional fault model developed for NASF Mainside. View is oblique, looking northeast along strike of the LFZ on the east margin of the Lahontan Valley. Select seismic lines shown to provide context. Top of Tertiary volcanics horizon observed cut by LFZ faults, reaching maximum depth near the northwest margin of the survey. Faults of the SFZ define a horst block near the northern margin of the survey are associated with significant structural complexity near their intersection with the LFZ.

III) Rainbow Mountain Fault Domain

The easternmost fault zone recognized in this study encompasses the 1954 rupture traces of the RMF; i.e., numerous north-northwest-striking faults mapped along the base of and within the linear rangefront (Figure 1). Here, the active trace of the RMF juxtaposes the Tertiary volcanic sequence with the Quaternary fan, alluvial, and colluvial deposits emanating from the Rainbow Mountain rangefront and the Stillwater Mountains near Lahontan Summit. These Quaternary deposits are likely interbedded with lacustrine sediments from successive highstands of Lake Lahontan. Near the southern margin of Rainbow Mountain, the RMF defines the contact between the Tertiary volcanic sequence and the presumed lacustrine deposits beneath Salt Wells Basin. Seismic lines crossing the Rainbow Mountain fault zone image numerous east dipping faults, some of which are coincident with 1954 rupture traces. Two faults are recognized between multiple seismic lines, both of which are roughly coincident with 1954 rupture traces and, in the south, both are well expressed as discontinuities in the deep lacustrine sediments of Salt Wells Basin flat. The longer of the two faults is relatively planar and dips 55-60 degrees southeast. At least 4000 feet of sub-horizontal, presumed lacustrine deposits are present within the Salt Wells Valley sub-basin, suggesting the basin is of significant age and or its bounding faults are characterized by relatively high slip rates.

Fault Kinematics and Implications for Geothermal Exploration

Existing subsurface temperature data indicate that the most promising geothermal gradients are located near the southeast margin of the mainside property and are likely associated with faults bounding the north-northeast-trending horst block mapped along the eastern margin of the Lahontan Basin (Bjornstad, 2012, pers comm). As outlined above, the Lahontan Valley domain of the seismic survey area is comprised of two primary fault systems: the northeast-striking west-dipping Lahontan fault zone and the west-northwest-striking Sagouse fault zone. Interestingly, faults related to the LFZ are more prominent in the seismic survey than those of the SFZ (perhaps because the survey does not entirely image the SFZ). However, the surficial geomorphic expression of the SFZ is far more prominent than the LFZ within the valley. At the only intersection between the two fault zones imaged by the seismic array, the LFZ fault appears to terminate into the SFZ fault, suggesting that the SFZ fault is older. Given that the SFZ displays prominent surficial geomorphic expression and that the LFZ deforms shallow lacustrine/ fluvial deposits in the seismic section, it is likely that both faults have been active during the Pleistocene and perhaps the Holocene.

Faults mapped east and southeast of NASF on the Morrison (1964) and NBMG maps indicate a general change in strike from north-northwest to north-northeast along a northwest-trending alignment approximately 2-7 km south of NASF. This alignment is also coincident with a prominent northwest-trending gravity gradient that appears to be coincident with the 10-15-km-wide Walker Lane/ Basin and Range transition (Figure 4). Collectively, these observations suggest that some of the northwest-directed shear along the Walker Lane margin is transferred to Basin and Range faults near the northwest-trending aligment. Together, the Sagouse and Lahontan fault zones may comprise a localized right step along the Walker Lane margin, which is a releasing geometry in the regional context of northwest dextral shear. It is possible that the regional change in structural strike, in combination with a transition from shear to extension, contributes to locally-increased fracture density that facilitates geothermal upwelling. Three geothermeral wells are located within several kilometers of the northwest-trending fault zone northwest of Bunejug Mountain; fault orientation is dominantly north-northeast where the wells are located (Figure 1), but these may be close enough to benefit from an increase in fracture density related to the change in fault orientation. This area southeast of NASF mainside is the most promising location to direct further geothermal studies.

Second, the intersection between the Lahontan and Sagouse fault zones may be a locus of enhanced secondary deformation where zones of high fracture density are likely under tension. If the Sagouse fault zone accomodates northwest-directed shear associated with Lahontan Valley extension, then fracture densities are likely to be higher near the fault intersection(s) and may be more conducive to upwelling of deep geothermal fluids. In addition, the structural high observed on line 4 may be a buried volcanic edifice, its location indicative of a previous crustal weakness and magma conduit.

Third, the well-defined graben imaged on lines 005 and 008 is indicative of localized extension. The graben is associated with significant deformation (both folding and faulting) of the upper fluvial/ lacustrine strata indicating significant Neogene displacement along faults bounding both its eastern and western margins. As with the previous two locations, this structure may be associated with higher fracture densities and localized extension.

In summary, the multi-faceted approach utilizing satellite imagery and detailed topographic analysis, existing geologic

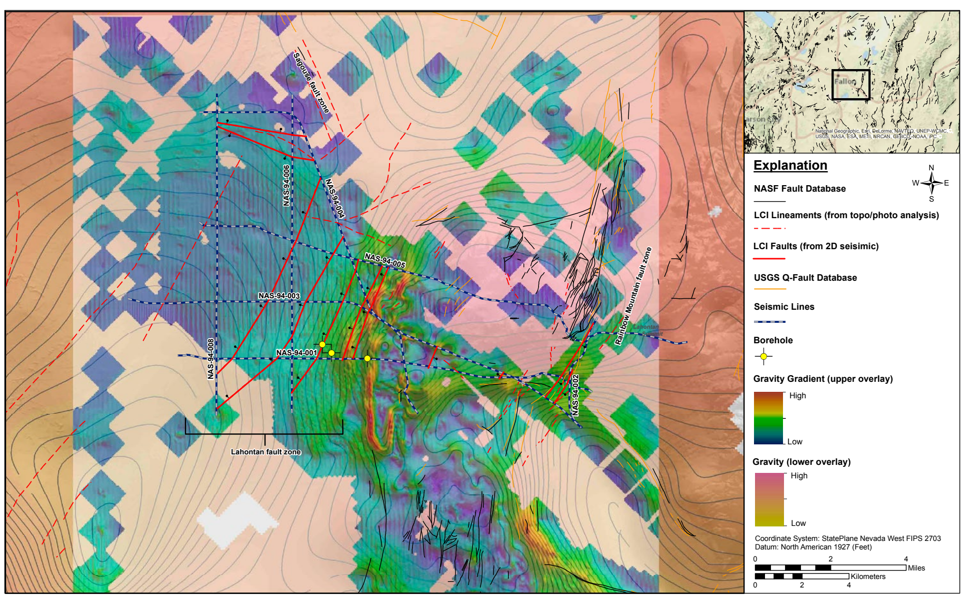

Figure 4. Gravity map with lineaments and subsurface faults from this study and faults compiled from NBMG geologic maps and the USGS Quaternary fault and fold database. Faults projected in subsurface to 3500′ elevation. Lower (contoured) gravity map showing gravity highs (pink) and low (yellows). Upper (blue to red) map showing gravity gradient where gradient highs are indicated in red and gradient lows are indicated in blue.

mapping, and an array of broadly-spaced depth-migrated 2D seismic reflection profiles yields new insights into the location and style of Neogene faulting within and adjacent to the Lahontan Valley. Ultimately, these new observations may help guide further geothermal resource exploration efforts in the region.

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