Structure of The Dixie Valley Geothermal System, a "Typical" Basin and Range Geothermal System, From Thermal and Gravity Data

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ABSTRACT

The Dixie Valley geothermal system, with temperatures up to 248°C in the Oxbow field and up to 285°C in the Dixie Valley Power Partners leasehold, is the hottest extensional (non-magmatic) geothermal system in the Basin and Range province. The structure of the Dixie Valley normal fault system and the role it plays in the associated geothermal system have been debated for some time. The primary structural model has been a single fault with 54° dip. New data including a detailed gravity survey, reprocessed seismic lines, and temperature-depth results from shallow and deep wells indicate a more complicated structure. In addition to the fault causing the topographic offset, piedmont (within the valley) faults accommodate most of the displacement between the range-valley topographic contact and the bottom of the valley fill. Splays and/or relay ramps are also present. This structure complicates development drilling, but suggests that additional targets for exploration may be present.

Introduction

The structure of Basin and Range faults and the manner in which that structure relates to geothermal systems has been subject of long and extended discussion as graphically illustrated by the history of models of the Dixie Valley geothermal field (Benoit, 1999). It is a typical Basin and Range system in the sense of the location, but has the highest temperatures (248°C Oxbow area, 285°C DVPP area) found in the province in a nonmagmatic system, and lies along one of the most active normal fault systems in the Basin and Range (Bell and Katzer, 1987; Caskey *et al.*, 1996). The Dixie Valley normal fault system is the contact of the Stillwater Range and Dixie Valley in Churchill and Pershing counties, western Nevada. In this paper we will discuss the structure of the range/valley contact as it relates to the geothermal system based on an analysis of a number of data sets.

The models of the range bounding fault in Dixie Valley span the gamut from low angle or listric (Plank, 1998; Plank *et al.*, 1999) to high angle (e.g. Okaya and Thompson, 1985). There are numerous published studies that argue both interpretations of the structure. However, in spite of abundant seismic reflection data and other information the details of the range bounding structures have been unclear. The model that has been used for most of the development of the geothermal system has been that of a range bounding fault dipping at 54° toward the basin (Benoit, 1999). This dip is based on the assumption that the fault encountered in the producing wells connects to the range/valley topographic contact (Figure 1). The wells are all at about the same distance from the range front and until recently there was little thermal or drilling information between the producing wells and the range front. As a result the dip of the structure associated with the production is constrained by drilling information only between depths of 2 and 3 km (6,000 and 10,000 ft).

In addition two wells were drilled by Dixie Valley Power Partners (DVPP) in 1993/94 in a block of sections to the south of the Oxbow field (diagonal rule pattern on Figure 1), 62A-23

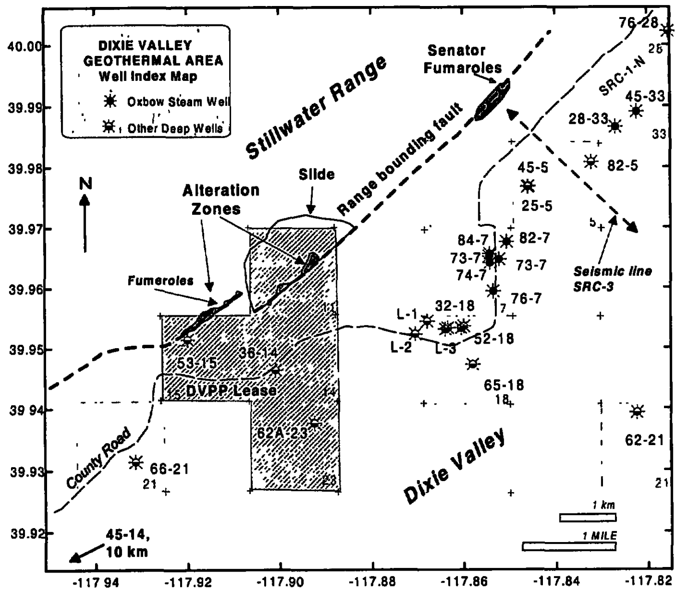

Figure 1. Index map of the Dixie Valley geothermal system.

and 36-14. Temperatures in 62A-23 reached 267°C (513°F), but no producible fractures were encountered while temperatures in 36-14 reached 285°C (545°F) and the well produced from fractures near the bottom. Even further to the south two hot deep wells were drilled (66-21 and 45-14) and have artesian flow, but were not commercial producers. Also there is geologic evidence for long-term and extensive high temperature fluid flow all along much of the Dixie Valley fault system (Parry *et al.*, 1991).

Also shown on Figure 1 is the inferred position of the range-bounding fault (at the edge of the topographic break between Dixie Valley and the Stillwater Range). In addition to that line, several subparallel high-angle normal faults were mapped within the bedrock of the range by Plank (1998). Several areas of active thermal manifestations are found along the range front such as the Senator fumaroles. Large areas along the range front may be covered by landslides. The geology of the Stillwater Range has been described by Speed (1976) and in more detail in the vicinity of the Oxbow field by Plank (1998).

Problems With The Single Fault Model

One of the "advantages" to the study of the structure of the range bounding fault in this area compared to other areas in the Basin and Range province is that there are a number of seismic profiles in the valley. These reflection profiles have been obtained by several different groups and there have been several publications related to presentation and interpretation of the results (UURI, 1981; Okaya and Thompson, 1985; Honjas *et al.*, 1997; Louie *et al.*, 1999). However, the seismic data have not been involved in the development of a geothermal model of the valley/range contact. The reflection technique is designed to image structures or beds that are flat lying or have a low dip in regions of low horizontal velocity contrasts. Thus, the steep nature of the range/valley contacts causes problems for reflection interpretation. Interpretation techniques, such as migration, that are designed to partially mitigate these short comings have become common since the data were collected in the early 1980s, but have not been applied to these old profiles until recently (e.g. Honjas *et al.*, 1998).

The seismic reflection interpretation most commonly cited (of SRC-3; Okaya and Thompson, 1985) is shown in Figure 2 and the location of the section is shown on Figure 1. The features of this interpretation that were emphasized were the 50° dip of the fault that bounds the Stillwater Range and the broken up reflections on the section southeast of the interpreted fault, attributed to disturbance of the signal by scattering in a coarse alluvial fan sequence along the downthrown edge of the fault.

One problem with this seismic interpretation became obvious from analysis of the thermal and drilling data from the deep wells. The seismic interpretation requires the section to be dominated by very coarse clastics that would be expected to be very permeable. The source of these coarse clastics was thought to be the rapid erosion of the uplifting Stillwater Range. During the drilling of the geothermal wells, lost circulation and drilling problems commonly associated with highly permeable formations are very rarely found in the valley fill section of the wells and fluid seems to be very limited below depths of 100 to 200 m. Finally the deep wells have not encountered much coarse alluvial material. Furthermore the limited thermal information above the reservoir suggests that conductive conditions dominate the heat transfer except within the production zone (implying insignificant fluid flow).

An explanation for the apparent low permeability of the valley fill near the active fault comes from the development of a new facies model for basin and range systems (Blackwell and Kelley, 1994). In this model (Leeder and Gawthrope, 1987) the active side of the valley, i.e. the one where the active normal faulting occurs, is the lowest part of the valley. Consequently the playa lake with its fine grained deposits is displaced toward the side of the valley that is actively subsiding instead of being centered in the basin and flanked on either side by alluvial fan

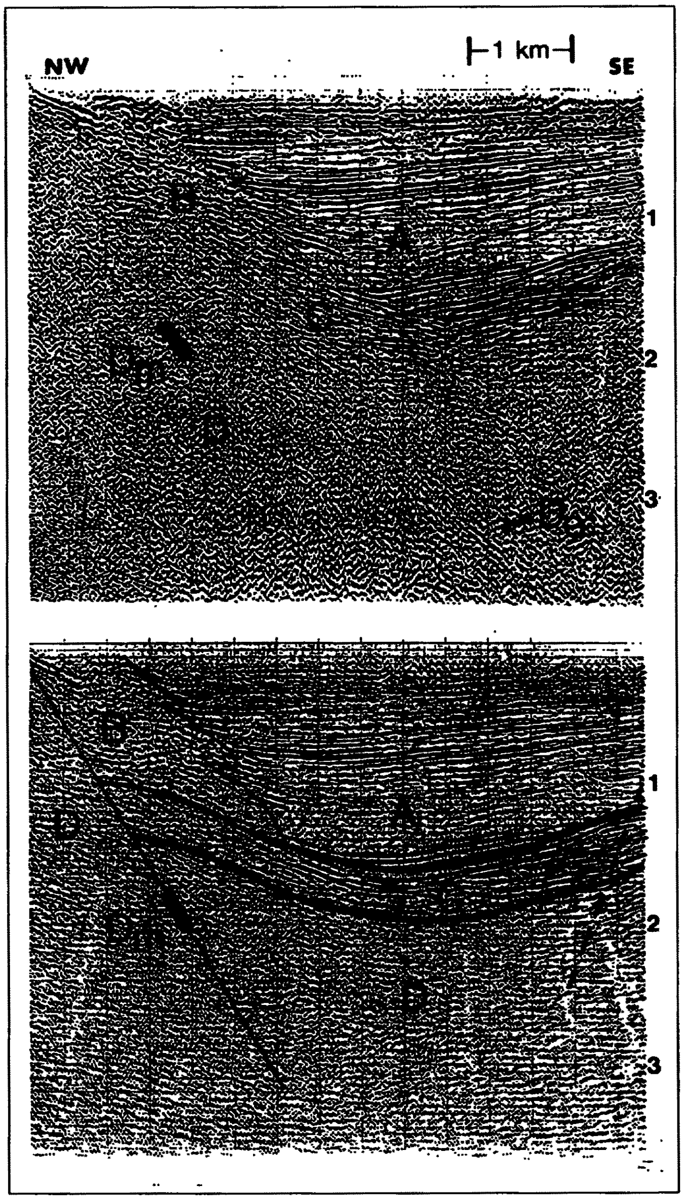

Figure 2. Seismic line SRC-3 as interpreted by Okaya and Thompson, (1985). Depth in seconds (two-way travel time).

material. When faulting slows down, alluvial fans build up the edges of the valley and push the playa toward the center of the valley. Near the site of the 45-14 well the playa is within a few hundred meters of the topographic break. This explanation of the thermal and drilling data leaves the seismic observations unexplained, however. Also any groundwater rich in Ca + Mg will deposit $CaCO_3$ + Mg silicates as it moves downward to hotter temperatures in the area of high temperature gradient.

Secondly, in 1993/1994 drilling by DVPP in sections 23 and 14 of T24N, R36E (Figure 1) demonstrated that the 54° model for the geothermal system could not be extended to the south of the Oxbow producing field. The two wells covered the possible extent of a southeast-dipping range-bounding fault with no evidence of a fault intersection below 1 km in either well although both well 62A-23 had a maximum temperature of 267°C (513°F), higher than any of the producing wells in the Oxbow field. The 36-14 well intersected productive fractures with 285°C (545°F) fluid at a position that constrains the dip of the fluid-bearing fractures to have a dip of 85 to 90° if the thermal source is the range front fault.

Thirdly, shallow drilling between the producing wells and the range front since 1994 has illustrated the existence of more upflow and shallow leakage of hot fluid into the valley fill then had been previously recognized. Areas of high temperature leakage and areas of lateral flow into the valley have been recognized. Mineralization has been found to be associated with one part of the leakage (Johnson *et al.*, 1999).

Although the Oxbow wells are about the same distance from the range front, they do not imply a uniform flow along the fault. The reservoir production model, based on well interference data, shows a series of heterogeneous connections within the "reservoir" (Benoit, 1999, Figure 9). There are low-permeability wells north, between, and south of the two groups of producing wells. However, two of the wells in section 5 (25-5 and 45-5) are used as injectors as are some of the wells south of section 7, and connection to the reservoir has been proved by tracer testing (Rose *et al.*, 1998). The wells in sections 21, 22, 23, and 14 have artesian reservoir pressures in contrast to the initially underpressured conditions in the Oxbow field.

Gravity Study

A detailed gravity survey of the area was undertaken in the summer of 1996 (Blackwell and Wisian, 1997) in order to understand the drilling results from the DVPP area and because of the ambiguities in the interpretation of the seismic profiles. The objective of the survey was to locate the position and map the displacement of the main offset between the fill in Dixie Valley and the Stillwater Range in the vicinity of the geothermal field. A total of 225 stations were occupied with the elevations determined with differential GPS to better than 0.3 m. In addition duplicate site locations allowed merging of several existing gravity sets to develop a detailed gravity map of the area utilizing a total of over 600 stations.

The complete Bouguer gravity residual-anomaly map is shown in Figure 3. It shows typical values of -20 mgal in the valley and +10 mgal in the ranges. This map was used in the interpretation after a first-order regional trend was removed from the complete Bouguer gravity map. This regional trend in the Dixie Valley area is very similar to the one used for this part of Nevada by Saltus (1988). We made gravity measurements as close to the range as possible all along the survey area so the gravity anomaly right up to and just into the range is constrained by our data.

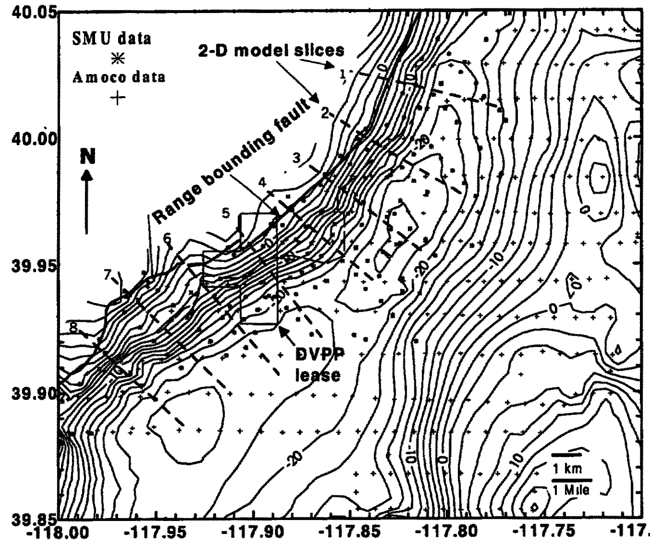

Figure 3. Complete Bouguer gravity residual-anomaly map and locations of sections in Figure 4. Gravity anomaly in mgal.

The detailed geometry of the contact between the Stillwater Range and Dixie Valley was investigated by calculating a series of closely spaced two-dimensional profiles perpendicular to the range-valley contact (Figure 4, overleaf). In addition the whole valley structure was investigated using a 3-D iterative solution. The 2-D models have higher resolution and were used to look at the details of the fault along the west side of Dixie Valley and are described here.

The 2-D sections show qualitatively the structure of the range/valley contact. The zero distance point of each cross section is the range/valley contact on the surface and the cross sections are numbered in order from the north to the south (see Figure 3). Also shown for reference are theoretical curves for single faults with dips of 45° and 54° from the surface contact of the range and valley and a single density contrast of -0.5 gm/cm^3. In most of the sections the observed gravity anomalies indicate that the faults that produce the major part of the anomaly, i.e. the location of the main density contrast, are displaced valleyward of the outcrop contact. The faults that are related to the topographic offset of the range and valley apparently often have little displacement of low-density valley fill against the basement.

There is a distinct change in the nature of the range/valley contact moving from north to south. Sections 2 and 3 in the north (Figure 4a) lie relatively close to the theoretical curves, #2 to the 54° line and #3 to the 45° line. The steepest gradients on lines #1 and #4 (Figure 4a) are displaced about 0.5 to 1 km toward the valley compared to the theoretical curves. The steepest changes in gravity anomaly on all four southern cross

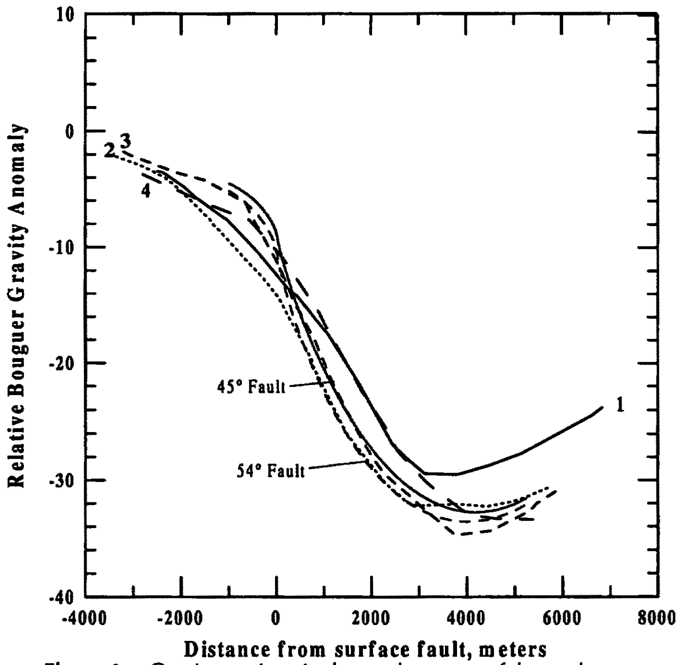

Figure 4a. Gravity sections in the northern part of the study area.

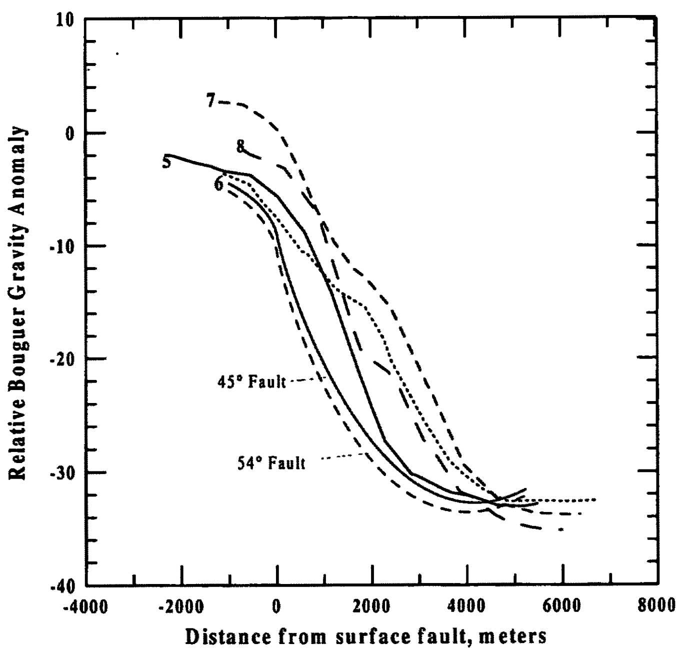

Figure 4b. Gravity sections in the southern part of the study area.

sections, are positioned at a distance of 1-2 km (5,000 to 7,000 ft) toward the valley compared to the theoretical curves. Thus the position of the major density contrast (fault?) causing the valley anomaly is displaced into the valley relative to the sections to the north. Thus the sections illustrate qualitatively the considerable variation of the position of the bedrock/valley fill contact from southwest to northeast along the contact of Dixie Valley and the Stillwater Range and the fact that along much of the distance the main displacement of the valley fill against bedrock is offset well toward the valley compared to a fault position at the range/valley topographic position (i.e. there are piedmont faults along much of the valley length). Normal faults which have a surface intercept in the valley are referred to as piedmont faults (see Bell and Katzner, 1987). These often have large displacement of the valley fill in contrast to the range bounding normal faults that appear to be responsible for most of the topographic displacement but little of the valley fill displacement.

In contrast to the complicated shape of the topographic expression of the basin-range contact the overall shape of the fault zone as expressed in the gravity gradient is relatively smooth and gently arcuate toward the northwest. The reentrant in the range between sections #7 and #8 at the south is not reflected in the larger scale shape of the valley bounding gravity gradient (Figure 3).

A perspective diagram of the range/valley contact with the valley fill removed is shown in Figure 5. The depths have been calculated based on a density contrast of -0.5 gm/cm^3 from profiles like those shown in Figure 4 and contoured. This density contrast was chosen as a best average based on comparison of predicted depths of fill to those observed from drilling and seismic data. These results show that the range/valley topographic break does not coincide with the position of the fault that represents most of the offset of the valley except in the north. At the north end of the producing field the valley offset and the edge of the range/valley contact most closely coincide. Indeed at the site of the northern production area (the wells in section 33) the valley/range contact is within 0.5 km of its topographic position. At the position of the producing wells in section 7, there is an offset of over 1.5 km and the fault causing the topographic offset cannot produce the valley fill offset. So the range bounding fault apparently splays into two main structures in or southwest of section 33.

To the southwest of section 7 there is a bend in the gravity contours and they become locally closer to the range front. In this area the lateral variation of the gravity field is of very high frequency indicating a steep structure. The drilling results from DVPP well 62A-23, located due south of the steepest part of the gravity gradient, indicate that the well did not penetrate a major normal fault. West of the DVPP area the gravity contours strike southwest while there is a reentrant in the range/valley contact so that again the fault responsible for the topographic offset is not the one that generates the offset of the valley fill. The geometry in this area is a ramp between piedmont faults to the north and to the south.

Discussion

The results of the gravity survey give a framework for understanding some of the complexity of the seismic reflection sections. The broken up area on the section shown in Figure 2 (Okaya and Thompson, 1985) is not valley fill at all, rather it is the expression of shallow fill on top of the basement wedge between the range offsetting fault and the valley offsetting piedmont fault. This inability to clearly image the structure in the vicinity of the fault zone is a common problem with all of the seismic sections. Recent reprocessing of several seismic lines

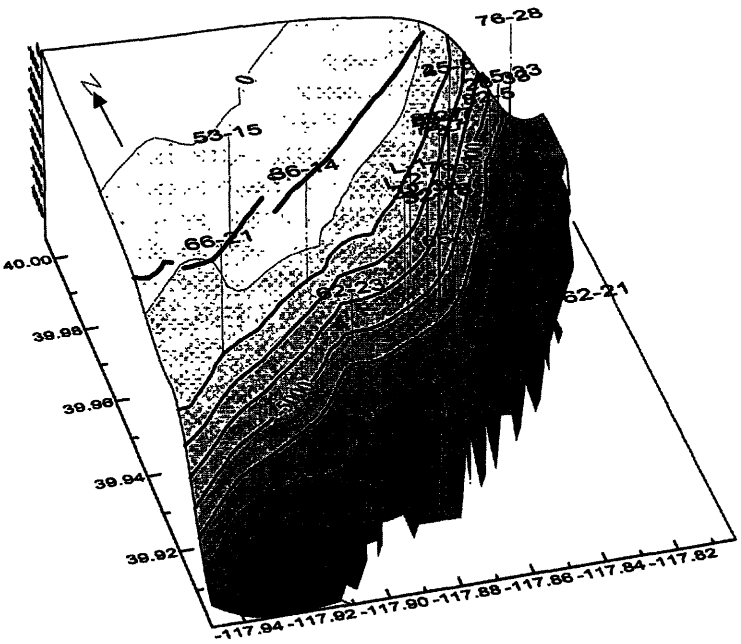

Figure 5. Perspective diagram of the range/valley contact with the valley fill removed. The depths have been calculated and contoured based on a density contrast of -0.5 gm/cm^3 from profiles like those shown in Figure 4. Well locations are also shown.

using migration techniques supports the idea that basement underlies the edge of the valley (Honjas *et al.*, 1998) as suggested by the gravity interpretation. The gravity together with the drilling data suggest that there are complex variations along the strike of the range/valley contact, and require that it be a series of faults rather than a single structure. For example, there are piedmont faults along most of the contact that take up much of the displacement between the range-valley topographic contact and the valley bottom similar to those documented at the southern end of Dixie Valley (Bell and Katzner, 1987, Figure 5). However, most of the topographic relief is due to a series of faults at the contact of the range and valley that in general have relatively little displacement of the valley fill. Finally the extension process is evident in the ubiquitous occurrence of antithetic faults forming grabens on the hanging wall (downthrown side) of the major faults. The gravity data do not resolve these smaller scale structures, but the drilling (Benoit, 1999) and the migrated seismic sections (Honjas *et al.*, 1998; Simtech, 1994) do.

Some implications of the geometry of the normal fault system for geothermal exploration are illustrated in Figure 6. Based on this model the fault system along the range front has several targets for drilling, not just one range-front fault. For example it implies that the Senator fumaroles are not directly updip on the production zone in section 33 since in this model any throughflow on the piedmont faults would be discharged into the valley fill. The discharge into the valley fill must happen for the zone feeding the wells in section 7 if there was any natural throughflow before production began. Pressure differences between the cold water in the basin and the hot geothermal fluids mean that there is probably little upflow on these faults. Similarly, the fumaroles in sections 14 and 10 are not updip on the main valley (piedmont) fault because its subcrop intercept at the base of the valley fill is several hundred meters into the valley.

The structure of the fault zone deduced here is by no means novel. For example, the structure of the fault zone in the area of the 1954 earthquake about 30 km to the south of the area described here is shown in Figure 7 based on studies of Bell and Katzner (1987). This section shows the features illustrated in Figure 6, the range bounding fault, the piedmont fault, and the antithetic graben. Thus, the features seen in the area of the geothermal field are similar to those to the south.

The pattern shown in Figure 6 is modified in three dimensions due to the change in strike of many of the faults. The major (piedmont) fault associated with the south end of the Oxbow field results from a bifurcation of a single range bounding fault in the area north of the Senator fumaroles. This piedmont fault dies out in the vicinity of the wells in section 18 T24S, R37E, southwest of the producing wells in section 7. Its displacement is taken up by the piedmont fault extending to the south in the DVPP lease area.

There is a fault plexus in the region of sections 10, 11, 14, and 15 where at least two normal faults mapped within the Stillwater Range (Plank, 1998), the range bounding fault, and two piedmont faults interact. This area is a source of upwelling fluid that is hotter than the fluid in the Oxbow producing area and so is an area of potential development. The complex

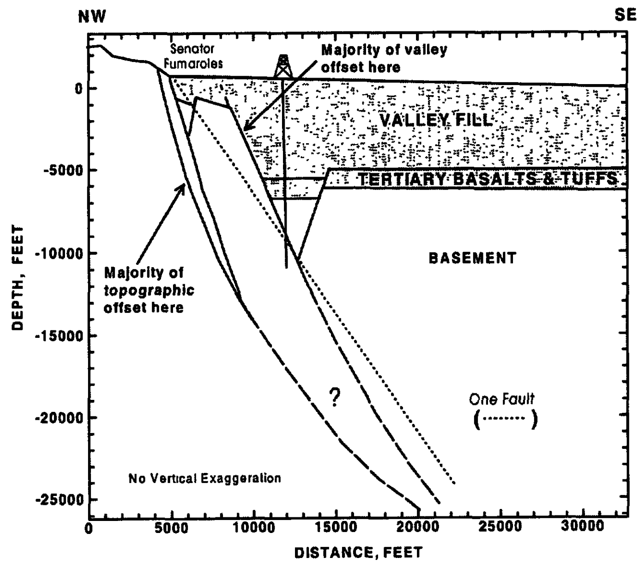

Figure 6. Fault splay model of the Dixie Valley/Stillwater Range bounding structure compared to the single fault model.

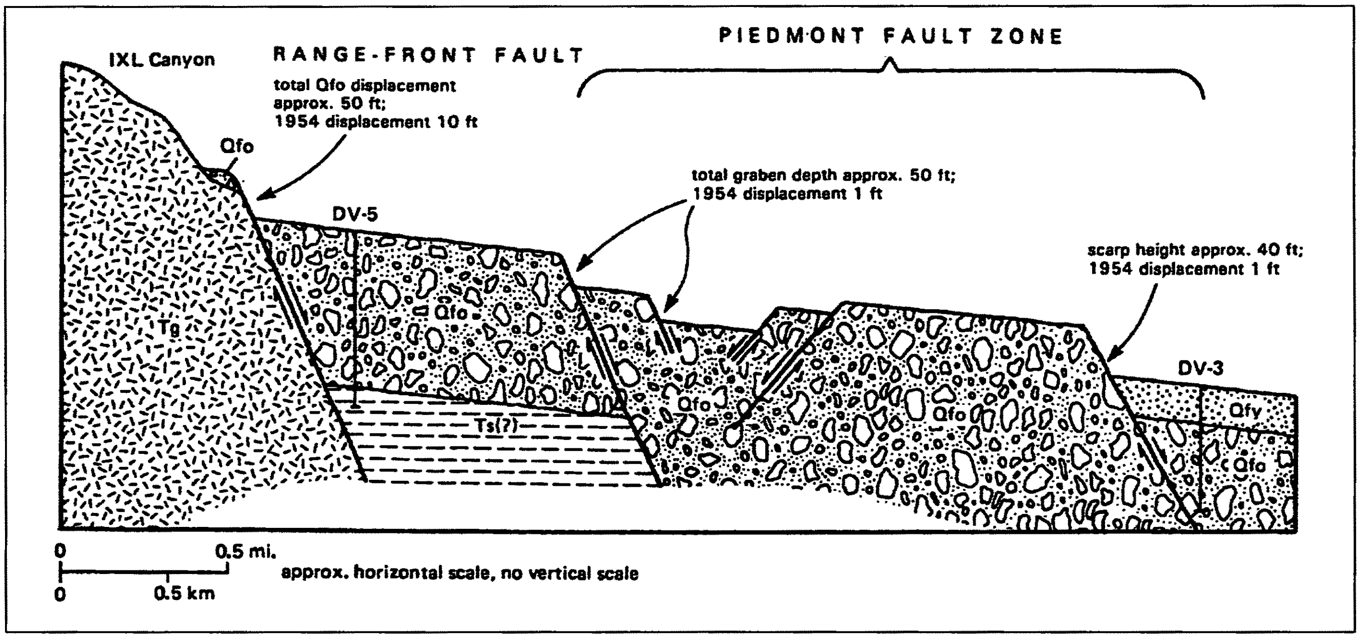

Figure 7. Schematic composite cross section of the IXL and East Job Canyons range-front and piedmont faults. Tg: Tertiary granite and granodiorite; Ts: Tertiary sediments; Qfo: old alluvial-fan deposits; Qfy: young alluvial fan deposits (from Bell and Katzer, 1987, Figure 37).

geometry of the faults can explain the results of the drilling in the DVPP lease at wells 62A-23 and 36-14. There is also additional complexity introduced by the existence of major cross structures from earlier Basin and Range episode (Parry *et al.*, 1991). The strike of these earlier faults is N-S and they can in at least one area just south of the area discussed here, be demonstrated to have controlled the surface expression of the present range bounding normal fault.

Considerable controversy exists about the overall dip of the Dixie Valley normal fault system. In contrast to the steep dips (greater than 45°) assumed by most investigators, e.g. Okaya and Thompson (1985) in the past, a model of shallow dipping normal faults has become popular. For example, Plank *et al.*, (1999) and Louie *et al.*, (1999) argue that the dip of the Dixie Valley normal fault system is low and that the piedmont step is actually a normal fault ramp structure. However, one of the discoveries of detailed mapping is that there are several steep normal faults parallel to the range front in the area of the Oxbow field (Plank, 1998). So that evidence seems to point to the range bounding fault being steep (greater than 45 °). The strongest evidence for the dip at depth comes from the thermal data. Significant over turns have not been observed below the producing zones in any of the wells (2.5 to 3 km in the Oxbow field). If the structures controlling the geothermal flow were shallow in dip, such overturns might be expected (Wisian, 1999). The temperature in both of the DVPP wells exceeds the maximum measured in the Oxbow field and the position of the highest temperature (in the 36-14 well) is not far from the range front and in both wells is at a depth of about 3.5 km. Thus, there is no doubt that some of the fractures that feed the geothermal system are steep (indeed they may be nearly vertical, 85 to 90° in places) within the upper 3.5 km of the crust (Figure 6).

Exploration and Production Implications

Development of the geothermal resources in Dixie Valley has been based the model that a conjunction of a normal fault and the permeable geologic units along the fault are required for production. Favorable units are ones that are brittle and keep open fractures such as the Humboldt lopolith units in contrast to other units such as the Triassic shales that do not appear to support open fractures even along the fault (Benoit, 1999). Recently it has been pointed out that the orientation of structures with respect to the regional stress field may play an important part in the permeability distribution (Hickman *et al.*, 1998; Barton *et al.*, 1998).

The model shown in Figure 6 has many possible fault strands all along the valley/range contact and within both the valley and the range. The deep drilling, temperature gradient exploration, and thermal manifestations together indicate most, if not all, of these strands have some high-temperature fluid flow in some places in the greater Dixie Valley geothermal system. The resulting complexity of the system offers challenges to the exploration and drilling, but it also offers production opportunities and potential reservoir volumes that were not expected based on the single fault model. The fact that none of the deep wells has a definite temperature rollover is consistent with the fact that the reservoir is much larger in volume than a single strand of a Basin and Range normal fault. Thus, within even within the Oxbow field there are a number of potential reservoir structures that have not been tested by drilling. These may already interact with the producing structures via cross faults and/or fracturing, or they may only interact at some unknown depth where all of the strands intersect. In addition there are clearly multiple potential fluid bearing structures in the DVPP area as well, some of which are carrying fluid at temperatures of at least 285°C.

Acknowledgements

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