The Geothermal Systems in Dixie Valley
By
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INTRODUCTION

Dixie Valley Nevada hosts at least a dozen different geothermal systems that have been explored or evaluated to varying degrees by the geothermal industry, research institutions, and academia (Figure 1). This work briefly describes what is known about each of these systems, what exploratory work has been performed to date, and provides some commentary as to what future work may be performed by the geothermal industry in the next few years. There are widely varying amounts of data from the different areas; some are characterized by little more than a crudely outlined shallow thermal anomaly or a thermal spring while the producing geothermal field is one of the most studied geothermal systems in the United States with over 60 published papers on various aspects of the geothermal system and many dozens of other papers dedicated to studies of the Stillwater Fault Zone and the general geology in the area.

The geothermal industry has not focused their efforts on the shallow boundary zones where the geothermal system flows into or mingles with the shallow ground water system. There have been multiple regional hydrologic studies of the regional Dixie Valley groundwater system but the only regional model that has specifically incorporated geothermal flow was done in 1988 (Karst, et al., 1988)

The United State geothermal industry has not historically gathered much shallow hydrologic information in the vicinity of the geothermal systems during its early stage exploration efforts. Only near the operating geothermal field has some hydrologic data been collected over the past 25 years but these data are not truly representative of the natural state of Dixie Valley due to agricultural uses and geothermal exploration and testing activities. In spite of these limitations it will be clear in the following pages that a considerable body of knowledge exists and this may open doors for either collecting new hydrologic information or for perhaps gleaning some additional data from sources identified in this report.

The known geothermal systems in a generally north to south order are 1) Jersey Valley, 2) McCoy, 3) Sou or Seven Devils, 4) Lower Ranch, 5) Hyder, 6) Dixie Valley (the operating geothermal field), 7) Coyote Canyon (formerly called the Dixie Valley Power Partners (DVPP) area), 8) the Dixie Comstock Mine, 9) Dixie Meadows, 10) Clan Alpine Ranch, 11) Pirouette Mountain, and 12) Eleven Mile Canyon (Figure 1). Although active geothermal leases are in place over the Humboldt Salt Marsh playa there has been no geothermal exploration to speak of due to surface access issues. It is possible that there could be one or more hidden geothermal systems beneath the playa but there are no reports of surficial geothermal manifestations, either active or fossil, to encourage any exploration within the salt marsh or damp playa. The known geothermal systems have a strong tendency to be located along the eastern and western margins of Dixie Valley but the McCoy and Hyder systems are located miles from either edge of the valley.

On the margins of Dixie Valley there are two known geothermal systems within the surrounding ranges (Figure 1) that could be discharging a small amount of subsurface geothermal fluid into the valley. Within the Stillwater Range there is one small geothermal system known in the upper reaches of Cottonwood Canyon about ½ mile upstream of the small ghost town of Bolivia that produces about 10

gpm of 84 ^{o} F water. This water flows into Dixie Valley through a combination of surface and subsurface flow in Cottonwood Creek. A very large extinct travertine deposit, presumably deposited by thermal waters, is located a short distance below Bolivia on the north slope of Cottonwood Canyon. The very large McCoy thermal anomaly in the mountains east of Dixie Valley could potentially be providing geothermal fluid in the subsurface to Dixie Valley, via an as yet undocumented underflow. As no productive wells have yet been drilled at McCoy the chemistry of the system is unknown.

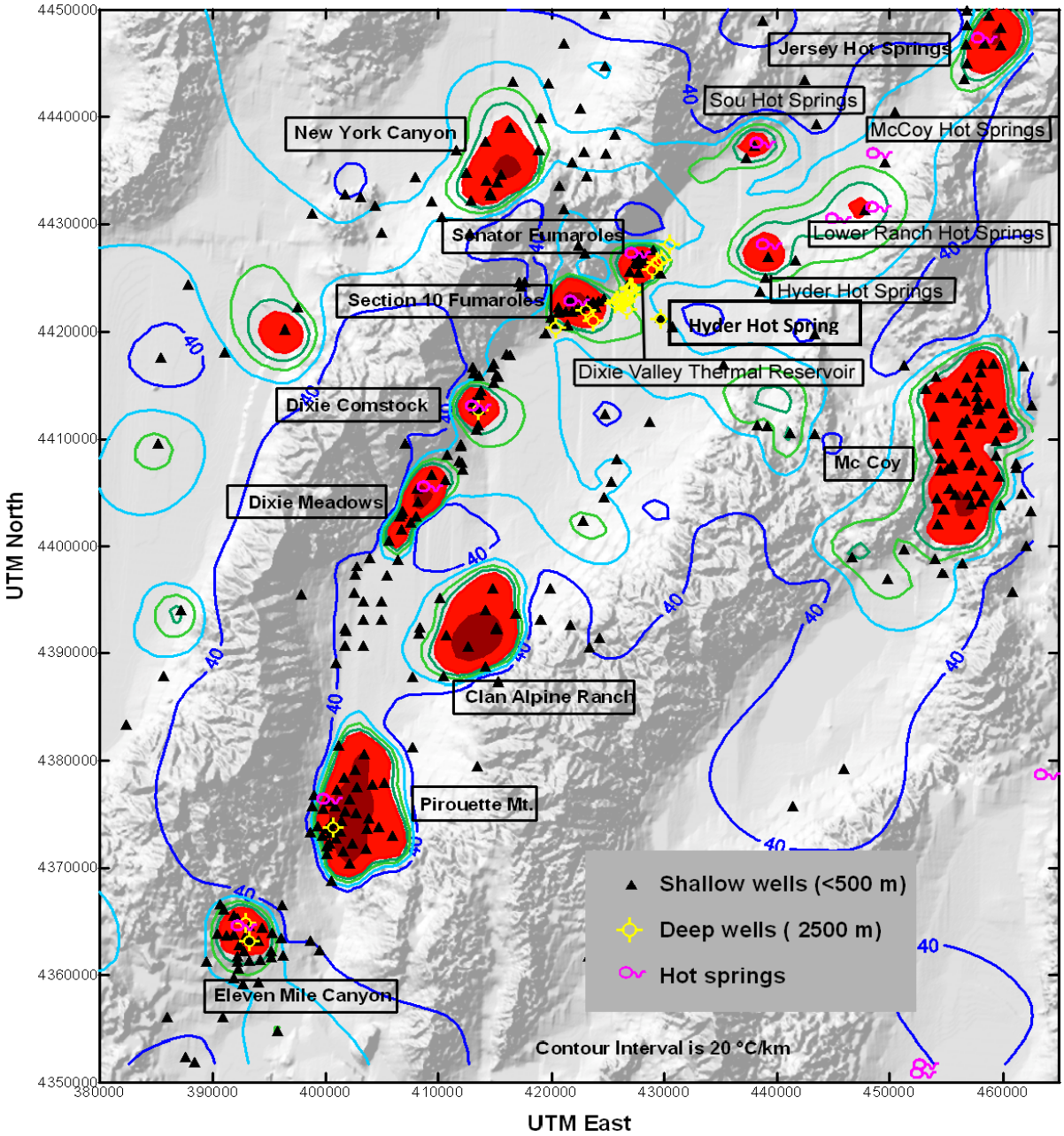

Figure 1: Dixie Valley area thermal gradient and well locations. Contour intervals are 20 °C/km. From 120 –250 °C/km the contours are a red fill and 500°C/km+ the contours are a dark red fill. Contours in the ranges are diagrammatic due to the lack of data. Well gradient locations are shown as black triangles for shallow wells (<500 meters) and as yellow circles for wells > 500 m. From Blackwell, et al. 2007.

THE DIXIE VALLEY GEOTHERMAL SYSTEM

During the time period between the mid 1980s and about 2002 dozens of technical papers on all aspects of the producing Dixie Valley geothermal field and geothermal in Dixie Valley in general were published. This occurred as part of a major research effort by Oxbow Power Services, the plant and field owner at the time, and numerous geothermal researchers, to obtain a much better understanding of the field and resource. Much of this was funded by the Department of Energy Geothermal Program with Oxbow providing data and access to the field. Since Oxbow sold the project in June 2000 and new management taking over the only publications represent a tailing off of the earlier research program. Since 2002 there have basically been no new data or interpretations made available to the geothermal community. Since 2000 the plant has continued to operate with no new production wells being added.

Twenty two wells between 6000' and 12,500' deep and 6 redrills have been completed into or close to the producing geothermal reservoir (Figure 2). In spite of this exceptionally large amount of data and interpretation by numerous individuals there still remains uncertainty as to the details of the structure hosting the geothermal reservoir. This is largely because most of the wells have been drilled along a NE-SW trending line 1 to 1.5 miles east of the range front basically giving a two dimensional view of the geothermal reservoir and the geology.

Dixie Valley Reservoir Boundaries and Limits

The producing Dixie Valley geothermal reservoir is located within a 4 mile-long northeast-southwest trending segment of the Stillwater fault zone that is notable for its surface outcrop linearity (Figure 1). The highly permeable part of the reservoir directly utilized by the power plant extends from the Section 18 injection area into the Southwestern quarter of Section 33 where the northeastern most production wells are located (Figure 2). To the northeast of the Section 33 wells, the Stillwater fault zone trends more northerly and both the near surface and deeper temperatures quickly diminish to near regional background in the 76-28 well (Williams et al., 1997). To the southwest of the producing field there is a sharp change in fault strike toward the west, which is partially obscured by two large landslides, but there is no reduction in the intensity of the thermal anomaly as shown by the shallow temperature gradients on Figure 2. The overall thermal anomaly containing the producing geothermal field lies along a much longer portion of the Stillwater fault zone than just the producing field area and at a minimum also includes the Coyote Canyon geothermal system (identified as the Section 10 fumaroles on Figure 1), formerly referred to as the Dixie Valley Power Partners or DVPP area.

To the southwest of the Coyote Canyon geothermal system the existing temperature data are sparser but multiple temperature gradient holes up to 1500' deep failed to encounter anomalous temperatures or temperature gradients (Figure 1). However, it is possible that this undeveloped area is impacted by subsurface flow of cool water from canyons draining the eastern slopes of the Stillwater Range which mask deeper anomalously high temperatures. No holes below a depth of 1600' (500m) have been drilled in this area to determine if a deeper thermal anomaly might extend further along the Stillwater fault zone. For this reason the southern boundary of the overall thermal anomaly hosting the Dixie Valley geothermal system is somewhat uncertain.

The Dixie Valley and Coyote Canyon areas are treated as separate geothermal systems in this report as they have substantially different temperatures, pressures, and water chemistry. In a truly global sense one might argue that they represent two convection cells within one thermal anomaly but for all

practical purposes at drillable depths they appear to be independent of each other. The fumaroles in Section 10 have shown no obvious changes in character since the power plant commenced operations but there has been no systematic monitoring to detect small changes.

The northeastern limit of the Dixie Valley reservoir has been defined by well 76-28 (Figure 2) that has two unproductive legs and a significant reduction in subsurface temperature in the 76-28 well as compared to the Section 33 production wells (Williams et al., 1997). The southwestern limit of the reservoir similarly has been defined by two unproductive legs in the SWL-2 hole, the westernmost well in the cluster of the Section 18 injectors shown on Figure 2. Maximum temperatures in wells 62A-23 and 36-14 are 513 F and 545 F respectively (Blackwell et al., 2000), substantially above the ± 480 F maximum temperatures measured in the productive reservoir (Figure 2).

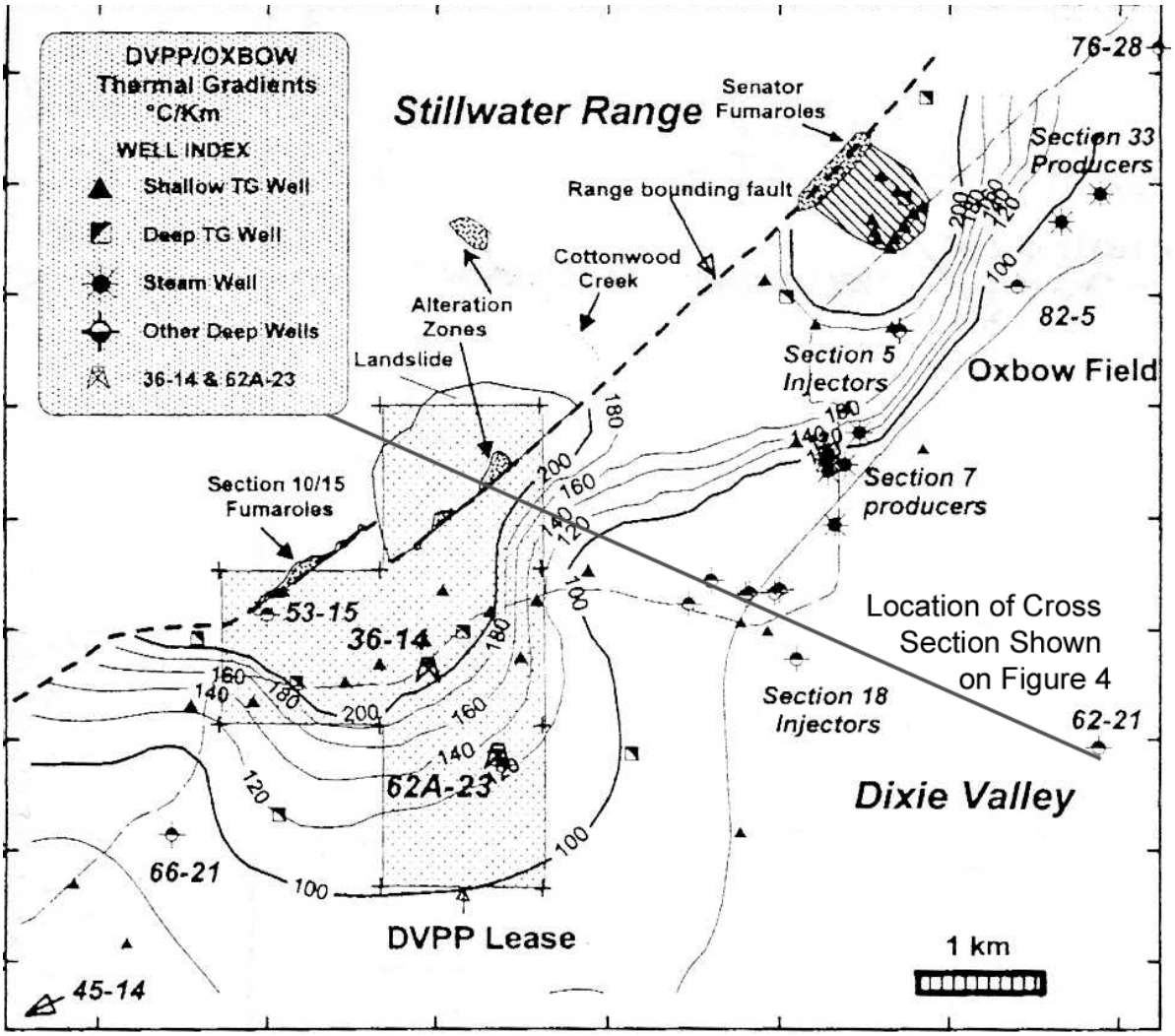

Figure 2: Index map of Dixie Valley Geothermal System. Geothermal gradient contours are in °C/km. Shaded area near Senator Fumaroles has a geothermal gradient of greater than 2000 °C/km. From Blackwell et al., 2000.

The northwest-southeast extent of the Dixie Valley geothermal reservoir is not as well known because there is very little spread of the wells in this direction to define the top or the bottom of the resource. To the northwest, the Stillwater Fault Zone becomes progressively shallower ultimately reaching the surface at the Senator fumaroles at the base of the range. Two "shallow" injection wells, 27-32 (TD=970') and 38-32 (TD=3832') have been drilled to the northwest of the line of deeper wells (Figure 3). These two are referred to as shallow because all the other injectors are deeper than 6000'. Although these two "shallow" injection wells have temperatures far below the 480 ^{o}F reservoir temperature, they penetrated permeability or fractures that are clearly a part of the reservoir as demonstrated by chemical tracers returning from them to the production wells (Johnson, 2002, Rose, 2002) and have been utilized as injectors for the past decade. It is debatable whether either of these "shallow" injectors has intersected the range front fault or a buried fault or have perhaps encountered a lateral outflow channel off of the main upwelling fault zone (Johnson and Hulen, 2002, Blackwell et al., 2007). No wells have been drilled close to the topographic base of the range to document the possible resource at very shallow depths.

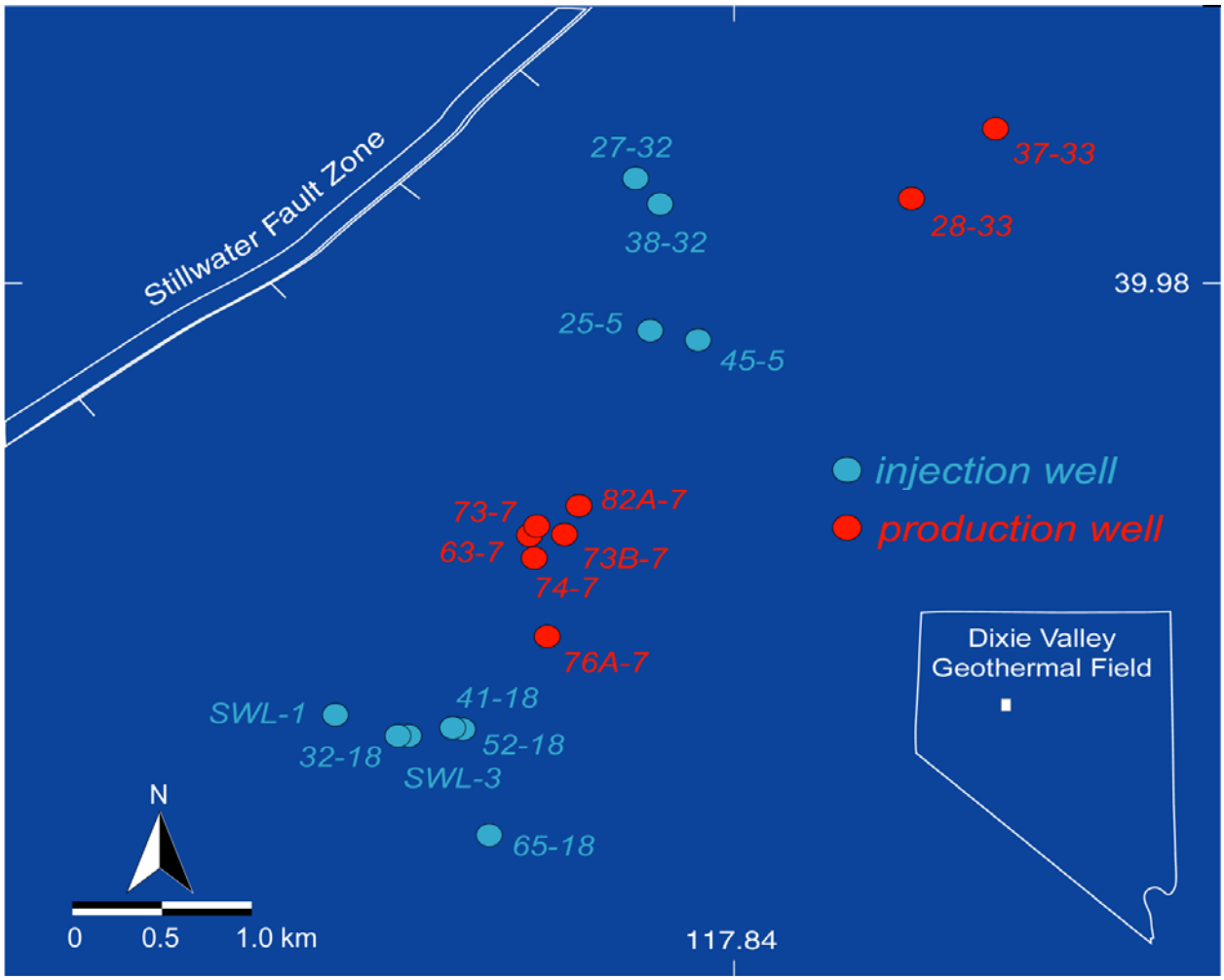

Figure 3: Dixie Valley Geothermal Field Well Distribution. Numbers refer to active well identifications. Idle well locations are not shown. The SWL-2 well is located 0.5 km southwest of the SWL-1 well. From Johnson, 2002.

To the southeast of the line of production and injection wells there has been no drilling, other than the unproductive well 62-21 located in the middle of the valley (Figure 2), to characterize the deeper parts or the bottom of the reservoir. The 62-21 well produces as much as 35 gpm of 169 ^{o}F water from bedrock below the cased depth of 8383' (Blackwell and Smith, 2005). The well 62-21 water is greatly different from the utilized geothermal fluid (Goff, et al., 2002), being a more dilute bicarbonate water rather than a mixed anion water like the produced geothermal fluid. Geothermometry suggests the 62-21 water equilibrated at a temperature of approximately 275 F (Goff et al., 2002). The 62-21 water also has 0.83 T. U. tritium which is more than most of the hot springs in the valley suggesting it may be a mixture of deeper and more recently derived shallow water (Blackwell et al., 2005). The geothermal reservoir must extend some distance below the deepest production wells but without any deeper wells in this area little can be said about the deepest parts of the reservoir. It seems unlikely that significantly higher temperature fluids are present at greater depths in the high permeability portion of the producing Dixie Valley geothermal field as none of the production wells have shown any trend of increasing temperatures over 21 ½ years of production.

Numerical thermal modeling studies (McKenna and Blackwell, 2004, Wisian and Blackwell, 2004, Blackwell, et al., 2005) suggest that the geothermal system at Dixie Valley extends to depths of at least 20,000 feet. By comparison the deepest well in the valley, 62-21, is 12,500' deep. This does not necessarily imply that the productive reservoir extends this deep, only that thermal water in the reservoir managed to circulate to a depth of 3.75 miles to gain the temperature that the hot water then transferred to the shallower production zone rocks. This great circulation depth allows the water in the geothermal system to access regional background temperatures at or above the 480 ^{o}F that have been measured in the Dixie Valley geothermal field and 545 ^{o}F measured at Coyote Canyon.

Nature of the Dixie Valley Geothermal Reservoir

The Dixie Valley reservoir supplying the production consists of open fractures in a variety of consolidated bedrock types. The details of the geologic structure of the Stillwater Fault Zone have long intrigued various authors and resulted in a variety of proposed conceptual models (Thompson et al., 1967, Benoit, 1999, Johnson and Hulen, 2002, Blackwell, et al., 2007). The most artistic and interpretative geologic cross section through the Dixie Valley reservoir presenting the overall geology with offset between valley and range along a single fault strand (Johnson and Hulen, 2002) is shown on Figure 4. Blackwell et al., (2007) prefer that most offset occurs along a buried normal fault with no surface expression about 1½ miles in front of and parallel to the range and have presented geophysical data, and thermal models (Figure 5) to support this interpretation. The maximum vertical offset on Miocene basaltic rocks across the Stillwater Fault Zone is approximately 11,000' to 12,000'. In both Figures 4 and 5 the production zones are closely associated with the 1 or 2 fault zones.

Individual productive fractures have apertures that probably range in size from a fraction of an inch to a few feet and are highly permeable. The wells initially had artesian flow rates of 1500 to 3500 gpm (Desormier, 1987) and produce from depths between 7000' and 10,000'. The wells completed below 8000' in depth are cased such that only the pre-Tertiary rocks can provide fluid to the well. A few of the 7000' deep wells are completed in Miocene basalt (Desormier 1987). In the southwestern part of the field in Section 18 the fractures at depths below 8000' are hosted by fine grained metamorphosed Jurassic basaltic rocks present on the front of the range above Section 18. A shallower horizontal thermal aquifer in the Section 18 area is present between 7000' and 7500' in Miocene basaltic lava flows

and is probably a result of primary permeability associated with the upper parts of sub horizontal lava flows that can be seen at the surface on the top of Table Mountain in the Stillwater Range. This aquifer is found locally in the SWL-3, SWL-3 and 32-18 wells and is laterally fed from the nearby range front fault (Desormier, 1987).

Morin et al., (1998) note that the deep wells have great variability. The productive wells have permeability-thickness values on the order of 10^5 millidarcy-meter (mD-m) and storativities of about 10^{-3} while cooler lower permeability wells outside of the field are artesian and have a permeability-thickness of about 10^1 mD-m and storativities of about 10^{-3}.

In the Section 7 area the permeable fractures are found in coarse grained Jurassic gabbroic rocks at depths between 8500' and 9500'. These gabbroic rocks are exposed on the face of the Stillwater Range uphill from Section 7. In the Section 33 area the permeable fractures are found in Jurassic quartzite between depths of 9000' and 10,000', also exposed above the wells on the face of the range. None of these rock types have any intrinsically high porosity or permeability. Close to 100% of the water in these rocks must be in secondary fractures and therefore is highly mobile (Hickman et al., 1997, Hickman and Zoback, 1998, Barton et al., 1998, Hickman et al., 2000).

It is not known whether any wells located slightly further to the northwest or southeast of the existing wells would be productive or if fractures in any such hypothetical wells would be encountered in different lithologies. To date, the deep producing fractures are primarily found in a narrow interval extending hundreds of feet above the fault contact with granitic rocks near depths of 6000' to 10,000' (Figure 4). The top of the granitic rocks defines the bottom of the Stillwater fault zone, the bottom of the Dixie Valley graben, and the top of the footwall. No permeable fractures have yet been encountered in the granitic rocks in the producing Dixie Valley geothermal field, even though two wells have been drilled several hundred feet into the granite. Above the granitic rocks the "typical" Dixie Valley well encounters 3 to 6 distinct fractures, each fracture being separated from the others by perhaps 50' of low permeability impermeable rock. These fractures are commonly described as being close to the bottom of the hanging wall of the fault.

As noted earlier there is a small area in Sections 7 and 18 in Miocene aged basalts near a depth of 7500' that has high permeability now used for injection purposes. These sub horizontal permeable layers apparently intersect the Stillwater fault zone and at least locally extend the reservoir away from the fault zone. There also is a near surface zone of outflow from the Stillwater fault zone in the Senator Fumarole area in the northern part of the producing field described by Allis et al., (1999).

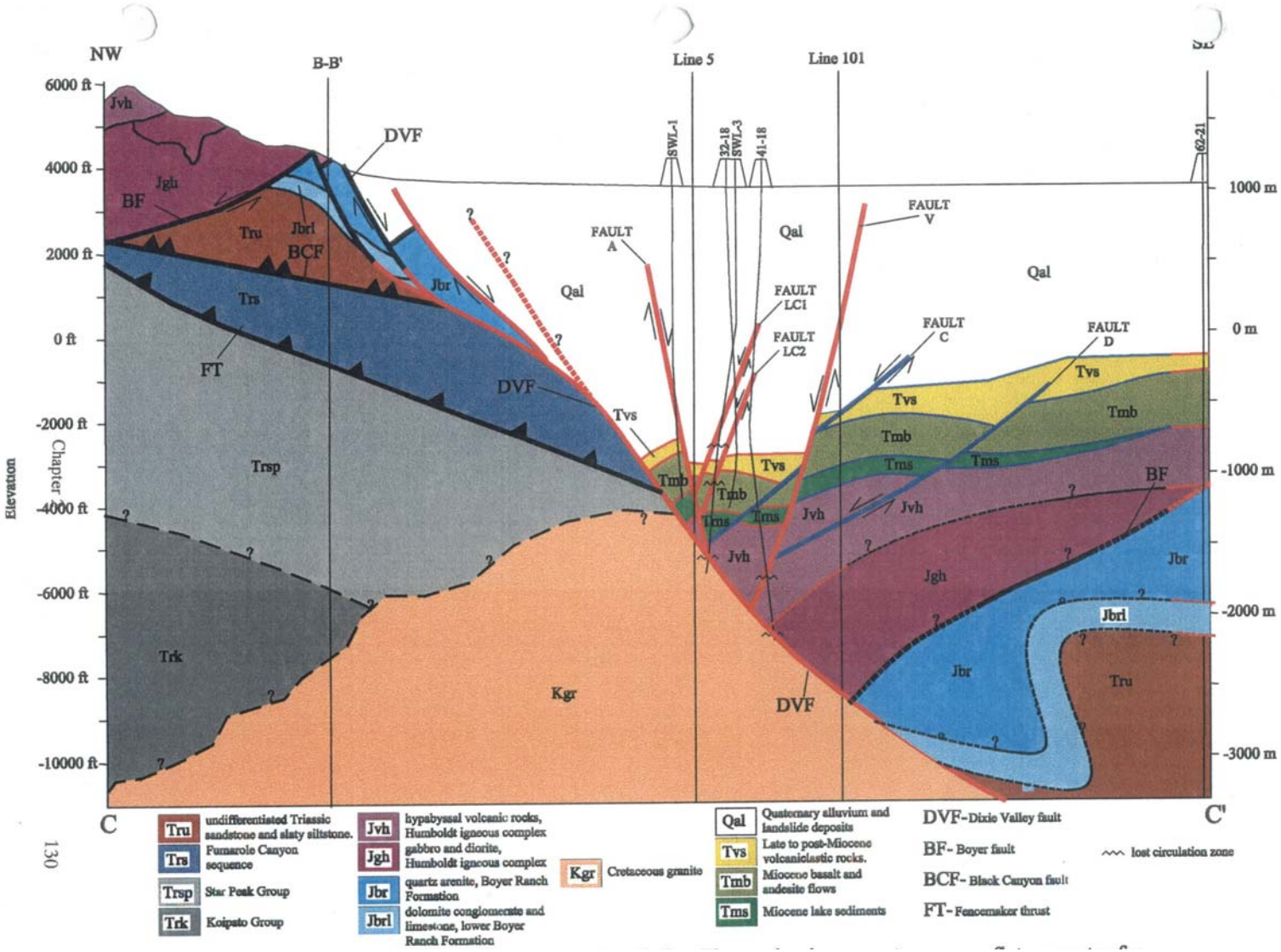

Figure 4: Geologic cross section through the Dixie Valley Geothermal Field. Taken from section C-C' from Johnson, 2002.

Nimz et al., (1999) used the $^{36}Cl/Cl$ ratio to interpret that the chloride in the Dixie Valley reservoir water is derived from granitic rocks. Previous speculation at Dixie Valley interpreted the bulk of the deep geothermal fluid to be stored in Triassic shale which is exposed in the Stillwater Range above the geothermal field and is probably the most volumetrically abundant rock in the region. This Triassic shale has been extensively penetrated in four deep wells outside of the producing field and three of these, 62-21, 66-21, and 45-14 have an artesian flow of thermal water to the surface (Williams et al., 1997). Only the 76-28 well penetrated the Triassic shale and does not have artesian flow. If Nimz et al., (1999) are correct, then the Dixie Valley reservoir water either spent considerable time in the granite perhaps located at depth beneath Dixie Valley, or flowed into the fault zone from granite known to be beneath the Stillwater Range, or very quickly and recently acquired the chloride in the fault zone in contact with the granitic rocks. This does not agree well with the previously mentioned limited drilling experience where no fractures have yet been penetrated in the granitic rocks in two wells. Geothermal reservoirs are not static fixed volume resources like oil or gas reservoirs; they are active features. A geothermal reservoir has to have a fluid throughput to maintain its temperature. The Dixie Valley geothermal reservoir prior to production had a miniscule visible discharge at the surface in the form of the Senator fumarole which probably amounted to a few pounds per hour of low pressure steam. There were no active thermal springs and there is no surface evidence of recently active fossil springs such as sinter or travertine deposits associated with the Dixie Valley geothermal system.

The amount of subsurface discharge of thermal water from the Dixie Valley geothermal system into the Quaternary valley fill of Dixie Valley is uncertain and difficult to determine in large

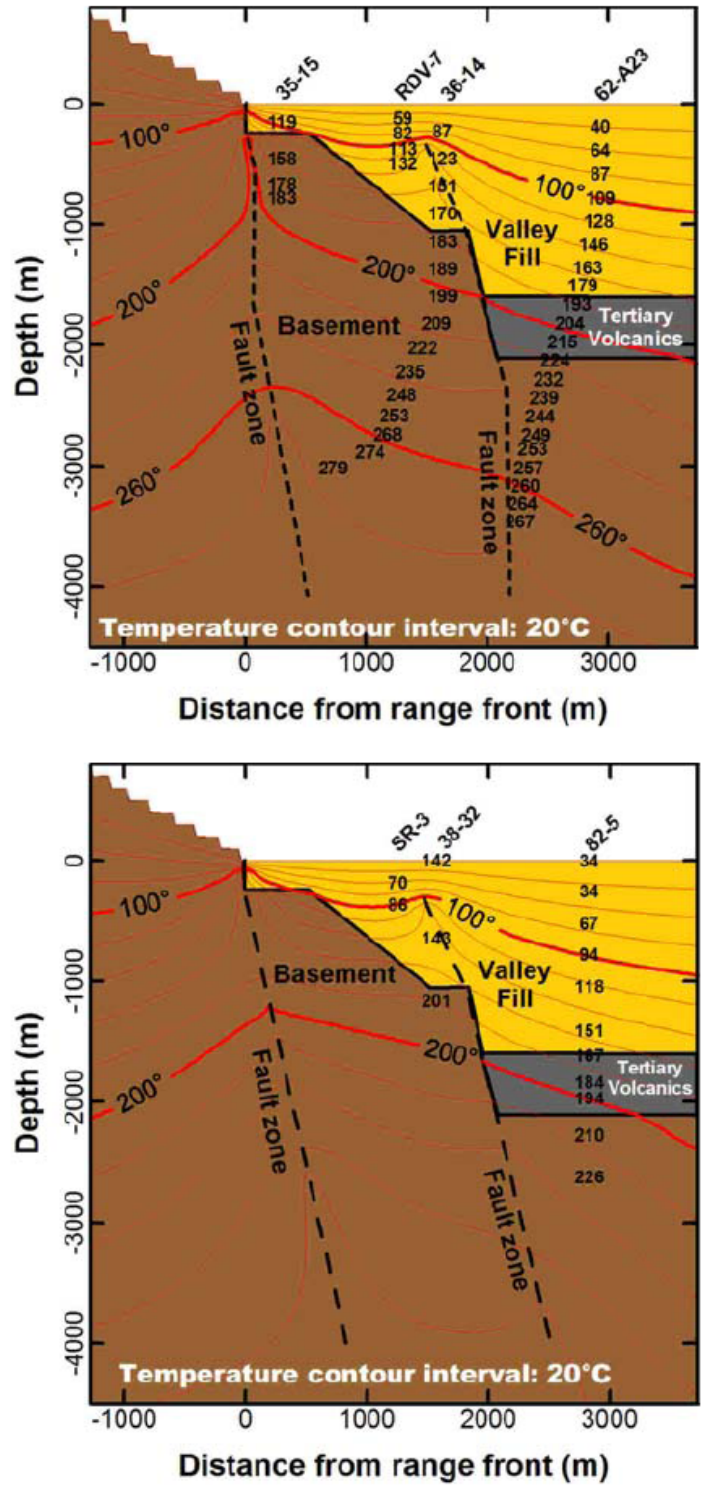

Figure 7. a) Thermal model for the DVPP area based on temperature matching in the deep wells (Blackwell et al., 2002). b) Thermal model for the DVPF in section 32/33 based on temperature matching in the deep wells.

part because there have been relatively few shallow holes drilled in the area to define areas of shallow thermal fluid leakage and the few analyses of shallow groundwaters show high chemical variability. By example Goff et al., (2000 Figure 2) present analyses of cool shallow ground waters from three sources within the boundaries of the Dixie Valley production area. These groundwater analyses labeled DV96-1, DV97-38, DV97-39, DV 98-96, DV97-59, DV98-160, and DV99-181 in Goff et al., (2000 Table 4) have a large range in total dissolved solids concentrations with chloride contents varying from 105 to 296 ppm. Bruton et al., (1997) arbitrarily utilized the analyses from the 34 ^{o}C domestic well for the power plant which contains 105 ppm of chloride in simple mixing model calculations to suggest that the local shallow groundwater contains about 15 to 25% geothermal brine mixed with regional recharge. This may be true for this particular water source. However, the Goerenger well which has produced far larger volumes of shallow groundwater is located only several hundred feet further downslope on the Cottonwood Creek alluvial fan and contains from 220 to 296 ppm of chloride and therefore would have about 2 to 3 times the calculated 15 to 25% component of geothermal fluid.

To further complicate the mixing calculation of Bruton et al (1997) the four analyses of waters from Cottonwood Canyon above the power plant in the Stillwater Range have from 216 to 630 ppm of chloride (Goff et al. 2002) and this is the water that is presumably recharging the Cottonwood Creek alluvial fan to supply the power plant domestic well. The greatest challenge to the Bruton et al. (1997) mixing model comes from the analyses of water samples collected from the two pairs of shallow groundwater monitoring holes 2A, 2B, 3A, and 3B provided by TerraGen (Appendix 1). These monitoring wells were not sampled by Goff et al., (2002) and are located 2 to 3 miles south of the power plant along the western bank of Spring Creek. The unpublished chemistry of these monitoring holes show chloride contents ranging from 110 to 2450 ppm. The higher chloride contents from the shallow monitoring well samples greatly exceed that found in the geothermal fluid demonstrating that at least one saline shallow groundwater is also present in the vicinity of the power plant. The point of this is that the local groundwater chemistry near the Dixie Valley power plant is highly variable and perhaps should be viewed as mixtures of more than just one ground water and the deep geothermal fluid. Unfortunately, funding was not available to complete 4 geochemical papers interpreting the Goff et al., (2002) data.

Allis et al., (1999) calculated a modest subsurface discharge of 80 gpm from the Senator Fumarole area in the northern part of the producing field. Unpublished numerical modeling results of the natural state of the Dixie Valley geothermal system indicated a discharge rate of about 100 gpm. Wisian et al., (2001) calculated a conductive heat loss of 1 X 10^7 watts for the Dixie Valley geothermal system. Unfortunately, this number is poorly defined due to the paucity of temperature gradient holes in and near the project and it is unclear if this value also includes the nearby Coyote Canyon area. In any event, the throughput of hot water in the Dixie Valley geothermal system natural state was very modest compared to other high-temperature geothermal areas in the world where throughputs can reach thousands of gallons per minute. As one spectacular example, the Long Valley Caldera geothermal system in Eastern California has a throughput of 4755 gpm of 392 ^{o}F to 536 ^{o}F water (Sorey, et al., 1978).

The Dixie Valley geothermal field is sub hydrostatic in that the first wells drilled into the reservoir had static fluid levels standing approximately 500 feet below land surface. All of the wells need to be lifted with air or nitrogen to commence artesian flow. It was not possible to consistently measure any natural state pressure trend over the length of the geothermal field with the mechanical Kuster tools available at the time. It is possible that the range of pressures between Section 18 and Section 33 (3 and 3/8 miles) was perhaps less than 10 or 20 psi, out of about 3500 psi at the main reservoir depth. This is another indication of very high fracture permeability along the Stillwater fault zone.

Agricultural water wells in the power plant area a couple hundred feet deep had and continue to have static water levels of 30 to 70 feet below land surface. These pressure relationships demonstrate that the geothermal field is for the most part well separated from the shallow groundwater system. Unfortunately, in the Senator Fumarole area where the geothermal system discharged most strongly into the shallow groundwater system (Allis et al., 1999) there were no shallow wells available to determine the relationships between the two water systems in the natural state (before geothermal production and injection commenced). Temperature gradient holes drilled after production commenced showed very high temperatures and gradients indicative of shallow downhill subsurface flow of thermal water that had risen above the level of the valley in the Stillwater Fault Zone and then flowed downhill into the shallow groundwater system. Once this lateral flow with temperatures above boiling was cut off by a lowering of the liquid level in the geothermal reservoir and the fault zone the pressures in the shallow outflow plume were reduced allowing boiling which temporarily created fumarolic activity at the toe of the alluvial fan (Allis et al., 1999) and a large temporary noncondensible gas flux (Bergfeld et al., 1998, Bergfeld et al., 2001).

Dixie Valley Production History and Injection Augmentation

The first fluids produced from the Dixie Valley geothermal field were during short term and small volume flow tests of individual wells starting in 1978. Most likely, the reservoir had adequate time following these tests to essentially refill from natural deep recharge. The first large volume extraction occurred in 1986 when Oxbow performed two multiwell flow tests (Figures 6 and 7, Appendix 2). The second, and much larger flow test in 1986, covered 73 days between late July and mid September and had as many as six wells simultaneously flowing, removing 866 million gallons (2658 acre-feet) from the reservoir at flow rates as high as 11,820 gpm (Desormier, 1987). This fluid was discharged into Spring Creek and flowed downhill toward the Humboldt Salt Marsh. Monitoring during the flow test showed that small amounts of fluid reached the northern end of the Humboldt Salt Marsh playa but did not create any significant standing water. The reservoir then remained mostly idle until mid 1988 when the power plant started operations. Analysis of the 1986 flow tests and preparation of a numerical geothermal reservoir model marked a clear beginning for injection efforts at Dixie Valley (Benoit, 1992).

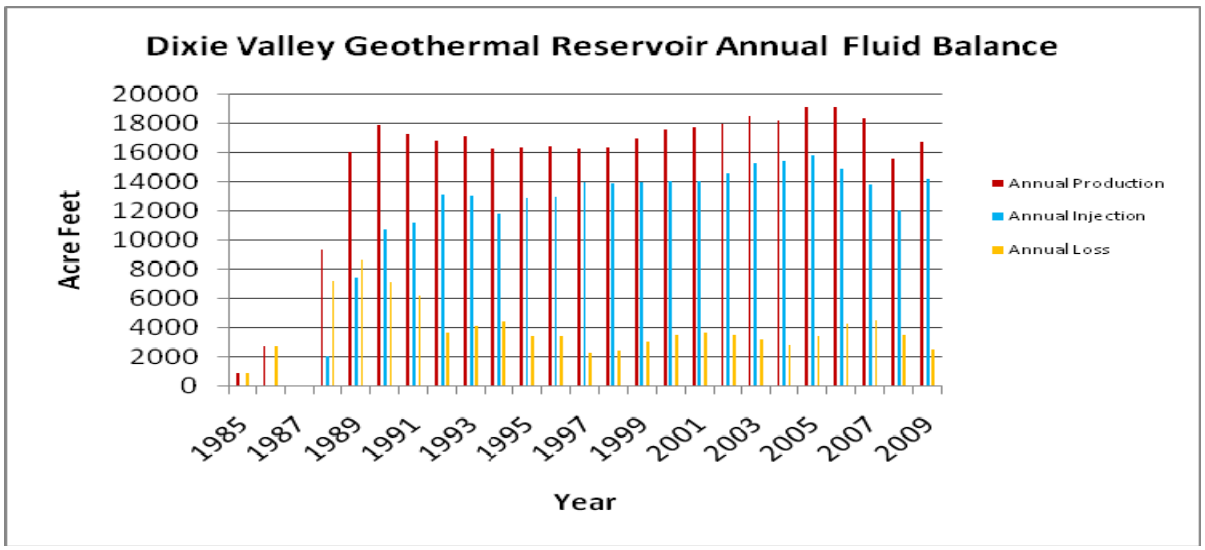

Figure 6: Histogram of fluid removal/injection, Dixie Valley Geothermal Field from 1985 through 2009

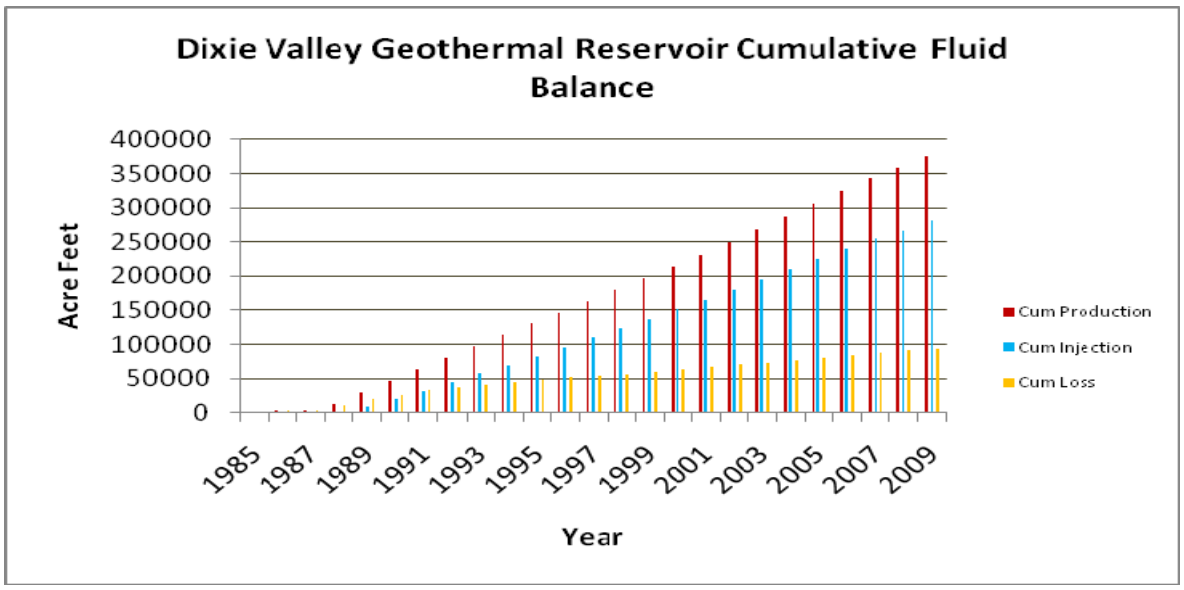

Figure 7. Cumulative producition, injection, and fluid loss from the Dixie Valley geothermal reservoir 1985 through 2009

In early July 1988 the power plant commenced operations but for the first two months the injection system was not completed so a comparable volume to the 866 million gallons of the six well flow test was again discharged into Spring Creek during the summer months. In September 1988 the injection system was placed in service but it could not accept all the produced fluid (Benoit, 1992). Oxbow had secured permission to surface discharge all the spent brine (± 10,000 gpm) with a TDS of about 2000 ppm from the power plant for up to 3 years so this was not a permitting problem. Additional injectors were drilled in 1989 and 1991 and in 1991 some injectors were worked over to improve their performance. By October 1991 the injection system was handling 8800 to 9000 gpm and all liquid discharges from the power plant were being injected (Figures 6 and 7). However, between 1985 and the end of 1991 a total of 63,931 acre feet of water had been produced but only 31,329 acre feet had been injected, giving an overall return of only 49% of the mass to the reservoir. By the end of 2009 the total volume fluid lost from the reservoir was 56,289 acre feet which amounts to 31% of the total produced mass (Appendix 1). However, these figures do not take into consideration any natural recharge into the reservoir.

Between 1992 and the start of the injection augmentation program in mid 1997 the field operated very consistently with about 77% of the produced mass being returned to the reservoir and about 16,500 acre feet being produced annually. The dominant mass loss since 1992 has been the cooling tower evaporation which amounted to 2455 acre-feet/yr (Benoit, et al., 2000). By the end of 1997 the total amount of volume lost from the reservoir was 53,812 acre feet which amounted to 33% of the total produced fluid volume. However, the overall mass loss had substantially reduced the pressure of the resource so a program of adding mass to the reservoir (injection augmentation) was implemented beginning in mid 1997 to reverse the pressure decline.

The augmentation program basically pumped 77 F groundwater from depths near 260' into the geothermal reservoir via dedicated injection wells to make up for the evaporative losses from the cooling tower (Benoit, et al., 2000). A significant exploration effort, including the drilling of four

exploratory wells up to a depth of 1800 feet, for a large volume of water with near boiling temperatures and low concentrations of calcium and magnesium was unsuccessful (although one of these wells has since been utilized as an injection well). Apparently the Quaternary alluvium/Tertiary basin-fill in Dixie Valley with temperatures above the 200 ^{o}F isotherm is largely impermeable (Benoit et al., 2000). This could be because the higher temperatures have "softened" the groundwater water by precipitating the calcium and magnesium as calcium carbonate and magnesium silicate (Bruton et al., 1997) greatly reducing the porosity and permeability. Therefore, at least in the vicinity of the power plant, it appears that the majority of the up to 6000' thickness of Quaternary alluvium/Tertiary basin-fill in the valley (Figures 4 and 5) is not a likely reservoir of good or bad (or hot or cold) quality groundwater. Only the uppermost hundreds of feet appear likely to contain a large volume of accessible groundwater.

Commencement of the augmentation program at various pumping rates and monitoring of the reservoir pressure in two idle wells began in 1997 and quickly demonstrated that only about 475 gpm (766 acre feet/year) was needed to stabilize the reservoir pressure (Benoit et al., 2000). With an annual average loss of about 1585 gpm (2557 acre feet/year) through the cooling tower, this means that about 1100 gpm (1774 acre feet/year) of presumably deep hot fluid is naturally recharging the highly permeable fracture network serving as the reservoir. Figure 8 shows the fraction of the total fluid returned to the reservoir being about 80 to 85% of the produced volume since the injection augmentation program was implemented.

Exactly where or how this recharge is occurring is uncertain. Possibilities range from a highly dispersed inflow spread over 3 3/8 miles of the Stillwater fault zone or perhaps one or more concentrated inflows in specific locations. This rate of recharge is occurring with the reservoir in a significantly depleted pressure condition relative to its natural state. It is not known how much the recharge rate would decline under higher reservoir pressure conditions such as the natural state. By the end of 2009 the total volume produced by the Dixie Valley geothermal field was 375,081 acre feet. This is enough water to cover 586 square miles with one foot of water.

The implementation of the augmentation program now means that the primary connection between the geothermal reservoir and the shallow groundwater system is controlled by the power plant operator. Augmentation rates have been as high as 2283 acre feet/year (2000 gpm) but over the past decade are more consistently near 2000 acre feet/year. How much shallow groundwater will be pumped into the deep geothermal reservoir in the future is uncertain as an increasing geothermal reservoir pressure makes it more difficult to inject additional fluid. The inverse of this was seen during the late 1980s and early 1990s when decreasing reservoir pressures resulted in significant increases in injection rates in individual wells (Benoit, 1992). At some point the overall injection system (wells and pumping capacity) may not have the ability to pump as much augmentation water into the reservoir and there will be less need to do so. No graphs of changing reservoir pressure with time during augmentation have been published since Johnson (2002) showed the pressures in the idle well 84-7 production well increased by about 20 psi/year in 2001 and the first half of 2002.

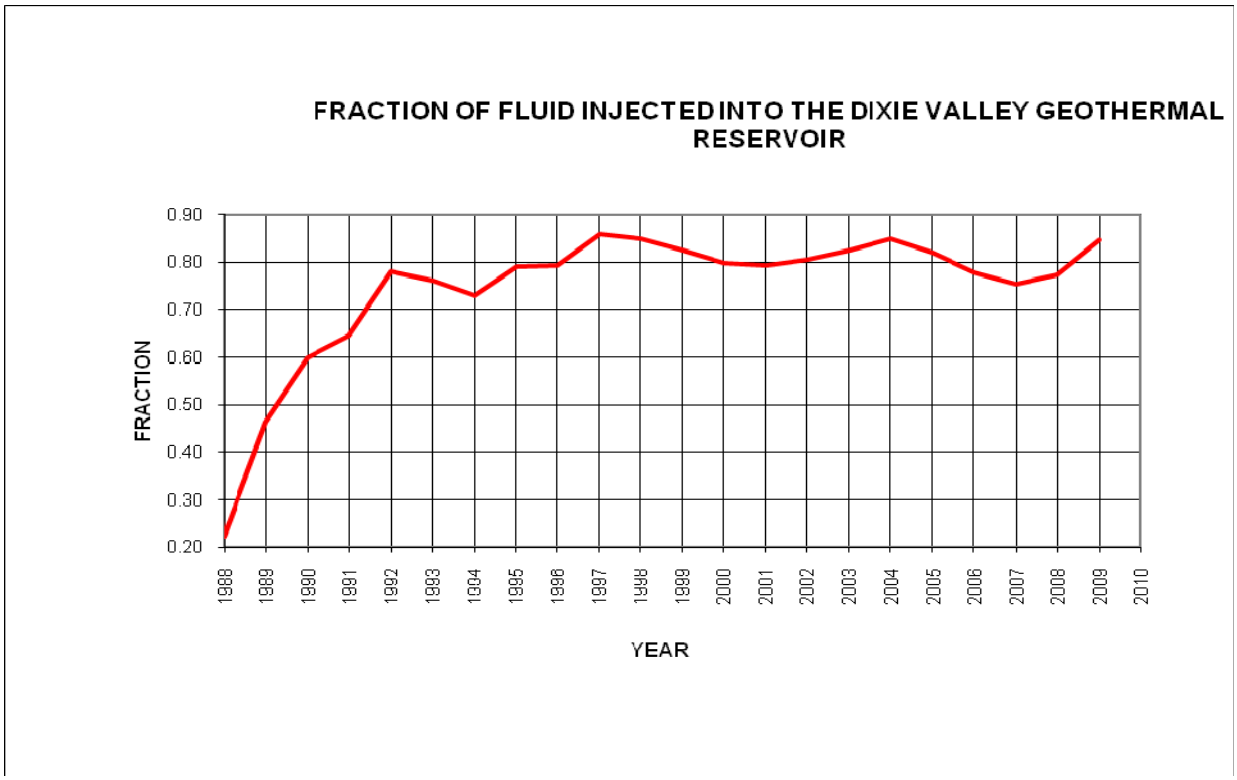

Figure 8: Fraction of geothermal water production offset by injection of water, 1988-1998.

Volume of the Dixie Valley Geothermal Resource

Estimating the volume of a geothermal resource requires such a large amount of data and analysis that it has seldom been attempted. Volumes of oil reservoirs which have a fixed amount of fluid with no recharge can be relatively easily estimated by knowing the long-term pressure declines and cumulative production numbers. A geothermal reservoir which has an unknown but significant amount of natural recharge and a large scale injection program is much more difficult to characterize. Simply defining the limits of geothermal resource can be an exercise in ambiguity. It is relatively easy to define the Dixie Valley resource volume as that volume of water stored in highly permeable fractures that can readily flow into the production wells. However, if this volume also includes shallower and cooler parts of the Stillwater Fault Zone then the definition includes a considerable amount of relatively cool water. It is known that there is a recharge of hot fluid into the Stillwater Fault Zone but how much of this water is coming from large permeable fractures and how much might be coming from dispersed small low permeability fractures is something that perhaps can be modeled but is not easily measured.

Dixie Valley is probably the only geothermal resource for which four published volume estimates are available. Three of these estimates come from an exceptionally complete set of tracer tests conducted in 7 of the 10 injection wells at Dixie Valley over a 10 year period starting in the mid 1990s (Rose, 2002, Rose et al., 2004, Reed, 2007). These estimates only include the volume of whatever fractures that the tracers utilized in traversing from the injection wells to the production wells. Rose (2002) estimated this fracture volume at 7 to 15 billion gallons utilizing tracer returns measured over a period of 1400 days. In 2004 Rose et al., recalculated values of 3.7 and 9.1 billion gallons. Reed (2007) using the tracer data of

Rose estimated a volume of 2.5 to 8.9 billion gallons swept by the same tracer tests using a moment analysis of tracer tests from several injection-production wells pairs.

A very crude fourth tracer test method used to estimate the volume comes from measurement of the chloride content of the produced and injected fluids over time. Chloride in the injectate is concentrated by up to 26% due to the loss of steam through the cooling tower. Between the beginning of 1989 and the end of 1994 the rate of increase of the chloride content in the injectate and production wells closely paralleled each other (Benoit, 1992, Kennedy et al., (1999)). By the beginning of 1995 the production wells were producing the same average chloride concentration as the injectate had at the beginning of 1989 shortly after the injection system became operational. This indicates that the entire volume of the resource being utilized by the production and injection wells had been swept and largely homogenized by the injection system in a six and one half year period. The volume of fluid injected in this time was 23.5 billion gallons (Kennedy et al., 1999.) This is about 2 ½ times the higher values proposed by Rose and Reed but certainly agrees with the order of magnitude of the highly permeable fracture network.

Linearly extrapolating the production history since 2001 (Johnson, 2002) indicates the Dixie Valley geothermal reservoir has now produced about 119 billion gallons of water which is anywhere from 5 to 48 times the estimated volume of the fracture network from the tracer testing. The injection program has repeatedly swept the fracture system. It qualitatively seems unlikely that the high permeability fracture volume could be swept 48 times without serious cooling having occurred.

Dixie Valley Geochemistry

The fluid present throughout the Dixie Valley geothermal field is fairly dilute sodium-mixed anion water with sub-equal amount of chloride, sulfate, and bicarbonate. Initially all wells had slightly different chemistry but over time mixing of the waters in the surface gathering and injection system has largely homogenized the fluid and has substantially increased the concentration of most aqueous chemical species while diminishing the noncondensible gas concentrations(Benoit, 1992, , Benoit and Hirtz, 1994, Kennedy et al., 1999). Numerous chemical analyses of waters and gases from the individual production wells are presented in Goff et al., (2002). Addition of augmentation water to the geothermal system since July 1997 has probably also further modified the overall chemistry of the produced water.

Dixie Valley Shallow Impacts Resulting From Geothermal Production

The only recognized surficial impacts of geothermal production at the Dixie Valley geothermal field have occurred in the northern part of the field in the vicinity of the Senator fumarole (Allis, et al., 1999, Bergfeld et al., 2001). A reduction in the liquid level in the Stillwater fault zone due to declining geothermal reservoir pressures cut off the flow of $\geq$330 F liquid to a shallow 80 gpm thermal aquifer (determined from heat loss calculations) that was flowing downhill to the east beneath the alluvial fan. This aquifer then was able to boil which temporarily resulted in the formation of new fumaroles near the toe of the alluvial fan, a large area of vegetation on the alluvial fan being killed, a subsidence bowl which has seasonally filled with water from Cottonwood Creek ("Lake Dixie"), and a network of associated semicircular surficial subsidence cracks partially rimming Lake Dixie. After a few years the fumarolic activity low on the fan greatly diminished but increased fumarolic activity along the range front at Senator Fumarole has continued now for over a decade. There has been no discernable change in the weak fumarolic activity seen at the Coyote Canyon area a couple of miles south of the operating geothermal field.

Pumping of the Goerenger well for the injection augmentation program resulted in temporary water table changes that were regularly monitored from mid 1997 into early 2000 (Figure 9) by three water wells located several hundred feet to about fifteen hundred feet north, southeast, and west of the Goerenger well and power plant. Pumping rates for the Goerenger well during this time period are not shown on Figure 7 but Benoit et al., (2000) and Kennedy et al., (1999) present the following generalized pumping rates. Pumping of the Goerenger well began on July 12, 1997 at about 700 gpm and continued at this rate until Oct. 20, 1997. There was no Goerenger well pumping from Oct. 20, 1997 until March 27, 1998 when pumping resumed, most likely at about 700 gpm. In late August 1999 a larger pump was installed in the Goerenger well and the pumping rate increased to as much as 2000 gpm resulting in significantly larger drawdowns in the shallow groundwater monitoring wells.

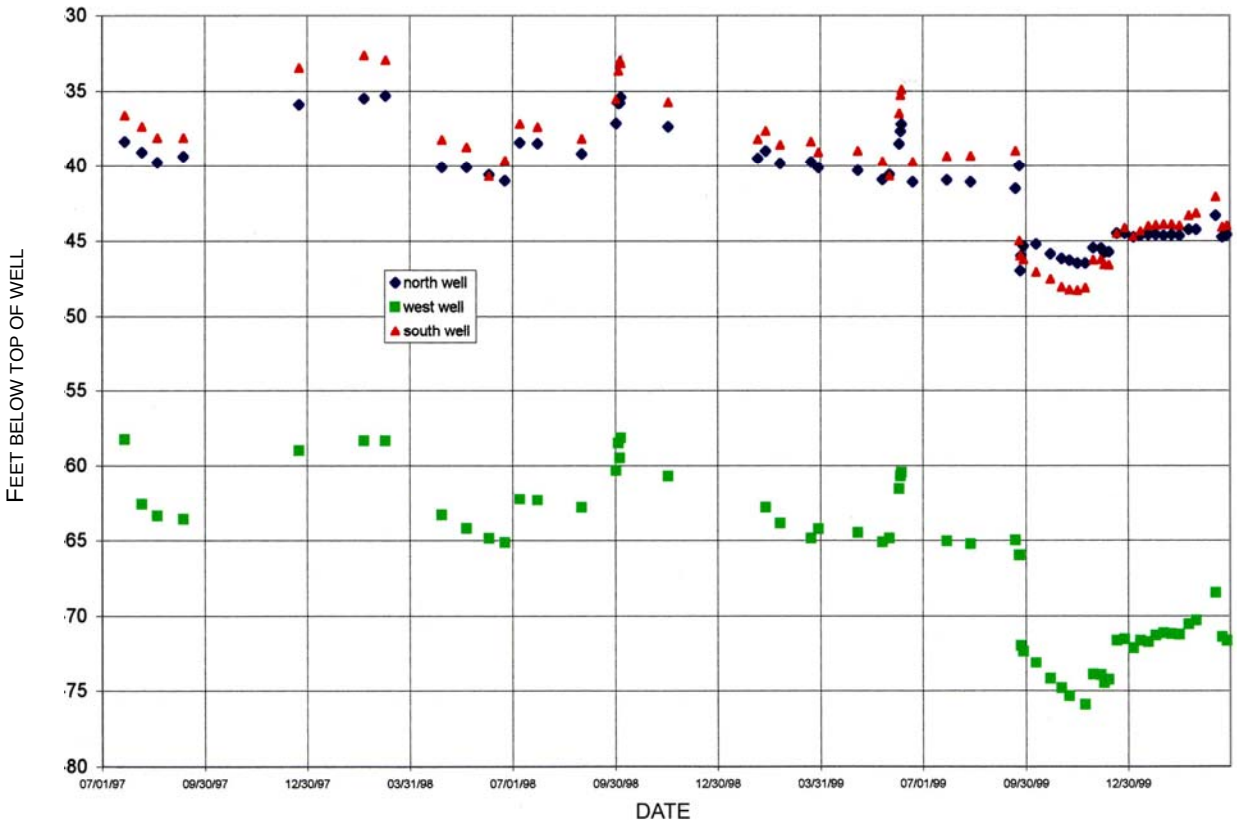

Figure 9: Water level trends in response to pumping of the Goeringer Well

Dixie Valley Numerical Modeling

The Dixie Valley geothermal reservoir was numerically modeled prior to the start of production (Doughty et al., 1986). This was a major modeling exercise utilizing the Tough code with pressure interference calibrations from the six-well flow test (Desormier, 1987). The TOUGH code is a multiphase flow code developed by researchers at the Lawrence Berkeley National Laboratory (Pruess, 1987). However, no attempt was made to incorporate any part of the shallow groundwater system into this

numerical model as no holes completed in the shallow groundwater system were monitored specifically for responses to geothermal production. The > 6000' vertical separation between the geothermal wells completed in the geothermal reservoir and the shallow groundwater system provided the justification for not monitoring any wells not known to be completed within the geothermal reservoir. Also, at the time (mid 1980s) there were only two existing shallow groundwater wells near the geothermal field and one of these, the Goerenger Well, was being pumped to irrigate an alfalfa field.

COYOTE CANYON GEOTHERMAL SYSTEM

Coyote Canyon Exploration History

The Coyote Canyon Area is located about 3 miles southwest of the operating Dixie Valley geothermal power plant and includes wells 53-15 and 36-14 (Figure 2). It is shown as the Section 10 Fumaroles thermal anomaly on Figure 1. It is about two miles from the southernmost active injection well in the producing field. Ironically, it was one of the first geothermal areas to be drilled to shallow depths and found to be hot in Dixie Valley as part of a mineral exploration program in the 1960s but one of the last to be explored at depth. Republic Geothermal drilled the 53-15 hole (Figure 2), which turned out to be the first geothermal exploration hole drilled in Dixie Valley with temperatures above boiling at 302 ^{o}F. The first true deep exploration well in this area, 66-21, drilled in 1979, found a temperature of 426 ^{o}F at a depth of 9780 feet but this hole produces only a few gallons per minute of warm artesian fluid at the surface (Williams, et al., 1997). The disappointing results from this hole effectively focused geothermal exploration on the nearby producing field until the early 1990's.

In the early 1990's Caithness Resources transferred a Standard Offer #4 Power Purchase Contract from Steamboat to Dixie Valley. This formed the basis for a second round of deep drilling in the area. In 1993 Dixie Valley Power Partners, a partnership between Caithness Resources and Florida Power and Light, drilled the 62-23 well and its redrill 62A-23 to a maximum measured depth of 11,401'. Neither leg of this well would produce (Blackwell and Smith, 2005) but the well was exceptionally hot with a measured temperature of 512 ^{o}F (Blackwell, et al., 2000). This led to the drilling of the 36-14 well in 1993 to a true vertical depth of 10,007' and a bottomhole temperature of 545 ^{o}F (Blackwell et al., 2000), which makes it by far the hottest hole ever drilled in Nevada. The 36-14 well produced from fractures near the bottom of the well (Blackwell et. al., 2000) but after the well was drilled Dixie Valley Power Partners sold the Standard Offer #4 Contract back to Southern California Edison and no further drilling has occurred in this area. However, recently TerraGen has acquired the geothermal leases in this area and is expressing a strong interest in resuming exploration and development at Coyote Canyon as evidenced by purchasing a single parcel during the July 14, 2009 BLM auction for $2.65 million and preparing an Environmental Analysis for the drilling of additional exploration wells.. There will be additional geothermal exploration efforts in this area; whether there is additional development will depend upon the exploration results.

Coyote Canyon Geology

The Coyote Canyon prospect has a very similar geology to the nearby producing field. It is located along the Stillwater Fault Zone in generally the same rocks as the producing field. There are weak fumaroles or steaming ground at the front of the range in the Coyote Canyon prospect in Sections 10 and/or 15, T 24 N, R 36 E which are similar in intensity to the Senator Fumarole in its pre-production state in the

operating field. There are also extinct or inactive siliceous sinter hot spring deposits in Sections 10 and 15 which demonstrate that relatively recently hot water was discharging just above the base of the range from the Coyote Canyon prospect. There may now be a subsurface flow of thermal fluid downhill from the range front into the shallow groundwater system that is similar to that described further north by Allis et al., (1999). Water from the sub hydrostatic Dixie Valley geothermal field apparently did not reach the surface to leave any siliceous sinter deposits. Blackwell et al., (2000) calculated a subsurface flow of thermal water in the Coyote Canyon prospect of a minimum of 3.2 gpm. This minimum seems unbelievably low compared to the 80 gpm that was calculated to flow out of the Senator Fumaroles area (Allis et al., 1999) when visually comparing the size and intensity of the two outflow plumes as shown on Figure 2 (Blackwell et al., 2000).

Coyote Canyon Hot Spring Chemistry

There are no active hot springs associated with the Coyote Canyon prospect. The chemistry of the water produced from the 36-14 well is not publicly available but it is true chloride water, much different and more saline than the mixed anion water present in the producing Dixie Valley field. Two high quality water analyses are available from the artesian flow produced by well 66-21 (Goff et al., 2002) (Table 1). The 66-21 water is also a sodium chloride type water significantly different from the mixed anion fluid produced in the operating field.

Geophysics

Much in the way of geophysics, such as airborne magnetics, gravity, seismic reflection lines, and temperature gradient hole drilling are available within and near the Coyote Canyon geothermal prospect. The temperature information is most relevant to the geothermal system because it responds directly to the geothermal resource. The shallow temperature gradients clearly show that Coyote Canyon and the operating field are parts of a larger thermal anomaly (Figure 2). To the southwest of the Coyote Canyon area there are relatively few temperature data available to closely constrain the temperature contouring (Figure 2).

Resource Speculation

With a measured temperature of 545 ^{o}F, the Coyote Canyon prospect has the highest temperature ever measured in Nevada or Utah. Only the Coso geothermal field which is clearly heated by magma has a higher measured temperature in the Basin and Range province. However, at the present time very little is actually known about the geothermal resource at Coyote Canyon other than that it is close to the operating Dixie Valley field but has different characteristics. The only published model of this resource (Blackwell et al., 2000 and Figure 5b) suggests that there are two fault zones that may host the reservoir and this model indicates that these faults have nearly vertical dips. The possible size and extent of this reservoir are not known with any certainty and there has been no speculation as to size other than the Pier Report (GeothermEx, 2004) which gives a minimum 107 MW for 30 years from an assumed volume of 4.69 mi^3 with the caveat that commercial levels of distributed permeability need to be established.

Coyote Canyon is the hottest and therefore one of the most likely prospects in Dixie Valley to be developed into a large power generation project. TerraGen has submitted a very extensive drilling program to the Bureau of Land Management for approval. However, until additional drilling is

performed and additional data become available or public there is relatively little that can be said about this resource and the timing of any development is unknown.

JERSEY VALLEY GEOTHERMAL SYSTEM

Jersey Valley Exploration History

The geothermal industry during its heyday of exploration in Nevada in the 1970s and 1980s largely ignored the very remote Jersey Valley. The only surviving results of this era are a dozen or so shallow temperature gradients outlining a thermal anomaly of moderate size and intensity (Figure 1) and a chemical analysis of the thermal water (Mariner et al., 1974, Goff et al., 2002). The Pier Report (GeothermEx, 2004) does not mention the Jersey Valley geothermal prospect. Only in the past few years has the Jersey Valley geothermal system been subject to any significant geothermal exploration by the Ormat Corporation after they obtained leases covering the thermal anomaly. Since late 2007 Ormat has drilled at least 2 "observation" holes to permitted depths of 3000' and at least five production wells to unknown depths.

Jersey Valley Geology

The Jersey Valley hot springs are located on alluvial fans in the SE ¼ of Section 29, T 27 N, R 40 E from ½ to 1 ½ miles east of the western front or scarp of the Fish Creek Mountains. Nosker (1981) describes one 133 ^{o}F spring pool flowing at approximately 1 gpm and a second spring source about 600' to the west of the pool with a temperature of 109 ^{o}F and a flow of about 1 gpm. Mariner et al., (1974) published a temperature of 84 ^{o}F, and a flow rate of 5 gpm. Goff et al. (2002) reported a much higher flow rate of 53 gpm and a temperature 138 ^{o}F. The cause or significance of these differences is not known. Both thermal water sources are within a 1 mile long (east-west) siliceous sinter and siliceous cemented alluvium deposit described as forming a low hill and extending for over half a mile in length and rising 3 to 4 feet above the surrounding valley floor (Garside and Schilling,1979, Nosker, 1981). If this mound is truly made of silica then this is one of the more significant young hot spring siliceous sinter deposits in Nevada and is worthy of significant geothermal exploration. Blackwell et al., (2005) describe the sinter mound as being composed of mixed travertine and sinter.

The geothermal exploratory work performed to date has been to the east of the Jersey Valley hot springs and to the west of the range front. The controlling structure for the Jersey Valley geothermal system seems to be the Jersey Valley Fault Zone (Anderson, 2000) which separates the Fish Creek Mountains from Jersey Valley. This little studied fault zone trends from north-south to northeast-southwest and as such is properly oriented to pull apart during movement and host a geothermal reservoir. The existing holes and Ormat drilling locations indicate targeting of a north-south segment of the Jersey Valley fault zone. Ormat must have proprietary data refining the targeting more specifically.

Jersey Valley Hot Spring Chemistry

The water from Jersey Valley hot springs is dilute neutral bicarbonate water that is very similar to many other thermal waters in Central Nevada, and has been analyzed by at least three different researchers (Mariner et al., 1974, Nosker, 1981, and Goff et al., 2002. Some species such as Li, B, and F reported by Nosker appear to be erroneously low and should probably be ignored. The chemistry gives predicted

silica temperatures of 288 to 309 ^{o}F using the quartz geothermometer and magnesium corrected Na-K-1/3Ca temperatures of 313 to 336 ^{o}F (Mariner et al., 1974, Goff et al., 2002). The Jersey Valley hot spring water has 1.1 T. U. of tritium suggesting a minimum age of around 40 years (Shevenell and Goff, 1995). This is somewhat unique for Nevada hot spring water in that most of them contain less than 0.1 TU (Mariner et al., 1983, Shevenell and Goff, 1995)

Jersey Valley Geophysics

The most definitive publicly available geophysical information on the Jersey Valley geothermal system is from Phillips Petroleum shallow temperature gradient information from the early 1980s. Ten holes were drilled to a maximum depth of 500' and mostly outlined a thermal anomaly underlying a very modest 4 to 6 square miles of land (Figure 1). The most intense part of the shallow thermal anomaly is adjacent to the Jersey Valley fault zone which indicates that a segment of the Jersey Valley fault zone is the structure controlling the location of the geothermal system; much like the Stillwater fault zone controls the Dixie Valley geothermal system. Geophysics of a more regional nature such as gravity and aeromagnetics are available in the Jersey Valley region (Nosker, 1981) but they are not described here as they probably are little influenced by the geothermal system.

Jersey Valley Resource Speculation

Compared to the shallow thermal anomalies associated with other currently producing geothermal fields in Nevada such as Beowawe, Desert Peak, or Bradys the Jersey Valley thermal anomaly is not particularly impressive either in terms of size or intensity. The large siliceous sinter mound indicates that in the recent past the thermal spring was much more active and that the temperature of the geothermal system was recently at or above 356 ^{o}F. This temperature is modestly above the 336 ^{o}F prediction of the magnesium corrected Na-K-Ca geothermometer.

All of the Ormat data to date from this drilling are confidential but on a Nov. 13, 2009 conference call to investors Ormat stated they have drilled 5 wells, completed a long-term flow test, and intend to have a 15 MW power plant operating at Jersey Valley by the end of 2010 and another 15 MW on line by the end of 2011. The first 15 MW power plant is now under construction. These represent the most concrete new geothermal power plant development plans in the Dixie Valley area. The type of cooling for the power plant has not been publicly specified. If water cooling is selected then this would potentially become a large user of Jersey Valley groundwater. There currently is no significant groundwater usage or development in Jersey Valley.

McCOY HOT SPRING GEOTHERMAL SYSTEM

McCoy Exploration History

The McCoy Hot Spring area (not to be confused with the large McCoy area located east of Dixie Valley (Figure 1)) has seen basically no geothermal exploration other than sampling and chemical analysis of the hot spring water. It is located in SW ¼ of NW ¼ Sec. 33, T 26 N, R 39 E in the northernmost part of Dixie Valley and is the unnamed hot spring located closest to Jersey Valley on Figure 1.

McCoy Geology

The Mc Coy hot spring is located in the central part of the northeastern arm of Dixie Valley. It discharges from a pool about 120 feet in diameter in Quaternary alluvium. The discharge rate is reported as $\geq$15 gpm of 115 ^{o}F water (Goff et al., 2002). This spring occurs along an unnamed north-south trending fault zone that extends from the southern end of the Tobin Range out into the northeastern arm of Dixie Valley (Anderson, 2000). This fault zone has not been studied in any detail and within the valley is largely defined by aligned spring discharges. The surface relief along the fault traces could be the result of spring-mound construction. These faults may be structurally continuous with the Tobin section of the Pleasant Valley fault zone but they apparently were not activated during the 1915 Pleasant Valley earthquake. No travertine or siliceous sinter deposits are associated with McCoy hot spring.

McCoy Chemistry

The thermal water produced by McCoy hot springs has some contradictory characteristics. It is fairly dilute mixed anion water quite rich in calcium and magnesium but it also has the highest chloride content (228 ppm) of any thermal water discharging at the surface in Dixie Valley. The chalcedony geothermometer predicts a subsurface temperature of only 124 to 133 ^{o}F and the magnesium corrected Na/K/4/3Ca geothermometer suggests a subsurface temperature of 136 ^{o}F (Goff et al., 2002). These are the lowest predicted subsurface temperatures of all the thermal waters in Dixie Valley.

McCoy Geophysics

No detailed geophysical surveys have been specifically targeted on the McCoy geothermal system.

McCoy Resource Speculation

The McCoy geothermal resource has been used only for limited agricultural irrigation purposes. Given the low predicted subsurface temperatures it is unlikely that there will be any serious exploration or development of this geothermal system for other purposes. GeothermEx (2004) did not include the McCoy geothermal system in the PIER Report. The McCoy geothermal system is the coolest in Dixie Valley in terms of chemically predicted subsurface temperatures. No exploration work has been performed on this system so nothing can be said about its possible size. Such low temperatures may imply that McCoy may be viewed as more of a deeper part of the shallow groundwater system than as a true geothermal system.

LOWER RANCH GEOTHERMAL SYSTEM

Lower Ranch Exploration History

The Lower Ranch area has seen no significant geothermal exploration other than water sampling by Mariner et al., (1974) and Goff et al., (2002) in 1997 and 1998. Lower Ranch is located in NW ¼ Sec. 16, T 25 N, R 39 E and is shown of Figure 1 with two closely spaced hot spring symbols southwest of Jersey Valley.

Lower Ranch Geology

Lower Ranch hot springs are located at the southern end of the Jersey Valley Fault Zone (Anderson, 2000), the same fault zone hosting the Jersey Valley geothermal system. The southern end of the Jersey Valley fault zone partially defines the eastern margin of the northernmost part of Dixie Valley. It is interpreted to have much less offset at Lower Ranch than at its northern Jersey Valley end (Anderson, 2000).

There is a cluster of several hot springs and seeps with a maximum temperature of 105 ^{o}F that flow from a 1 ¼ mile long northeast trending travertine deposit, the largest such deposit within Dixie Valley. The total flow of thermal water has been reported at 100 gpm (Blackwell et al., 2005), making it the largest thermal water flow in Dixie Valley. This deposit is located about 1 mile west of the front of the Augusta Range and has been offset by a recently active normal fault with up to 130 feet of vertical displacement (Blackwell et al., 2005). The northeastern end of the deposit contains some siliceous sinter near the bottom of the deposit which has provided U-Th and U-Pr disequilibrium dates of 54,000 and 39,000 years (Goff et al., 2002). The siliceous sinter implies that the thermal fluid was much hotter 39,000 to 54,000 years ago as geothermal water needs to be hotter than about 360 ^{o}F to deposit siliceous sinter.

The samples contain <0.07 T.U. of tritium indicating the thermal water has been out of atmospheric circulation for about 80 years (Shevenell, L., and Goff, F., 1995). This would be in agreement with the low measured and predicted subsurface temperatures.

Lower Ranch Chemistry

There are three good quality analyses of the thermal waters (Mariner et al., 1974, and Goff et al., 2002). This water is dilute bicarbonate water with a high magnesium content of 13 to 15 ppm. The chalcedony geothermometer predicts a subsurface temperature of only 145 ^{o}F. The magnesium corrected Na/K/4/3Ca geothermometer gives a predicted subsurface temperature of only 108 to 135 ^{o}F (Goff et al., 2002).

Lower Ranch Geophysics

No site specific geophysical surveys are known to have been performed in the vicinity of the Lower Ranch hot springs.

Lower Ranch Resource Speculation

The Lower Ranch geothermal system is one of the coolest systems in Dixie Valley in terms of measured surface and predicted subsurface temperatures. No exploration work has been performed on this system so little else can be said about its possible size. GeothermEx (2004) did not include this geothermal system in the PIER Report. Such low temperatures may imply that this may be viewed more a deeper part of the shallow groundwater system than as a true geothermal system. It is unlikely that there will be any large scale industrial use of this water in the foreseeable future.

SOU or SEVEN DEVILS GEOTHERMAL SYSTEM

Sou Exploration History

Sou Hot Springs are located in the SE ¼ of Section 29, T 26 N, R 38 E at the southern edge of the Sou Hills, about 7 ½ miles northeast of the Senator Fumarole area (Figure 1). Mariner et al. (1974) published a water analysis of the hot spring water and Republic Geothermal Inc. drilled the shallow (≤ 500') hole RDV-2A and the RDV-5 to a depth of 1530' about ¼ mile south of the hot springs during the mid 1970s. Sun Oil also drilled one shallow hole near the springs in the same time frame. During this time the Mackay Minerals Research Institute (1981) performed some regional chemistry and air photo studies that included the Sou area. As both the hot spring geothermometers and the RDV-5 hole were not particularly encouraging no additional drilling has been performed near these springs for the past 3 decades. A University of Nevada Reno Master's Thesis (Nosker, 1981) describes the thermal springs, their travertine deposits, and the local geology. The PIER Report (GeothermEx, 2004) optimistically gives Sou Hot Springs a potential reservoir temperature range of 180 to 370 ^{o}F and a possible generation capacity of 3.3 to 9.5 MW, which must in large part be based on the 370 ^{o}F value.

In August 2007 Ormat picked up geothermal leases near Sou Hot Springs at a competitive BLM auction. Since then Ormat has reportedly acquired 7 sections of additional Federal leases issued to Great Basin Geothermal prior to 2007 in the vicinity of the hot springs. There is no record of Ormat having performed any additional drilling at the Sou resource.

Sou Geology

Sou Hot Springs are located at the southernmost point of the Sou Hills and have temperatures currently ranging from 86 to 163 ^{o}F. Sou Hot Springs are not located on the Stillwater Fault Zone which passes about 4 miles to the west of the hot springs at the eastern base of the Stillwater Range. The hot springs are along what has been interpreted to be an east-west trending left-lateral strike slip zone at the western end of the "Sou Hills-Eureka-Ely transverse zone" which separates east-tilted ranges to the north from west-tilted ranges to the south (Nosker, 1981). The maximum topographic relief across this transverse zone near Sou Hot Springs is about 1500'. This general structural setting makes the Sou geothermal system somewhat unique in Dixie Valley that it is not associated with a known or inferred N-S to NE-SW trending normal fault which control and host most Nevada geothermal systems. The closest such fault to Sou Hot Springs is the Sou Hills section of the 71 km long NNE trending 1915 Pleasant Valley fault scarp sequence (Anderson and Machette, 2000). However, the closest of these scarps are more than 3 ½ miles to the north of Sou Hot Springs.

Nosker (1981) identified 5 or 6 east-west trending lineaments in the southern part of the Sou Hills but none of these lineaments appear to have offset any formational contacts in the Mesozoic or Tertiary rocks. She generally describes the southern Sou Hills as being intensely faulted but does not describe any of the individual faults. None of Nosker's east-west trending lineaments appear on the U. S. Geological Survey Quaternary Fault and Fold database which implies that the east-west trending features are relatively old. All this leads to the general observation that the structural controls of Sou Hot Springs have not yet been convincingly identified.

Nosker (1981) notes eight thermal springs at Sou surrounded by travertine mounds 100' to 120' in diameter and 10' to 25' in height. There is no mention of these mounds having any particular alignment

but examination of aerial images shows a fairly strong north-south elongation of the mounds. No previous author has proposed a north-south structure to be controlling the discharge of the geothermal system. The travertine found at the Sou hot spring complex is a fairly reliable indicator of relatively low resource temperatures.

Sou Hot Spring Chemistry

There are 10 more or less complete high quality analyses of the Sou thermal water collected over a period of 25 years and analyzed by three different laboratories. All of these samples are quite similar indicating little or no change in the water chemistry with time or temperature. The water is truly mixed water with no single major cation or anion species dominating the composition and none being present in trivial amounts. Perhaps the most striking feature of the Sou water chemistry is the high magnesium content of 20 to 22 ppm in water as hot as 163 ^{o}F at the surface.

The silica geothermometer predicts subsurface temperatures of 228 to 246 ^{o}F and the chalcedony geothermometer predicts 176 to 194 ^{o}F temperatures. The Na-K-4/3Ca geothermometer used by Mariner et al., (1974) and Mackay Minerals Research Institute (1980) gave predicted temperatures of 212 and 199 ^{o}F respectively, but correcting for the high magnesium content reduces these predicted temperatures to the 172 to 181 ^{o}F range (Goff et al., 2002)which is in close agreement with the chalcedony geothermometer. In this case it is likely that the chalcedony geothermometer is more appropriate than the quartz geothermometer due to the Na-K-Ca geothermometer predicting temperatures below boiling.

Surface water temperatures as high as 178°F were reported in the 1870's (Hague and Emmons, 1877) and the liquid levels were then near the top of the travertine mounds. Now water levels are on the order of 10 or 20 feet lower and reported temperatures are 15 F cooler. The total discharge from Sou Hot Springs is about 50 gpm, making it the largest volume thermal discharge along the western edge of Dixie Valley, and second only behind the Lower Ranch Hot Spring. It is possible or even likely that extensive irrigation pumping by the Brinkerhoff Ranch to the east of Sou Hot Springs has lowered the hot spring liquid levels and discharge rates. A sample of water from the hottest discharge at Sou Hot Springs contains no measurable tritium (Shevenell and Goff, 1995).

Sou Geophysics

The most significant geophysical measurements near Sou Springs are the temperatures in the 1530 foot-deep RDV-5 hole located a short distance south of the Sou Hot Springs. This well found a temperature of 142.5 ^{o}F at a depth of 1530' with a bottomhole temperature gradient of only 0.6 ^{o}F/100'. This is very low, perhaps ¼ of what the regional background temperature gradient should be. With only one other hole near Sou Springs it is difficult to infer much about the geothermal system, other than to note that the limited subsurface temperature data are consistent with the low geothermometer temperatures. Several additional temperature gradient holes would need to be drilled around Sou Hot Springs to determine the amount of any subsurface discharge, delineate the true extent of the geothermal system, and identify what structure is controlling the rise of the thermal water. However, most of the area to the north and west of Sou Hot Springs lacks existing road access which probably explains why holes have not already been drilled here.

Three shallow temperature gradient holes, as part of a regional temperature gradient hole program, have been drilled 4 to 5 miles east and north from the hot springs. These have abnormally low to regional background temperature gradients of 1.3, 1.4 and 2.9 ^{o}F/100' and therefore provide little information on the geothermal system.

Allis et al., (1999 Figure 1) indicate a large hot water outflow zone flows south from Sou Hot Springs into Dixie Valley toward Hyder Hot Springs. The existence of a plume the size shown is highly questionable as there are no temperature gradient holes in most of this area. Several more holes would be required to confirm the presence of a plume extending 5 or 6 miles south of Sou Hot Springs. The temperature contouring of Blackwell et al., (2007)(Fig. 1) showing Sou Hot Springs as a small isolated thermal anomaly is more realistic.

Sou Resource Speculation

Following the drilling of the RDV-5 hole the geothermal industry has avoided further work at the Sou geothermal system. The most realistic predicted subsurface temperatures from the chemical geothermometers are less than boiling so provide no encouragement that a resource with temperatures high enough for electrical power generation exists in this geothermal system. In spite of this knowledge, nearly all Federal lands within a two to three mile radius of the hot springs have been leased within the past few years. At the present time it appears that Ormat controls most of these leases but has done no new exploration work in the area.

HYDER GEOTHERMAL SYSTEM

Hyder Exploration History

The Hyder geothermal system is shown near the center of the valley due east of the Senator Fumaroles area (Figure 1). They are in the SW ¼ of Section 28, T 25 N, R 38 E at the eastern edge of the flat valley floor of Dixie Valley. Mariner et al. (1976) published a water analysis of the thermal fluid and five shallow ($\leq$ 500') temperature gradient holes were drilled within 1 to 1.5 miles of Hyder Hot Springs (RDV-3A, RDV-4A, RDV-5A, G-1, and C-1) by three different exploration companies in the late 1970s. One deeper hole, RDV-2 was drilled to a depth of 1580' about ¾ mile NNE of Hyder Hot Springs by Republic Geothermal. The Mackay Minerals Research Institute (1981) performed some regional chemistry and air photo studies that included the Hyder area. However, as both the hot spring geothermometers and the RDV-2 hole were not particularly encouraging no significant exploratory work has been performed near Hyder Hot Spring for the past 3 decades.

The PIER Report (GeothermEx, 2004) optimistically gives Hyder Hot Springs a potential temperature range of 180 to 310 ^{o}F and a possible generation capacity of 5.5 to 15 MW, which must in large part be based on the admittedly uncertain 310 ^{o}F resource temperature value. Much of the Hyder resource capacity predictions in the PIER Report were based on default parameters as so little is known about the geothermal system. A few years ago the Federal lands to the north and west of Hyder Hot Springs were leased to Great Basin Geothermal LLC. These leases have reportedly been acquired by Ormat in 2008. Federal lands to the east and south of Hyder Hot Springs may be unleased.

Hyder Geology

Hyder Hot Springs have a maximum temperature of 144 ^{o}F. A gentle alluvial fan or pediment rises to the east of Hyder Hot Springs. The nearest bedrock outcrop is 3 to 5 miles to the east of Hyder Hot Springs. Hyder Hot Springs have deposited the highest travertine mound associated with any geothermal system in the Dixie Valley area. Unfortunately, travertine is a fairly reliable indicator of relatively low resource temperatures. The total surface discharge from Hyder Hot Springs is about 30 gpm. Hyder Hot Springs are located just south of an unnamed fault zone that extends into Dixie Valley from the south end of the Tobin Range (Anderson, 2000). Grauch, (2002) shows a number of inferred sub parallel shallow faults, based on a low altitude aeromagnetic survey on both sides of Hyder Hot Springs with trends ranging from N-S to NE-SW. However, there are no recent fault scarps in the immediate vicinity of Hyder Hot Springs. The lithologic log from the 1580 foot-deep RDV-2 hole does not appear to be in the public record so little is directly known about the subsurface geology near Hyder Hot Springs.

Hyder Hot Spring Chemistry

There are 9 complete high quality analyses of the Hyder thermal water collected over a period of 22 years and analyzed by three different laboratories. All of these samples are quite similar indicating little or no change in chemistry with time or temperature. The Hyder thermal water has an abnormally high 10 ppm of magnesium for a fairly hot spring.

The quartz geothermometer predicts subsurface temperatures of about 239 ^{o}F and the chalcedony geothermometer predicts 183 to 192 ^{o}F temperatures. The chalcedony geothermometer is more appropriate and with near pH neutral conditions there is no pH correction needed. The Na-K-4/3Ca geothermometer used by Mariner et al., (1974) and Mackay Minerals Research Institute (1980) gave predicted temperatures of about 257 ^{o}F, but correcting for the high magnesium content reduces these predicted temperatures to the 160 to 172 ^{o}F range (Goff et al., 2002) which is in reasonable agreement with the chalcedony geothermometer. A sample of water from the hottest discharge at Hyder Hot Springs contains 0.12 T. U. (Shevenell and Goff, 1995).

Hyder Geophysics

The most significant geophysical measurement near Sou Springs are the temperatures in the 1580 foot-deep RDV-2 hole located about ¾ mile NNE of Hyder Hot Springs. This well encountered a very high temperature gradient to a depth of 1100'. However, below 1200' the temperature profile is isothermal at 160 ^{o}F, which happens to be very close to the Na-K-4/3Ca-Mg geothermometry. There is no way to predict how much deeper the temperature of 160 ^{o}F might extend. With only one deeper hole near Hyder Springs it is difficult to infer much about the geothermal system, other than to note that the modest temperatures found in RDV-2 are consistent with the low predicted geothermometer temperatures. Several additional temperature gradient holes would need to be drilled around Hyder Hot Springs to determine the amount of any subsurface discharge, delineate the true extent of the geothermal system, and identify which structure is controlling the rise of the thermal water. However, most of the area to the south and east of Hyder Hot Springs lacks existing road access which probably explains why holes have not already been drilled in those locations.

Hyder Resource Speculation

Following the drilling of the RDV-2 hole the geothermal industry has avoided further work on the Hyder geothermal system. The most realistic predicted subsurface temperatures from the chemical geothermometers are between 160 and 192 ^{o}F and so provide no encouragement that a resource with temperatures high enough for electrical power generation exists in this geothermal system. In spite of this knowledge, much of the Federal lands within a two to three mile radius of the hot springs have been leased within the past few years. At the present time it appears that Ormat controls most of these leases but has done no new exploration work in the area.

DIXIE COMSTOCK MINE GEOTHERMAL SYSTEM

Dixie Comstock Mine Exploration History

The Dixie Comstock Mine geothermal system is an informal name given to a blind geothermal system located between the Coyote Canyon and Dixie Meadows geothermal systems (Figure 1). Near boiling water was first encountered in this geothermal system during mining operations in the Dixie Comstock Mine in the 1930s. Intense heat below a depth of 75 feet restricted the mining activity. About a dozen temperature-gradient holes were drilled in the vicinity of the mine by Southland Royalty Company in the late 1970s. In 1979 Thermal Power Company drilled the 45-14 well to a depth of 9022' immediately east of the County Road and about 1000' east of the range front. This well encountered a maximum temperature of 385 ^{o}F at the bottom of the hole and currently produces a few gallons per minute of boiling artesian fluid. No significant geothermal exploration work has been performed in this area since 1979.

Dixie Comstock Mine Geology

The geothermal system here is clearly hosted at shallow depths by the Stillwater Fault Zone and has been described in detail by Vikre (1994). The bedrock geology in this area is very similar to that at Coyote Canyon and the operating field with rocks of the Humboldt Lopolith exposed in the range above the mine. However, the 45-14 well failed to encounter these rocks. Instead 45-14 primarily penetrated Triassic shale. Presumably the Triassic marine shale lies a short distance (hundreds of feet?) beneath the mountain range at this point. Eroded siliceous sinter deposits are present on the west side of the Stillwater Fault zone and demonstrate that in the past several thousand years hot water actively discharged from the geothermal system in the vicinity of the Dixie Comstock Mine.

Dixie Comstock Mine Chemistry

The water produced from the still flowing deep 45-14 well is a chloride rich water much more similar to that from well 66-21 in the Coyote Canyon area than to the Dixie Meadows fluid located further south (Goff et al., 2002). There are not enough data available to conclusively determine if the Dixie Comstock water and the Coyote Canyon water come from a common source. The chemical geothermometers from the well 45-14 water predict a subsurface temperature of about 392 ^{o}F, virtually identical to the bottomhole temperature of the well (Goff et al., 2002).

Dixie Comstock Mine Geophysics

The dozen or so temperature gradient holes drilled within a few miles of the Dixie Comstock Mine partially outline a modest size shallow thermal anomaly, perhaps 3 miles long (Figure 1). The anomaly is only modestly intense away from the mine area. The short distance between the playa and the range front largely confine the temperature data to two dimensions. The limits of this thermal anomaly are not well defined, as it is possible the cooler north and south limits might be impacted by flows of cold subsurface water out of the mouths of canyons, White Rock and Mississippi being the most important. The temperature profiles from these holes are mostly linear indicating that there is only a very modest flow of hot water through the shallowest parts of this geothermal system at shallow depths.

Dixie Comstock Mine Resource Speculation

The fact that there has been no significant exploration in this area for 30 years is a reasonable indication that the geothermal industry has fairly low expectations for the Dixie Comstock Mine area. The area has been continuously under geothermal lease for over 30 years but there are no indications that any significant exploration work will be performed in the foreseeable future.

DIXIE MEADOWS GEOTHERMAL SYSTEM

Dixie Meadows Exploration History

Dixie Meadows was one of the first areas to be drilled for geothermal exploration purposes in Dixie Valley with shallow temperature gradient holes in 1976, as it was privately owned at that time. There has been no additional drilling at Dixie Meadows for the past 3 decades but the area has been included in some more regional geological, geochemical, and geophysical studies. In the August 2007 BLM lease auction 2038 acres partially surrounding Dixie Meadows brought in a bonus bid of $200/acre ($407,800 total) by Ormat. However, since purchasing this lease there is no public record of Ormat performing any additional exploration in the Dixie Meadows area.

Dixie Meadows Geology

The Dixie Meadows Hot Springs lie immediately east of the Dixie Valley road in SE Sec. 5 and NE Sec. 8, T 22 N, R 35 E (Figure 1). The hot springs discharge from unconsolidated Quaternary lacustrine sediments. There are many seeps and springs, Bohem et al. (1980) estimated 35, with temperatures ranging from cold to 182 ^{o}F (Goff et al., 2002) in an area covering perhaps a square mile along the western edge of the playa. The hottest springs however are concentrated in an area probably less than ¼ square mile in size near the Dixie Valley gravel road. There are no travertine or sinter deposits associated with these springs. The total discharge is difficult to estimate but has been reported at 50 gpm (Garside and Schilling, 1979). The largest spring near the road discharges 2.5 gpm.

Equally significant, from a geothermal perspective, two fumaroles have recently been located west of the road (Kennedy-Bowdoin et al., 2004). It is unknown how long these fumaroles have existed. One is located on the alluvial fan between the road and the range front and the second is located in a dozer cut at the base of the range front in hydrothermally altered rocks. These fumaroles had not been mentioned in the literature prior to 2004.

Two basic conceptual possibilities exist to explain the presence of the hot springs and fumaroles at Dixie Meadows (Blackwell and Smith, 2005). A series of faults paralleling the range front (splays of the Stillwater Fault zone) might allow thermal fluids to rise up generally beneath the thermal features (Smith et al., 2001, Kennedy-Bowdoin et al., 2004). The second possibility is that thermal fluid rises up along the Stillwater fault at the base of the range and then flows laterally downhill to the east to intersect the ground surface at the elevation of the playa. This would also allow steam to be present along the range front and the hot water to be present some distance away from the fault and resembles the conditions postulated in the northern part of the operating Dixie Valley geothermal field. There has not been enough drilling to conclusively distinguish between these two possibilities.

In a more regional perspective the Dixie Meadows Hot Springs occur close to the southern margin of the gabbroic rocks of the Humboldt Lopolith as exposed in the Stillwater Range (Speed, 1976). As such Dixie Meadows is the southernmost of several closely spaced high-temperature geothermal systems associated with the combination of both the Stillwater Fault Zone and the Humboldt Lopolith. Also, Dixie Meadows and these other geothermal systems extending up to the operating field are located mostly north of the surface ruptures associated with the 1954 earthquakes in the Stillwater Gap (Caskey and Wesnousky, 2000). The 1954 ruptures terminate about 2 miles NE of Dixie Meadows. To the south of Dixie Meadows it is 20 or 30 miles to the Eleven Mile Canyon geothermal system. Fourteen cold temperature-gradient holes document a major separation between these two thermal anomalies (Figure 1).

Dixie Meadows Hot Spring Chemistry

The Dixie Meadows thermal water is very dilute sodium chloride/sulphate water with an exceptionally high fluoride content of 11 to 16 ppm and very low calcium and magnesium contents. The silica geothermometer for this water needs to be pH corrected as the pHs range from 8.2 to 8.8. Without the pH correction the quartz geothermometer gives values of 280 to 300 ^{o}F. The pH correction reduces these to the 261 to 284 ^{o}F range. The Na-K-Ca geothermometer needs no magnesium correction and gives predicted temperatures of 241 to 291 ^{o}F (Mariner et al., 1974, Goff et al., 2002). In geothermal systems the lower predicted temperatures often seem to be more correct. However, the lower predicted temperatures at Dixie Meadows should be viewed with some skepticism as a maximum temperature of 291 ^{o}F has been measured at a depth of 230 feet in a 1475 foot deep temperature gradient hole, Mobil 8g3 (Blackwell and Smith, 2005). A tritium content of -0.16 T. U. suggests that the thermal water has been out of atmospheric circulation for longer than 60 years (Shevenell and Goff, 1995).

Dixie Meadows Geophysics

Eight shallow (300') and relatively closely spaced temperature gradient holes have drilled in the vicinity of the thermal springs (Figure 1) for which the data are publicly available (Blackwell and Smith 2005). Additional nearby holes may still be proprietary but they assist in controlling the temperature contours defining the Dixie Meadows thermal anomaly as shown on Figure 1. All of the holes drilled near Dixie Meadows are basically in a NNE trending line and as such there is only a two dimensional representation of this thermal anomaly. Access (mud) and wilderness study area issues have historically limited drilling to the east and west of Dixie Meadows. Most of these 8 holes produced low temperature gradients and near background temperatures but two of them, 8g1 and 8g2 have high near-surface temperatures and

isothermal temperature gradients below depths of 100' and were drilled adjacent to thermal springs. Other nearby holes such as 8g4 are much colder showing that at least some of the margins of this thermal anomaly are very sharp, possibly from an interplay of shallow thermal water and cold groundwater discharging in the subsurface from the mouth of Hare Canyon. One deeper hole, 8g3, reached a total depth of 1500 feet and had a maximum temperature of 290 ^{o}F. The geology penetrated by this deeper hole is not known.

There is a sinuous zone of high gravity gradients running from 1 to 2 miles east of the Stillwater Range front for over 30 miles from South of Dixie Meadows to north of the operating geothermal field. This has been interpreted as representing a major buried normal fault strand that is responsible for most of the vertical offset between the valley and mountain range (Blackwell, et al., 1999, 2007, Smith et al., 2001). This high gravity gradient zone passes beneath the Dixie Meadows hot springs and thermal anomaly. Therefore, it is possible that hot water is rising from depth along this postulated fault to support the Dixie Meadows thermal anomaly (Kennedy-Bowdoin et al., 2004).

Dixie Meadows Resource Speculation

There has been enough exploration and drilling at Dixie Meadows to arrive at some fairly strong conclusions about the nature of this resource at least to depths of a couple of thousand feet. The predicted resource temperatures from the geothermometers, 284 ^{o}F for the pH corrected quartz thermometer and 291 ^{o}F for the Na/K/1/3/Ca geothermometer, are so close to the maximum measured temperature of 291 ^{o}F measured in the Mobil 8g3 hole that there is little doubt that the deeper parts of this resource will be close to 291 ^{o}F. It has been over two years since Ormat purchased the BLM geothermal lease in August 2007 and they have not yet initiated any drilling activities or permits for this area. It is unknown if Ormat will perform any further exploration activities in this area. TerraGen, who also has a lease position in the area, has recently proposed an extensive exploration drilling program to the Bureau of Land Management at Dixie Meadows.

CLAN ALPINE RANCH

Clan Alpine Ranch Exploration History

Clan Alpine Ranch is the northernmost of the three significant blind shallow thermal anomalies located south of the Humboldt Salt Marsh in Dixie Valley (Figure 1). All three (Clan Alpine Ranch , Pirouette Mountain, and Eleven Mile Canyon) at first glance appear to be located along a NE trend but this trend (if it really exists) cuts across the valley and doesn't follow any specific fault zone or trend identified on the U. S. Geological Survey Quaternary Fault and Fold Database or by any previous authors. The Quaternary Fault and Fold Database show each of these three thermal anomalies to lie on a different identified fault zone. The Clan Alpine Ranch thermal anomaly is located near the southeastern edge of Dixie Valley and is most likely associated with the Gold King Fault (Caskey et al., 1996) which is part of an unnamed fault zone in eastern Dixie Valley (Sawyer, 1999). The Clan Alpine Ranch anomaly is the least explored of the three southern thermal anomalies with only 14 shallow holes to maximum depths about 300 feet (Figure 1). Amax discovered this thermal anomaly in the late 1970s but there has been no further exploration in this part of the valley since 1979. There is rumor of a deeper hot water well or exploration hole drilled by Paul Plouviez.

Clan Alpine Ranch Chemistry

There are no known thermal springs in this part of Dixie Valley and apparently no water samples were collected from the Amax shallow temperature-gradient holes so no basic chemistry or chemical geothermometry are available.

Clan Alpine Ranch Geophysics

Temperature profiles from the shallow temperature-gradient holes show that hole 903-2, the hottest hole, has an isothermal temperature profile at about 162 ^{o}F below a depth of 230 feet (Blackwell and Smith, (2005). This might be an indication that this could potentially be the subsurface temperature of this geothermal resource.

Clan Alpine Ranch Resource Speculation

On July 14, 2009 3790 acres of BLM land within the immediate vicinity of the Clan Alpine Ranch thermal anomaly were leased (geothermal rights) to an individual named Paul Plouviez from Fallon. He has reportedly been attempting to interest geothermal exploration companies in this prospect.

PIROUETTE MOUNTAIN GEOTHERMAL SYSTEM

Pirouette Mountain Exploration History

The blind Pirouette Mountain geothermal system was discovered by Hunt Oil Company in 1976 as part of a regional temperature gradient exploration program (Figure 1). Over the next several years Hunt Oil drilled 19 shallow exploratory holes to a maximum depth of 500', 8 intermediate depth holes to 2000', and one deep well (66-16) to a depth of 7362'. Nothing was published on this area until Richards and Blackwell (2002) provided a natural heat loss estimate of 19 MW (thermal) for the Pirouette Mountain resource. Unfortunately, the Pirouette Mountain and Eleven Mile Canyons appear to be the only geothermal systems in Dixie Valley for which there were adequate data for the natural heat loss values to be calculated. In the PIER Report (GeothermEx, 2004) reported a maximum temperature of 189 ^{o}F at a depth of 2000' (GeothermEx, 2004). In 2008 the results of a detailed gravity survey and structural interpretation of the area and the locations of the geothermal exploration holes were published (Mankhemthong, et al., 2008). Thus only recently have even the hole locations at Pirouette Mountain have been made readily available to the public.

Pirouette Mountain Geology

The Pirouette Mountain geothermal system is located in the relatively narrow southern part of Dixie Valley. Contouring by Blackwell et al., (2007) indicates the thermal anomaly associated with this system may be the largest in Dixie Valley in terms of aerial extent and extends most or all of the way across the valley at this relatively narrow point (Figure 1). A more detailed map (Mankhemthong, et al., 2008) shows that the thermal anomaly is strongly associated with the eastern edge of Dixie Valley, possibly originating at the western base of Pirouette Mountain. The core of the thermal anomaly is about 3 to 5 miles north of the northernmost ruptures of the 1954 Fairview Peak rupture sequence. There are no active thermal features nor any known fossil features associated with this geothermal system. There are no publicly available lithologic logs or descriptions of the holes to assist in better understanding this geothermal system.

Pirouette Mountain Chemistry

There are no thermal springs in the area and there has been no written record of any thermal waters being recovered from any of the Pirouette Mountain holes.

Pirouette Mountain Geophysics

The primary geophysics available for this geothermal system are the 27 temperature-gradient holes which outline a large north-south elongated thermal anomaly (Blackwell and Smith, 2005) of about 5 ½ miles. The overall shape of the thermal anomaly would be in agreement with a northward flow direction of thermal fluid through Quaternary alluvium. The temperature profiles from most of the holes inside the Pirouette Mountain thermal anomaly show sharp reductions in temperature gradient to near isothermal conditions at depths of 300' to 350'. This is a possible indication that the thermal water in this system primarily lies 300' to 350' below the surface. Below a depth of 500'only the coolest holes show significant positive temperature gradients. The fluid level depths in these holes are not known, but it is possible that the sharp temperature gradient declines might represent the change from dry to water saturated conditions. A few of the temperature profiles show negative temperature gradients near a depth of 500' which must result from the lateral flow of water at temperatures between 86 and 185 ^{o}F.

Well 66-16, was drilled to a depth of 7363' with a bottomhole temperature of 165 to 185 ^{o}F (Blackwell and Smith, 2005). This is exceptionally cool for that depth, possibly being the lowest temperatures ever measured in Northern Nevada at that depth. Unfortunately, the temperature profile from well 66-16 is not publicly available but it is obvious that the temperature gradients in this well below a depth of 2000' must be extremely low or even locally negative because nearby temperatures at 2000'are already as high as 188 ^{o}F (Blackwell and Smith).

Blackwell et al., (2000) describe the deepest well (12,500' deep) in Dixie Valley, 62-21, which is located in the central part of the valley to the east of the Dixie Valley power plant as being representative of regional background thermal conditions. At a depth of 8200' the temperature in well 62-21 is about 300 ^{o}F, which is over 115 ^{o}F hotter than temperatures reported from the Pirouette Mountain 66-16 well. Therefore, Pirouette Mountain is not a normal Nevada geothermal system with abundant heat located beneath a shallow thermal anomaly. Instead there may actually be a deficiency of heat beneath at least part of the shallow thermal anomaly which presumably can be explained by downward moving water.

Pirouette Mountain Resource Speculation

The PIER report (GeothermEx, 2004) gives minimum, most likely, and mean possible electrical megawatt outputs of 16, 23, and 40 MW for the Pirouette Mountain geothermal resource. This is based on possible resource temperatures of 190 to 440 ^{o}F. The calculated heat loss of 19 MW (thermal)for Pirouette Mountain is quite interesting but given the low temperatures encountered to date, this may be a case where the heat is simply too dispersed over a large area to be recoverable as geothermal energy. Blackwell and Smith (2005) indicate that the minimum assumed temperature in the PIER report (190 ^{o}F) is most likely. A temperature of 190 ^{o}F in Dixie Valley will not produce any electricity. It seems unlikely that any additional exploration will be performed at Pirouette Mountain under present economic conditions.

ELEVEN MILE CANYON GEOTHERMAL SYSTEM

Eleven Mile Canyon Exploration History

The Eleven Mile Canyon geothermal prospect is the southernmost geothermal system known in Dixie Valley and is localized along the Stillwater fault zone (Figure 1). It was discovered by Hunt Oil Company in 1976 as part of a regional temperature gradient exploration program. Over the next several years Hunt Oil drilled 17 shallow exploratory holes, 6 intermediate depth holes to 2000', and two deep wells (72-23 and 52-14) to depths of 8248' and 7362'. These holes also had low enough temperatures that the prospect was abandoned and no further exploration has occurred. Nothing was published on this prospect until Richards and Blackwell (2002) provided a very modest natural heat loss estimate of about 4 MW (thermal) for the Eleven Mile Canyon resource. The 2004 PIER Report (GeothermEx, 2004) acknowledges the existence of the Eleven Mile Canyon geothermal area but present no data and make no predictions as to its possible generation capacity. In 2008 the results of a detailed gravity survey and structural interpretation of the area were published, and for the first time the locations of the geothermal exploration holes were documented (Mankhemthong, et al., 2008).

Eleven Mile Canyon Geology

Mankhemthong et al., (2008) show the Eleven Mile Canyon geothermal resource being located in a reentrant in the Stillwater Range near the mouth of Eleven Mile Canyon. This prospect is located adjacent to the southernmost surface ruptures of the 1954 Stillwater earthquake. Interestingly, the two deepest wells are located to the west of the east-dipping surface ruptures. This implies that the wells were either collared in the Stillwater Range block or passed into the bedrock of the range at shallow depths. The thermal anomaly shown by both Blackwell and Smith (1995) and Mankhemthong et al., (2008) does not extend any significant distance east of the 1954 surface ruptures. John (1995) does not show any Quaternary hot spring deposits associated with the Eleven Mile Canyon thermal anomaly. There are no publicly available lithologic logs or descriptions of the holes to assist in understanding this geothermal system.

Eleven Mile Canyon Chemistry

There are no thermal springs at Eleven Mile Canyon and there is no record of any thermal waters having been obtained from any of the drill holes.

Eleven Mile Canyon Geophysics

The primary geophysics available for this geothermal system is the temperature-gradient holes which outline a small circular thermal anomaly (Figure 1). The temperature profiles from nearly all of the holes in or near the Eleven Mile geothermal system have been linear to depths of 500' to 750' showing no significant convective thermal fluid movement above these depths. At or below 750' all of the deeper holes suffer major declines in the temperature gradient or show indications of an impending decline if they were slightly deeper.

Two wells, 72-23 and 52-14, were drilled to depths of 8248' and 7461' and reportedly had bottomhole temperatures less than boiling (Blackwell and Smith, 2005), much like the deep well at Pirouette

Mountain. The temperature profiles from these holes are not publicly available but it is clear that the temperature gradients below a depth of 2000' must be very low or even negative because temperatures at 2000' are already 167 to 176 ^{o}F. As was the case at Pirouette Mountain, there appears to be no anomalous or excess heat deep below the deeply drilled parts of the Eleven Mile Canyon shallow thermal anomaly.

Eleven Mile Canyon Resource Speculation

This resource has not received any attention or geothermal exploration for the past two decades and it is unlikely that any company would want to perform additional exploration given the low temperatures reported from the two deep wells. This is not a normal Nevada geothermal system. The low calculated heat loss of 4 MW (thermal) for this geothermal system is a very strong indication that it is a small and weak geothermal system of little importance.

DISCUSSION

The exploration work performed to date in Dixie Valley indicates that perhaps 15 or 20% of the valley has temperature gradients significantly above background levels (Figure 1). Within shallow thermal anomalies in Nevada the truly productive portions are yet another small percentage. Therefore, within Dixie Valley the percentage of land in which it is possible to drill a productive geothermal well is probably at most a couple of percent and may actually be much less than one percent. This is partially confirmed by a lack of successful wells drilled outside of the operating Dixie Valley field.

All of the geothermal systems in Dixie Valley, with the sole exception of Sou, are closely associated with and controlled by 5 recently active fault zones that trend from north-south to northeast-southwest.
All of the geothermal systems located in the central or eastern part of Dixie Valley, with the sole exception of Jersey Valley, have both measured and predicted subsurface temperatures less than 200 ^{o}F.
All of the geothermal systems located along the Stillwater Fault zone on the western side of the valley, with the sole exception of Eleven Mile Canyon have already measured temperatures significantly above 200 ^{o}F. The Sou geothermal system probably should be included with the lower temperature systems located in the central or eastern parts of Dixie Valley.

The east- central part of Dixie Valley, east and south of the operating power plant, is the largest area within the valley that lacks an identified geothermal system. It is possible that a very small geothermal system could be present between the existing temperature gradient holes. This part of the valley has a discontinuous unnamed fault zone (Lidke, 2000) that has not yet been viewed as interesting or important enough for any detailed studies. This would be the only fault zone in Dixie Valley described in the Quaternary Fault and Fold Database that does not host a known geothermal system.

The shallow thermal anomalies drilled within Dixie Valley with the possible exceptions of the cool Clan Alpine and Pirouette Mountain anomalies are quite restricted in size compared with other thermal anomalies such as Desert Peak, Soda Lake, Stillwater, or Carson Lake in the Carson Sink area that cover more than a township in size. The larger thermal anomalies in the Carson Sink area tend to be characterized by aerially extensive lateral outflows of hot water flowing perhaps hundreds of gallons per minute that can extend several miles from a much more restricted upwelling source. These lateral outflows appear to be missing or are quite restricted in Dixie Valley. The small outflows in the Senator, Coyote Canyon, and Dixie Meadows areas are the only subsurface outflows documented to date. Most

of the Dixie Valley hot springs have moderate to low surface discharges of water of perhaps a few tens of gallons per minute. Therefore, it can be realistically anticipated that the geothermal systems in Dixie Valley do not have a large throughput that is rapidly invading or mixing with large volumes of the shallow groundwater system. However, given enough time in an enclosed basin, even small amounts of geothermal water inputs can have a significant chemical impact on the surrounding or overlying groundwater system.

The Dixie Valley geothermal fluids show a wide range of character from bicarbonate, to mixed anion, to chloride rich but most are quite dilute. Only the water from the 36-14 well in the Coyote Canyon area is comparable with some nearby Nevada geothermal areas like Desert Peak, Soda Lake, or Rye Patch where chloride contents are in the 2500 to 3500 ppm range. Blackwell and Smith (2005) briefly discuss the question of whether or not the Dixie Valley geothermal systems are manifestations of one big system or represent several isolated systems. They concluded that the differing systems display such different ratios of conservative species that "they are all related in some general way to a deep geothermal system along or near the Dixie Valley fault" and "Each thermal system is geochemically unique and has evolved along a distinctive path that is influenced by the sources of water, interactions with local wall rocks, and relationship to crustal heat sources." Geothermal systems along other fault zones would be even more remote or completely independent of each other.

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APPENDIX 1

Table of Annual Production, Injection, Augmentation and Surface Discharge

Year	Geothermal Fluids Produced	Geothermal Fluids Injected	Fresh Water Augmentation for Pressure Support	Geothermal Fluids Removed	Geothermal Surface Discharge to Spring Creek
	acre-feet				
1985	857	0		857	643
1986	2,657	0		2,657	1,993
1987	15	11		4	11
1988	9,313	2,072		7,242	3,494
1989	15,974	7,396		8,577	2,163
1990	17,894	10,730		7,164	?
1991	17,228	11,120		6,108	992
1992	16,831	13,126		3,705	221
1993	17,096	13,030		4,066	500
1994	16,242	11,845		4,397	1,037
1995	16,301	12,894		3,407	470
1996	16,401	13,000		3,400	482
1997	16,231	13,965	265	2,267	310
1998	16,334	13,891	749	2,443	246
1999	16,931	13,950	1,048	2,981	368
2000	17,527	14,008	1,986	3,518	500
2001	17,728	14,042	1,866	3,686	528
2002	18,003	14,493	2,017	3,510	341
2003	18,446	15,229	2,284	3,217	528
2004	18,172	15,438	1,798	2,734	298
2005	19,169	15,730	1,631	3,439	9
2006	19,115	14,858	1,002	4,256	
2007	18,285	13,788	1,803	4,497	
2008	15,598	12,062	2,257	3,536	
2009	16,738	14,200	2,052	2,538	

(The produced volume was originally reported in pounds and a conversion factor of 8.0 lbs/gal was originally utilized due to the temperature of the water. At some indeterminate date the DWR required that a conversion factor of 8.34 lgs/gal be utilized. The injection numbers were all based on 8.34 lbs/gal so no change was needed. The surface discharge numbers should be viewed as minimums as water leaking into the individual wellsite sumps was not counted in the totals but this should not be a very significant correction. The produced and injected numbers through 1998 come from Oxbow records and more recent produced, injected and augmentation numbers were obtained from DWR records. The surface discharges for 1985 through 1987 were obtained by assuming a 25% evaporation due to flashing. The 1988 and 1989 surface discharge numbers were annual averages estimated from figures in the the Oxbow Injection Plan Review. The surface discharge numbers after 1991 were supplied by TerraGen.)