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Structural Analysis of Southern Dixie Valley using LiDAR and Low-Sun-Angle Aerial Photography, NAS Fallon Geothermal Exploration Project, Dixie Valley, Nevada

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ABSTRACT

The goal of this study is to map and characterize Quaternary faults in southern Dixie Valley for the Department of the Navy Geothermal Program Office's NAS Fallon Geothermal Exploration Project. We will use this information to better characterize the regional structure and geothermal resource potential of the area, with a focus on determining the structural controls for two known geothermal anomalies. Previous structural investigations at other geothermal sites in Nevada have shown that Quaternary faults provide the best potential for geothermal fluid flow. Information on the structural characteristics, such as slip sense and relative age, will be synthesized into a structural kinematic model. The resulting structural kinematic model will help us identify the slip and dilation tendencies of the faults in southern Dixie Valley. This model will allow a better understanding of what faults control these two geothermal anomalies and aid in exploration and selection of drilling targets.

In order to detect and characterize young faults, high resolution LiDAR and 1:12,000-scale low-sun-angle (LSA) aerial photography was acquired for the NAS Fallon study area. The LSA photos were flown during early morning, when the sun angle ranged between 10-25°. Slopeshades and hillshades using low sun angles (25-45°) were generated using LiDAR for fault detection. Elevation change and tonal lineaments were used to define possible faults in both the LiDAR and LSA photo data sets.

The LiDAR and LSA photo analysis has identified a large number of previously unmapped faults. Field investigations will determine slip sense and age of these newly mapped faults. Preliminary structural analysis using the newly mapped faults, in conjunction with shallow 2-meter temperature surveys, suggests that the two known geothermal temperature anomalies occur in complex structural settings. A possible 3rd low temperature anomaly was also detected, but will require further investigation.

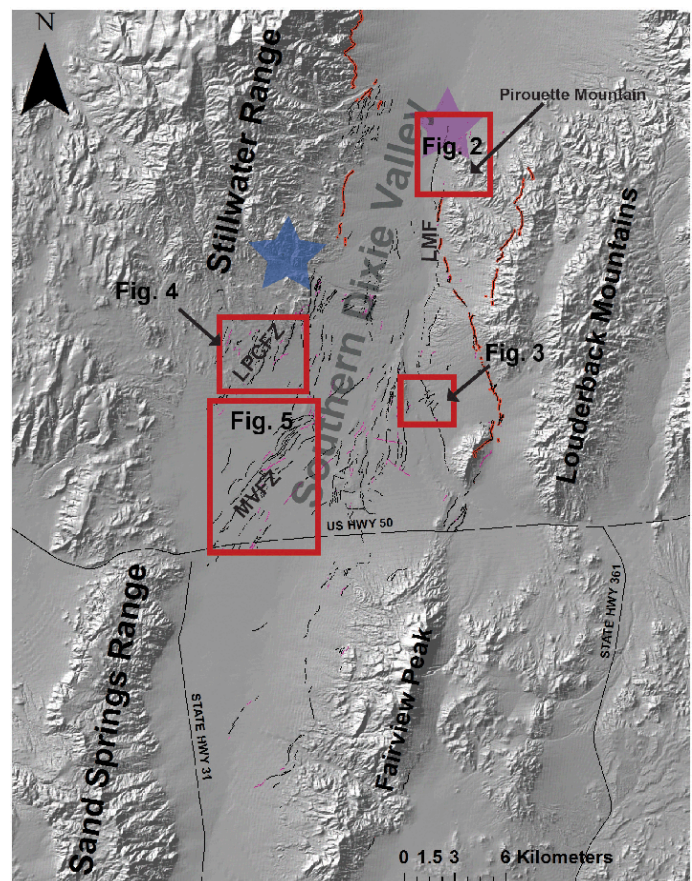


Figure 1. Location map of the general project area in southern Dixie Valley. Only Quaternary fault traces have been mapped. Solid black lines represent well located faults, dashed black lines represent approximately located faults, and dotted black lines represent faults that are inferred. Lines highlighted in red are faults that experienced 1954 rupture (Caskey et al., 1996). Pink dashed lines indicate lineaments seen in aerial photography and LiDAR. LMF: Louderback Mountains Fault. LPCFZ: La Plata Canyon Fault Zone. MVFZ: Mid-Valley Fault Zone. The red star represents the approximate location of the Pirouette Mountain geothermal anomaly. The orange star represents the approximate location of the Elevenmile Canyon geothermal anomaly. Red numbered rectangles indicate areas of subsequent figures.

Introduction

The study area is located in southern Dixie Valley (Figure 1), which is 64 km south of the Dixie Valley geothermal power plant. The Dixie Valley geothermal power plant utilizes the hottest known geothermal system in Nevada (285°C at 3 km) (Blackwell et al., 2009). The Department of the Navy Geothermal Program Office's NAS Fallon Geothermal Project is evaluating geothermal resource potential in the southern part of the valley.

Although northern Dixie Valley has been termed a west-tilted half graben (Okaya and Thompson, 1985), the project area is bounded by active faults on both the east and west sides. Southern Dixie Valley (Figure 1) is bounded to the west by the northeast-trending, down-to-the-east Stillwater and Sand Springs range front faults. It is bounded to the east by the north-trending, down-to-the-west Louderback fault.

The project area experienced surface rupture during the December 16, 1954 Fairview Peak-Dixie Valley earthquakes (Figure 1; Caskey, 1996). The Fairview Peak (M_s 7.2) event was followed 4 minutes and 20 seconds later by the Dixie Valley (M_s 6.8) event. Caskey et al. (1996) described the surface rupture along the Louderback Mountains fault. Approximately 1-1.5 m of offset was recorded on the Louderback Mountains fault, and based on offset stream channels the faulting was right-oblique. Kinematic models of the 1954 surface ruptures associate the rupture along the Louderback Mountains fault with the Fairview Peak event (Caskey et al., 1996).

Preliminary field reconnaissance and analysis of existing geologic mapping suggests that there is no surface expression related to recent geothermal activity in the study area, i.e. no hot springs, sinter or travertine deposits, or hydrothermal alteration (John, 1993; John and Silberling, 1994; John, 1995; John, 1997). Alteration related to Mesozoic plutonism and Tertiary volcanism is present throughout southern Dixie Valley, but plutonism and volcanism ceased by middle Miocene (John and Silberling, 1994).

Two potential geothermal resources in the project area have been identified based on existing temperature gradient well data: Elevenmile Canyon and Pirouette Mountain (Figure 1; Blackwell et al., 2009; Mankhemthong et al., 2008). Our goal is to characterize the age, slip-sense, and orientation of the structures within these two geothermal systems. These data will be used to create a conceptual structural-kinematic model of southern Dixie Valley.

Methods

A spatial relationship between Quaternary faults and potential geothermal resources has been recognized in previous studies in Nevada (Bell and Ramelli, 2009). We have created a detailed preliminary Quaternary fault map of southern Dixie Valley to better understand the spatial relationship between Quaternary faulting and the geothermal anomalies in the project area (Figure 1). In addition to fault detection using the remote sensing techniques that are the focus of this paper, creation of the fault map also involved digitization of an historic fault rupture map (Caskey, 1996) using ArcGIS software. Information on the structural characteristics of the Quaternary faults, such as slip sense and relative age, will be synthesized into a conceptual structural-kinematic model of southern Dixie Valley. The resulting kinematic model will help us

identify the slip and dilation tendencies of the faults in the study area, most importantly those within the two geothermal anomalies.

In order to detect and characterize Quaternary faults, high resolution LiDAR and large-scale low-sun-angle (LSA) aerial photography were acquired for the NAS Fallon study area. The LiDAR and LSA photo acquisitions were funded by the Department of the Navy Geothermal Program Office. LiDAR was acquired at a point resolution of 8.6 points/m², providing a vertical accuracy of 3.7 cm/m².

The LiDAR analysis involved processing various iterations of bare-earth slopeshades and hillshades of the area. We used elevation change and tonal variation to delineate potential fault scarps and other areas of interest to be investigated in the field. Preliminary hillshade analysis has shown that the best sun azimuths for fault detection are those that provide light oblique to the orientation of a fault. The best sun angles have been low, approximately 20-45°, mimicking either early morning or late afternoon sunlight.

Low-sun-angle aerial photography was flown at 1:12,000 scale under early morning sun conditions, with sun angles ranging between approximately 10-25°. The low-sun-angle methodology, like LiDAR, is useful for detecting small amounts of offset on young fault scarps and is considered a complementary tool. The newly acquired LSA aerial photos together with existing LSA photography were used to define tonal lineaments and vegetation that could not be detected as well in the LiDAR data set. Preliminary analysis of this data set has shown that LiDAR illuminates features that do not appear in the LSA aerial photos. Conversely, LSA aerial photos allow identification of cultural features that may appear to be faults on the LiDAR. Based on this information, the combination of these two techniques provide a more thorough structural investigation.

Results

Preliminary Quaternary fault mapping has shown that southern Dixie Valley is dominated by several structural zones: the Louderback Mountains fault (LMF), the La Plata Canyon fault zone (LPCFZ), and the Mid-Valley fault zone (MVFZ). Four areas illustrate the principal Quaternary faults detected in these structural zones using the LSA photos and LiDAR data set (Figure 1). These areas are likely the primary structural components for the kinematic fault model that may explain the occurrence of the geothermal anomalies.

Louderback Mountains Fault

The Louderback Mountains fault (LMF) bounds the western side of the Louderback Mountains and the eastern side of southern Dixie Valley. At the northern end of the LMF, near Pirouette Mountain, there is one main fault that has been identified (Figure 2). This fault trends approximately due north and is down-to-the-west. Preliminary LiDAR and LSA photo analysis have detected normal motion along this fault; however, the southern portion of the LMF ruptured in 1954, and right-oblique motion was recorded (Caskey et al., 1996). A trench study has been planned for the northern segment of the fault in Figure 2 for summer 2011 to better constrain the age and slip sense for the northern portion of the Louderback Mountains fault.

Shallow 2-meter temperature surveys were performed in this area by Skord et al. (2011) during late summer and fall of 2010. The highest shallow temperatures in the study area were recorded at the north end of the LMF, in the area of the Pirouette Mountain geothermal anomaly (Figure 1; Figure 2). Previous authors have extended this anomaly farther to the north and west of the termination of the LMF (Blackwell et al., 2009; Mankhemthong et al., 2008), but these elevated temperatures at depth are also being reflected at shallow depth near and directly west of the LMF trace.

At the southern end of the LMF, we detected fault sets of two different orientations on the LiDAR: due north and NNE (Figure 3). Based on the crisp tone and sharpness of the lineaments in contrast with other faults and lineaments in the project area, we interpret the NE trending faults that cross-cut the more prominent N-S trending fault in Figure 3 to be possible unmapped surface ruptures from the 1954 Fairview Peak event. These features trend more towards the east and are southwest of the ruptures associated with the 1954 sequence (Figure 1). The faults appear to have experienced only normal slip; no dextral motion was detected with the LiDAR on these faults. Preliminary field investigations suggest that these faults are likely associated with the 1954 Fairview Peak event.

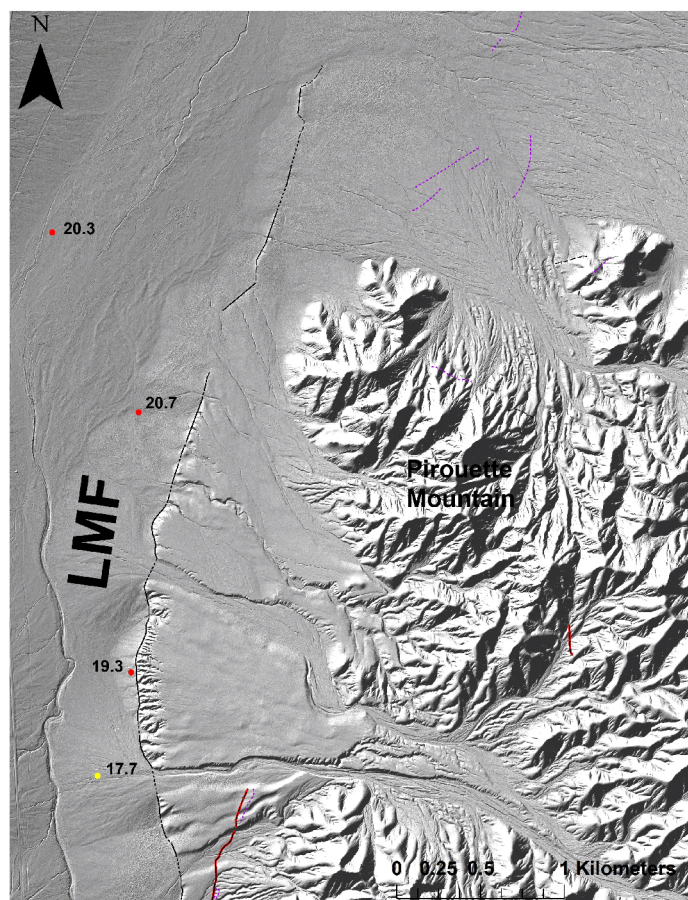


Figure 2. LiDAR image of the Pirouette Mountain area, at the north end of the Louderbuck Mountains fault (LMF). Red, orange, and yellow points indicate places where shallow 2-meter temperature surveys were performed by Skord et al. (2011). Temperatures in degrees Celsius are next to the points. Background 2-meter shallow temperature: $\sim 17^{\circ}\text{C}$. See Figure 1 for location.

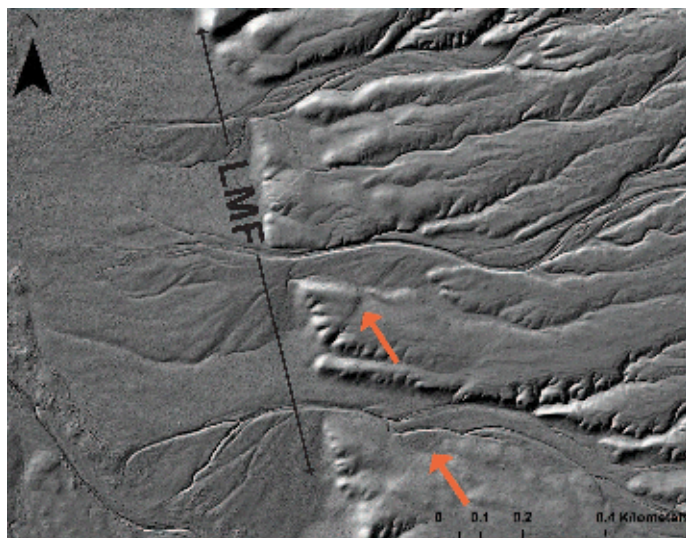


Figure 3. LiDAR image of the southern end of the Louderbuck Mountains fault (LMF). Orange arrows are pointing to NE trending faults which cross-cut the more prominent N-S trending fault. These ruptures are likely associated with the 1954 event. See Figure 1 for location.

La Plata Canyon Fault Zone

The LPCFZ is located in the southern Stillwater Range, at the mouth of La Plata Canyon (Figure 4). The faults at the mouth of La Plata Canyon trend approximately NNE and are down-to-the-east. The faults that are approximately 2 km to the WSW of the mouth of the canyon also trend NNE, but are down-to-the-west. These two fault sets appear to form graben-in-graben structures at the mouth of La Plata Canyon. Previous trench studies across a fault segment in La Plata Canyon indicated that the Quaternary motion along these faults has likely been only dip-slip, and that the most recent slip occurred during late Holocene time (Bell et al., 2004).

The LPCFZ is located approximately 6 km south-southwest of the Elevenmile Canyon geothermal anomaly. A 2-meter temperature survey was performed in La Plata Canyon during the same time as the survey in the Pirouette Mountain area (Figure 2). No 2-meter temperature anomalies were anticipated in this area prior to survey, but a low-temperature anomaly was recorded (Figure 4). Further temperature surveys in the LPCFZ will be performed summer in 2011, closer to the faults to see if hotter shallow temperatures occur. If hotter temperatures do occur, further field work will be required to determine whether this is related to the geothermal anomaly to the north, or a new, previously unidentified system that may separately be related to the La Plata Canyon faults.

Mid-Valley Fault Zone

The faults in the MVFZ were mostly undetected prior to the LiDAR acquisition (Figure 5). These mid-valley structures trend approximately N45E, oblique to the general northerly trend of the Stillwater, Sand Springs, and Louderbuck Mountains faults. Upon preliminary analysis using only the LiDAR, the faults appear to exhibit only normal motion, with either NW or SE dip directions. Based on apparent dip direction inferred from the LiDAR, these structures appear to form a series of complex nested graben. The faults are oriented approximately perpendicular to the $\sim\text{N60W}$

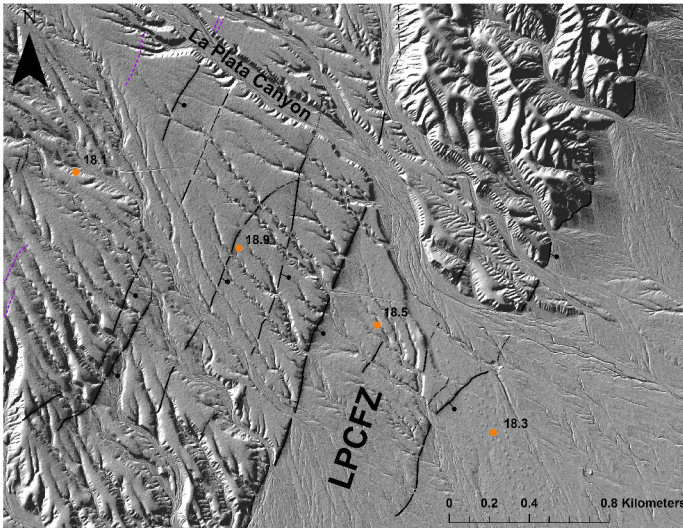
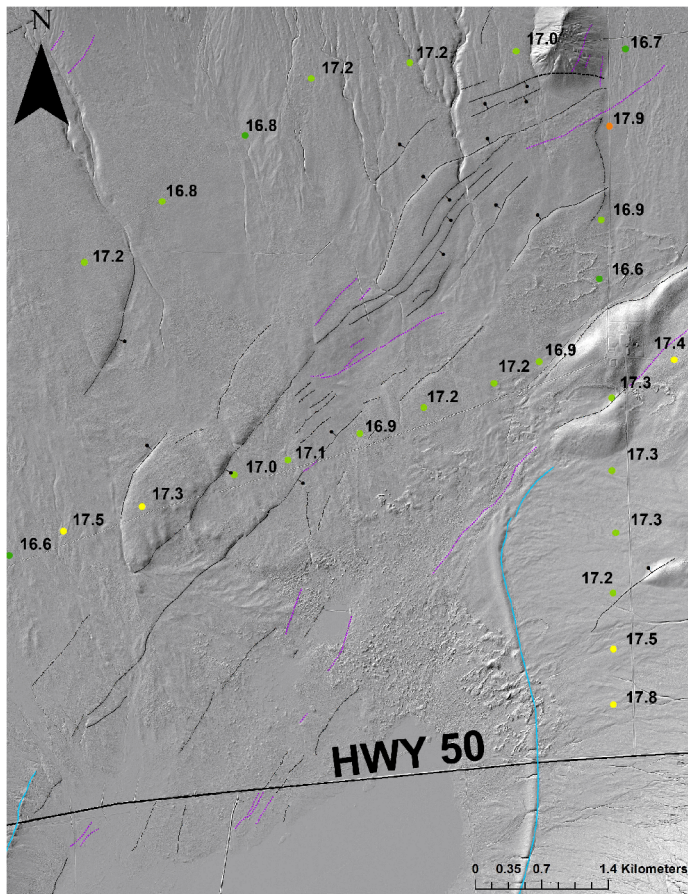


Figure 4. LiDAR image of NNE trending faults within the La Plata Canyon Fault Zone (LPCFZ). Bar and ball on downthrown side of fault. Red, orange, and yellow points indicate places where shallow 2-meter temperature surveys were performed by Skord et al. (2011). Temperatures in degrees Celsius are next to the points. Background 2-meter shallow temperature: ~17°C. See Figure 1 for location.

Basin and Range extension direction (Hammond and Thatcher, 2007); although this is a favorable orientation for fault extension, the shallow 2-m temperatures are not significantly elevated (Figure 5). Based on this relationship, these faults could be some of the



youngest prehistorical structures in the study area. Based on fault orientation alone, these faults do not appear to fall into the Sand Springs, Stillwater, or Louderback fault systems, but they may be kinematically linked and further field analysis is underway to determine this.

Preliminary Structural Models

Pathways for upward migration of geothermal fluids are largely dependent upon the slip and dilation tendencies of the faults, with dilation being considered one of the most important factors (Moeck et al., 2010). Slip and dilation tendencies are dependent upon fault orientation and geometry within the present stress field. Understanding the structural kinematic motion of these faults is key to developing a conceptual exploration model. Some previous studies have shown that geothermal systems in the Basin and Range often occur at fault terminations or in fault step-over (releasing bend) zones (Faulds et al., 2006). This is likely due to the enhanced permeability created by these structural features. While one or both of these models may apply to the two anomalies within the project area, it is important to note that there are multiple kinematic models which could create fault dilation. The structural zones in southern Dixie Valley may be linked, meaning that movement on one fault, or within one fault zone, may create dilation on another set of adjacent faults.

The Pirouette Mountain geothermal anomaly appears to occur near the termination of the LMF. LiDAR and LSA photo analysis shows no other faults in the area of the Pirouette Mountain anomaly, only the N-S trending, down-to-the-west fault trace seen in Figure 2. However, it is possible that a continuation of the LMF is concealed beneath alluvium to the north. It is poorly understood why the Pirouette Mountain anomaly, if it is related to the N-S trending LMF, occurs where it does, because the LMF is not optimally oriented for dilation in the current N60W stress regime.

The faults in La Plata Canyon may comprise a structural step-over between the Sand Springs and Stillwater range front fault systems. Based on the Faulds and Varga (1998) model, the Sand Springs and Stillwater range front faults may be connected by a right-stepping accommodation (releasing bend) zone within the La Plata Canyon area. At the same time, the La Plata Canyon faults in the step-over strike north towards the Elevenmile Canyon thermal anomaly, suggesting that the anomaly may also be related to the La Plata Canyon fault. However, these structural relations are presently being studied, and it is not clear whether or not the LPCFZ and the Elevenmile Canyon anomaly are genetically related.

As noted, faults within the MVFZ are preferentially oriented for dilation, as they are roughly perpendicular to the N60W Basin and Range extension direction (Hammond and Thatcher, 2007), but no shallow temperature anomalies have been recorded by Skord et al. (2011). Preliminary analysis of this fault zone sug-

Figure 5. LiDAR image of NE-trending faults in the Mid-Valley Fault Zone (MVFZ). Blue line represents a possible shoreline. Bar and ball on downthrown side of fault. Red, orange, and yellow points indicate places where shallow 2-meter temperature surveys were performed by Skord et al. (2011). Temperatures in degrees Celsius are next to the points. Background 2-meter shallow temperature: ~17°C. See Figure 1 for location.

gests that it contains numerous young (Holocene-age) faults that may structurally link the northern end of the Sand Springs fault zone with the Louderback Mountain fault zone. This includes some possible 1954 rupture traces that lie near the northern end of the Sand Springs Range and also cross-cut the Louderback Mountains fault (Figure 3). Such complex structural relations may play an overall role in the occurrence of geothermal potential in southern Dixie Valley and will be the basis for the development of a conceptual exploration model.

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