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Geologic and Geophysical Evidence for Intra-basin and Footwall Faulting at Dixie Valley, Nevada

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Abstract
A "nested graben" structural model, in which multiple faults successively displace rocks downward to the deepest part of the basin, is supported by recent field geologic analysis and correlation of results to geophysical data for Dixie Valley. Aerial photographic analysis and detailed field mapping provide strong evidence for a deep graben separated from the ranges to the east and west by multiple normal faults that affect the Tertiary/Quaternary basin-fill sediments. Correlation with seismic reflection and gravity surveys shows that some faults recognized by minor displacements at the surface produce significant stratigraphic offsets at depth in basin-fill sediments and help to explain gravity gradients displaced basin-ward from the range-front. The concept of a complex series of faults (both synthetic and antithetic) separating the Stillwater Range from Dixie Valley allows for the possibility that the geothermal circulation encompasses multiple faults both inboard and outboard of the range-front fault. This geometry increases the exploration potential of the area by providing additional possibilities for fault-controlled permeability and larger volumes of permeable rocks.

Introduction and Methods
Geologic evidence for intra-basin and footwall faulting in Dixie Valley was examined by aerial photograph analysis and field mapping in 2000, following development of geophysical information suggesting that the "single range-front fault" model does not adequately describe the producing geothermal reservoir (Blackwell et al., 1999, 2000; also, see the summary of different models in Benoit, 1999). The purpose of this field re-examination was to develop a geologic map of recognized fault features in the region surrounding the geothermal reservoir (Figure 1), and to merge the field observations with available geophysical data and borehole information.

The methods for this study consisted of the following steps:

1. Review of the published literature on the structural geology and tectonics of the Dixie Valley area. This review revealed that several investigators in the past have presented evidence for and interpretations of a stepwise downward displacement of the valley along multiple faults that underlie and affect the valley-fill sediments (Thompson et al., 1967; Whitney, 1980; Wallace and Whitney, 1984).
2. Standard field mapping techniques were used in the area surrounding the geothermal reservoir. In this area, a series of available seismic reflection lines and detailed gravity surveys provide an independent basis on which to evaluate field mapping results (Figure 1). A set of false-color, infrared aerial photographs, which provided stereoscopic coverage of the area of Figure 1 at a scale of 1:24,000, were examined for evidence of faulting. It was found that surface displacements of greater than about half a meter were recognizable, and that

lineaments associated with faulting were easily recognized. Springs were readily identified by vegetation. All features indicative of faulting were transferred to 1:24,000 topographic maps of the area. These maps served as base maps for the field mapping effort in which recognized scarps and lineaments were examined. Initial aerial photographic interpretations were verified or modified by the field observations, and surface displacements measured where possible.

3. Examination of seismic reflection sections to identify offsets and folding of reflectors for correlation with structural features identified in the field mapping effort.
4. Acquisition of gravity data in the area and construction of a gravity contour map for correlation with structural features identified in the field mapping effort.

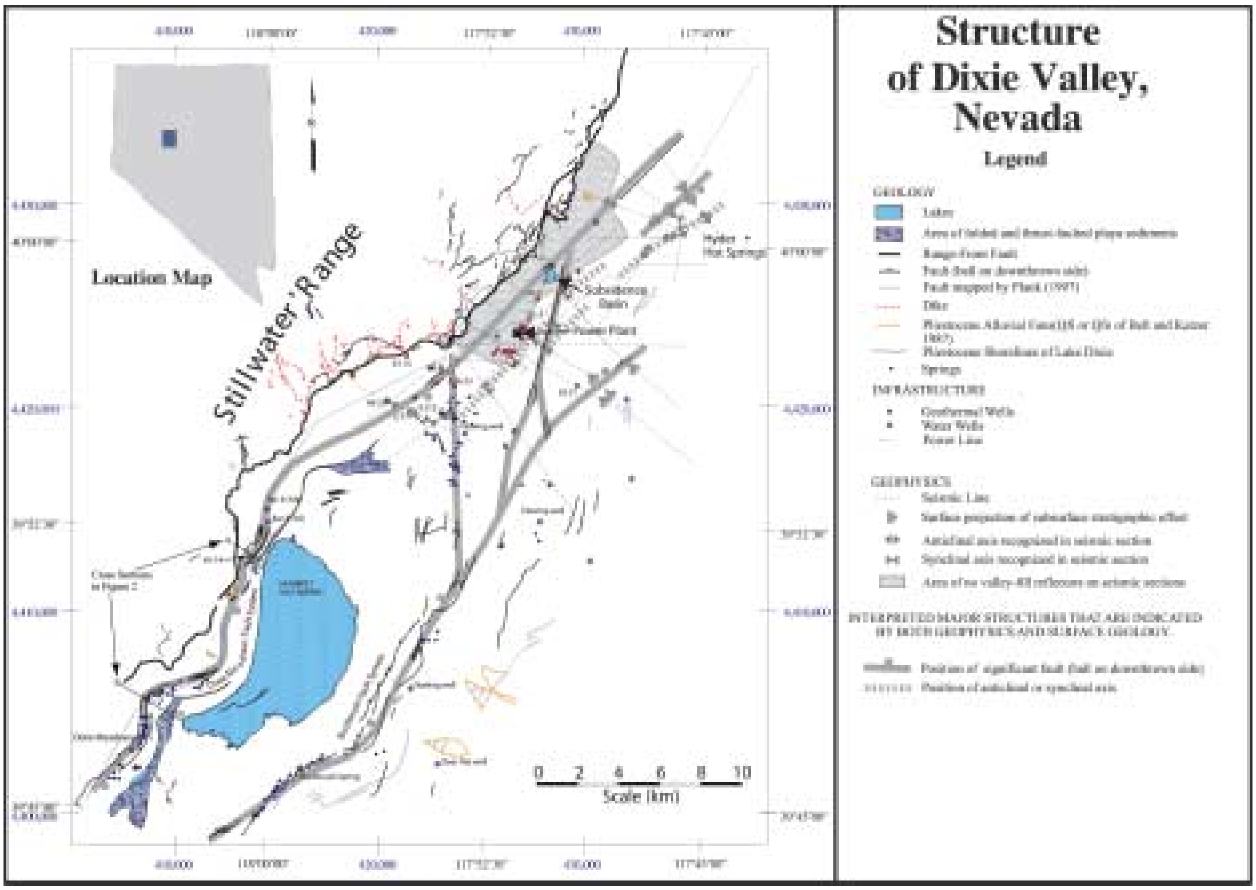

Figure 1. Map of Dixie Valley showing mapped features related to faulting and subsurface structures recognized from geophysical surveys.

Intra-Basin Faults

Intra-basin faults are recognized by scarps with up to a meter of surface displacement, fissures, graben, linear arrangements of springs, and lineaments (both tonal and vegetation alignments) in basin-fill sediments. The Buckbrush fault, in the eastern side of the basin (Figure 1) exhibits down-to-the-west displacement and may have two branches that curve into the range-front fault in the vicinity of the geothermal power plant. Synthetic (down-to-the-east) faults occur in the Dixie Hot Springs area and affect both alluvial fans from the range front and playa sediments of the salt marsh. In some areas, alluvial fan deposits on the hanging wall of the faults have slid basin-ward on fine-grained water-saturated playa sediments, forming wide graben systems where they pull away from the fault scarp and belts of folded and thrust-faulted playa sediments ahead of the slide blocks (Figures 1 and 2). The numerous warm springs at the Dixie Hot Springs/Dixie Meadows area are localized by one of these pull-apart zones, and the playa sediments to the east are crumpled by the eastward movement of the toe of the alluvial fan.

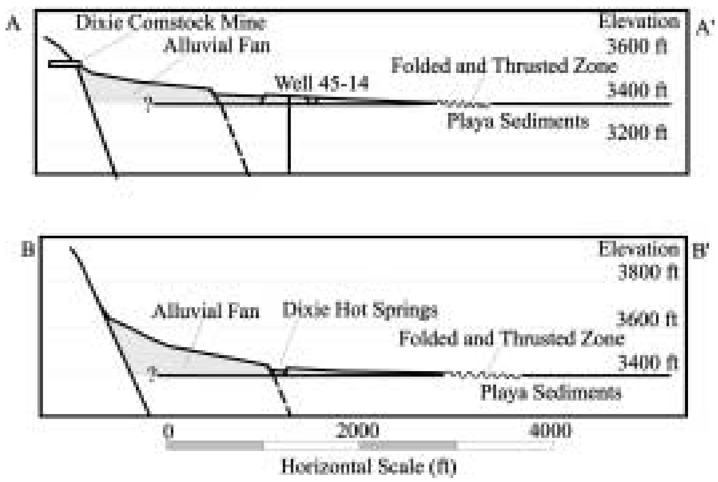

Figure 2. Cross sections of wide graben and folded playa sediments along the Dixie Meadows fault zone. See figure 1 for locations of cross sections.

Springs in Dixie Valley

Springs along the Buckbrush fault system bring cold, fresh water from artesian aquifers at depth to the surface. As indicated by driller's logs of wells in the map area and in the settlement of Dixie, just south of the map area, those artesian aquifers are layers of gravel and sand beneath clay-rich playa sediments (hardpan) at depths of 100 to 400 feet below the surface. The fault system cuts through these aquifers and provides permeable channels of disrupted materials along the fault surfaces for water to move to the surface. In several places along the Buckbrush system, inactive springs characterized by dead vegetation (grass, shrubs, saplings) occur. This suggests that plumbing systems for the springs are ephemeral and become sealed with time, and that repeated displacements on the fault system are required to maintain active springs. Some of the inactive springs may have been abandoned during the 1954 earthquakes, as new fault movements rearranged passageways. A likely mechanism for sealing of permeable passageways in these springs is plastic deformation of clay-rich playa and lake sediments.

Springs in the Dixie Meadows area, on the west side of the valley (Figure 1) are hot or warm springs, and probably tap geothermal waters moving up the Dixie Meadows fault system directly beneath. The maintenance of plumbing systems for these springs also require repeated fault movements, but in this case because of sealing of fractures by hydrothermal mineralization from the ascending hot waters. These springs may have been affected by 1954 ground motion and minor fault displacements, and were probably rejuvenated, or perhaps even initiated, by the pre-1954 earthquake event (the Bend Event). That event has been bracketed in age between 1.5 and 6.86ka by paleoseismic studies along the southern part of the Dixie Valley fault (Caskey et al., 2000). The mid- to late-Holocene age of this event is probably also responsible for rejuvenation of permeability and hydrothermal fluid transport in the producing geothermal reservoir and at several fumaroles along the range-front fault between Dixie Hot Springs and the north end of the Dixie Valley.

Footwall Faults and Mafic Dikes

Southeast-dipping faults with dip-slip slickensides occur in the bedrock of the Stillwater Range several kilometers behind the range-front. Some of these were mapped in the power plant area by Plank (1997). A large southeast-dipping fault south of the power plant area curves southwestward from drill hole 53-15, forming a large spoon-shaped sliver behind the range-front fault (Figure 1). It may represent an abandoned segment of the fault system as the range-front fault moved basin-ward in Late Tertiary or Quaternary time, or a relay ramp structure between two segments of the fault. This fault has not accumulated significant displacement because little or no offset of mafic dikes (Figure 1) is discernable where they are cut by the fault.

Mafic dikes were mapped in the footwall to provide displacement and age control for faults occurring there. We hoped to find a suite of late Tertiary dikes that may have served as feeders for the Miocene basalts that cap the Stillwater Range and floor the valley-fill sediments in the basin. Such a suite of dikes would have allowed easy distinction between late Tertiary extensional faults and older faults unrelated to Basin and Range extension. However, the only young dikes found were the two in Little Cottonwood Creek, just west of the power plant, that were mapped and dated by Plank (1997). All the others shown on Figure 1 are older dikes, emplaced in Mesozoic or early Tertiary time during or shortly after formation of the country rocks. They show, as indicated above, that the footwall fault south of the power plant has not accumulated significant displacement, but do not provide much age information for the faulting.

Seismic Reflection Lines

Seismic reflection lines (Figure 1) were examined to locate stratigraphic offsets (offsets of reflectors) in the valley-fill sediments. Faults were inferred in places where offsets were unambiguous, and projected to the surface. The surface projections of those faults are shown in Figure 1, and in several areas correspond to faults identified at the surface by surface mapping. The positions of anticlinal and synclinal axes recognized in the seismic sections are also indicated in Figure 1.

Gravity Surveys

Gravity data provides a useful constraint on the subsurface structure in Dixie Valley. A detailed gravity study of the valley was conducted in 1996 (Blackwell et al., 1999) and extended in 2000 to a total of nearly 1000 points. The resultant data were merged with regional gravity data to produce a Bouguer Gravity map for the Dixie Valley area (Figure 3); the surface faulting and generalized interpretations of major structures are also plotted. The regions of strong gradients on the west side of the valley define the structural offset between the basement and valley fill. 2-D modeling of the gravity data (Blackwell et al., 1999) shows that along much of the valley, piedmont faults accommodate most of the displacement between the range-front and the valley bottom. These findings agree with those of Bell and Katzer (1987) for the southern section of the valley. In the area just northeast of “the Bend” the mapped trace of the fault diverges significantly from the position that would be interpreted from the gravity gradient – it is unclear weather this is due to structural complexity or to compositional (and density) variations in the footwall rocks. The gravity data suggests that along the whole of the western side of Dixie Valley, faults are steeply dipping.

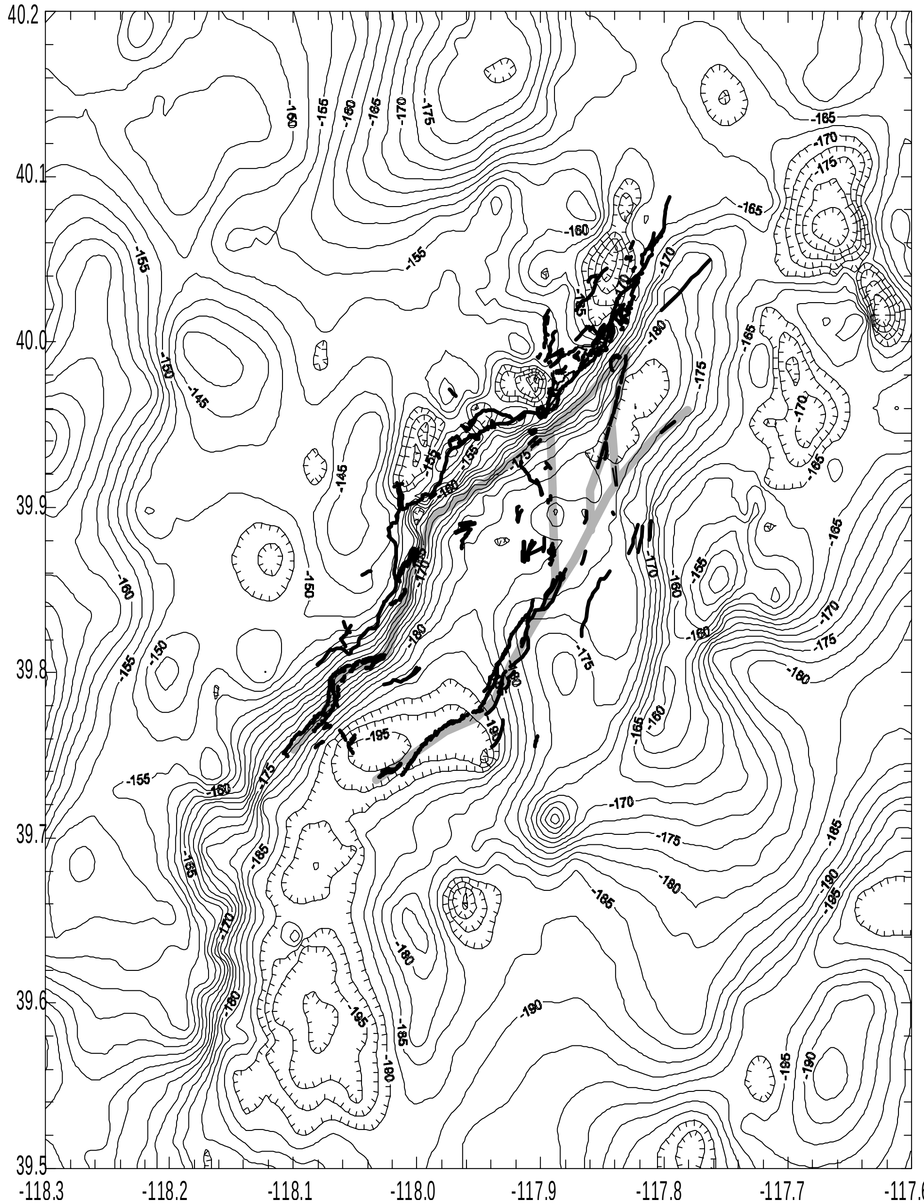

Figure 3. Gravity map of Dixie Valley with mapped faults in heavy solid lines, and inferred generalized fault systems in broad gray lines (from figure 1). Ground ruptures of the 1954 earthquake (from Caskey *et al.,* 1996) shown by dashed lines.

Structure in the eastern side of Dixie Valley is less clearly related to the gravity data. The trends of surface faulting correlate weakly with areas of gravity gradient. The gradients themselves are not as strong on the eastern side as would be expected for this highly asymmetrical valley. In places where the surface faulting cuts across the valley, there is some correlation with north trending gradients, but it is not clear whether the north trending high gradient areas are structural or compositional in origin.

Interpretations and Conclusions

Our best interpretation of locations of significant intra-basin faults are shown as broad gray lines in Figure 1. The Buckbrush and the Dixie Meadows fault zones appear to be continuous from the southern margin of Humboldt Salt Marsh to the power plant area, and to form a deeper graben within the topographic expression of Dixie Valley. Within this graben, several anticlinal and synclinal axes recognized in seismic sections, appear to have northeasterly trends in the power plant area (Figure 1). The fault pattern suggests that several faults intersect or closely interact with each other in the area of the producing reservoir. The intersection of the Dixie Meadows fault system with two or more north-trending branches from the Buckbrush fault system occurs in the area of the geothermal reservoir and in the area in which reflectors are absent in seismic reflection sections. Large volumes of fractured rocks at these fault intersections may help to explain both the location of the reservoir and the absence of seismic reflectors in the area.

Surface geologic mapping and geophysics support the concept of a complex series of synthetic and antithetic faults separating the Stillwater Range from Dixie Valley and allows for the possibility that the geothermal circulation encompasses multiple faults both inboard and outboard of the range-front fault. This geometry increases the exploration potential of the area by providing additional possibilities for fault-controlled permeability and for larger volumes of permeable rocks.

Future Work

Correlation of fault data from geologic mapping and geophysics with well logs (both lithologic and geophysical) with be the next step in this project. We hope to be able to make a more definite assessment of the fault(s) hosting the reservoir and to provide criteria for selection of new drill targets.

Acknowledgements

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Figure Captions

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