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EXPLORATION AND DEVELOPMENT AT DIXIE VALLEY, NEVADA: SUMMARY OF DOE STUDIES

David D. Blackwell[1], Richard P. Smith, and Maria C. Richards[1]
[1]Department of Geological Sciences, Southern Methodist University,
Dallas, Texas, 75275-0395 blackwel@smu.edu
[2]Nathrop, CO 81236

ABSTRACT

Dixie Valley is the hottest (> 285 °C at 3 km) and one of the largest geothermal systems (63 MW power plant operating for almost 20 years) in the Basin and Range province. The heat source is deep circulation in a high heat flow, highly fractured upper crust without a significant magmatic thermal input. Many hot springs in the Basin and Range Province share many of the characteristics of the Dixie Valley system. Thus major geothermal resource questions are how significant are these systems, what determines their location, and what are the best ways to evaluate and develop them. The USDOE sponsored extensive research associated with the Dixie Valley system in the period from approximately 1995 to 2002. These studies have been summarized in an extensive report to be published by the Nevada Bureau of Mines and Geology (Blackwell et al., 2007). This paper briefly summarizes the contents of that report including the main studies, their results, and interpretation of their significance as related to Basin and Range fault reservoir definition and development.

Techniques applied as part of the research activities on a regional basis (Dixie Valley, the Stillwater Range and the Clan Alpine/Augusta Range) included but are not restricted to geology, geophysics, hydrology, and hydrogeochemistry. Within the producing area there were studies of the subsurface geology, thermal regime, fluid geochemistry, seismic reflection characteristics, and potential field structural mapping. In particular a gravity study, an EM survey, and a low level, high resolution magnetic survey were completed. In conjunction with extensive older geophysical data the combined data sets were used to develop a geological model of the system.

A number of geochemically focused studies were carried out. These included initial pre-production composition measurements, non-condensable gas and water isotope composition measurements, regional He isotope studies, chemical evolution-time series (evidence for compartmentalization) measurements, tracer tests (reservoir connectivity), and dating of sinters and travertine.

Remote sensing studies included air photo interpretation, hyperspectral studies of Dixie Meadows, INSAR Synthetic Aperture Radar Interferograms for ground subsidence, and infared measurements.

Finally numerical modeling of generic natural state Basin and Range flow systems and specific applications to the Dixie Valley geometry were used to develop constraints on the deeper aspects of the flow system. These studies help in the evaluation of other Basin and Range systems by confirming that the Dixie Valley system must be in a transient state to reach the high temperatures observed.

The results of these studies are summarized and a model of a Basin and Range geothermal system like Dixie Valley is described. The system is not a simple fault plane, but a complicated flow system with much character related both to the Basin and Range normal faulting and the permeability of the country rocks. The fluid flow paths are complicated and vary on a small scale leading to a complex reservoir system. The complexity indicates a much larger “reservoir” than would be the case if the system was a simple planar fault zone. The system is probably in a transient condition related to events on a 10,000 to 100,000 yr time frame. Much of what has been learned in Dixie Valley is transferable to other Basin and Range geothermal systems.

INTRODUCTION

Why Focus on Dixie Valley

This paper briefly describes the results of a synthesis prepared for the Dixie Valley area of the Western Nevada Basin and Range. This focus on the Dixie Valley geothermal system is because of many factors. It is the largest and hottest Basin and Range deep circulation system known at the present time. The production of 63 MW of energy from only part of the larger geothermal system is significantly greater than that of any other geothermal system that is not associated with recent magmatic activity. For this reason alone the system is worthy of study as a case example for a Basin and Range system. Moreover, previous to the drilling on the Dixie Valley Power Partners (DVPP) lease in 1993/1994, the system was thought to be relatively well understood. The results of that drilling were so surprising and important that additional studies were initiated to help understand the significance of the new information for geothermal resource exploration and assessment. Furthermore, because of the complexity of the structural setting at Dixie Valley, and the great amount of heat present over a large area at relatively shallow depth, the potential for development of additional resources in the area is great.

The amount and diversity of previously collected direct and indirect subsurface information (deep wells, seismic reflection surveys, surface geophysical surveys, hydrologic investigations, geochemistry) available for Dixie Valley from the literature, DOE sponsored projects, and from shared company data are greater than that for other geothermal areas in Nevada. This expanse of available subsurface and surface information offers a unique opportunity to develop an understanding of this system. That understanding can provide concepts for exploration and development of other Basin and Range systems having less available data.

Dixie Valley Geothermal System

The Dixie Valley geothermal system (DVGS) is defined as a large area along the fault zone bounding the Stillwater Range and Dixie Valley in Churchill and Pershing Counties, Nevada (Blackwell et al., 2007). It is considered to extend from the area of the 63 MW Dixie Valley Producing Field (DVPF) on the north to Dixie Hot Springs (Dixie Meadows area, DM) on the south, a distance of about 30 km (see Figure 1). As presently known there are a number of areas with thermal manifestations and deep drill data along this length of the Stillwater Range front associated with relatively shallow (~3 km) temperatures of over 200°C. The resource has been partially delineated by many production, injection, and exploration wells (2500 to 3500 m deep), and a rich variety of geological and geophysical data. There are also other geothermal areas in Dixie Valley and vicinity that are not at this time known to be directly associated with the DVGS as defined above. These extend from the Sou-McCoy Hot Springs in the north to the Eleven Mile Canyon anomaly in the south. The complete nature of the relationship, if any, between all of the thermal areas remains to be developed, but they are probably related in some general way with the large crustal scale fluid flow system.

In addition to the geothermal potential of the valley, attention has been focused on Dixie Valley because of its historic earthquakes. These include the 1915 Pleasant Valley earthquake to the north of Dixie Valley, the July 6 and August 23, 1954 Rainbow Mountain earthquakes to the west of Dixie Valley, and the December 16, 1954 Dixie Valley-Fairview Peak earthquakes in and to the south of Dixie Valley (Figure 1). These large surface-rupturing earthquakes drew the attention of numerous researchers who generated a plethora of seismic, paleoseismic, geophysical, and geologic data in the area. Finally, gold mining has been an economic factor driving interest in the Earth resources within Dixie Valley.

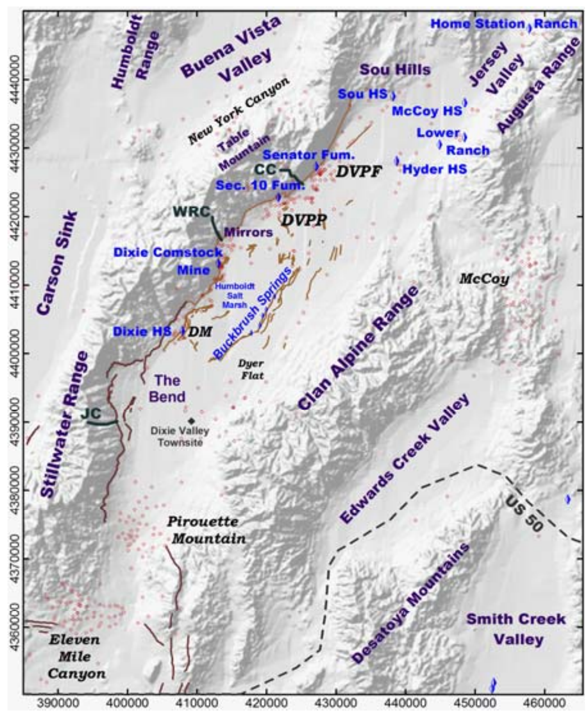

*Figure 1. Dixie Valley (DV) Index Map. Drilling areas shown in black italic (*DVPF – *DV Producing Field,* DVPP – *DV Power Partners,* DM – *Dixie Meadows). Canyons are drawn along ridge (CC – Cottonwood Canyon, WRC – Whiterock Canyon, JC – Job Canyon). Red diamonds - drilling locations. Dark brown lines - 1954 DV Fault break. Light (thin) brown lines - range-front fault and valley faults.*

Because of the many interests in Dixie Valley, the collection and interpretation of subsurface data (Figure 2) had not been previously been coordinated, focused or synthesized. The available information is in a wide variety of sources ranging from published journal articles and reports, to unpublished company reports, to numerous reports and presentations given at conferences but published only in the gray literature, to un-interpreted or barely interpreted data from companies that have performed various geoscience activities in the valley. Therefore, a compilation and careful analysis of the existing information is not only warranted, but also necessary to take full advantage of previous work in the area.

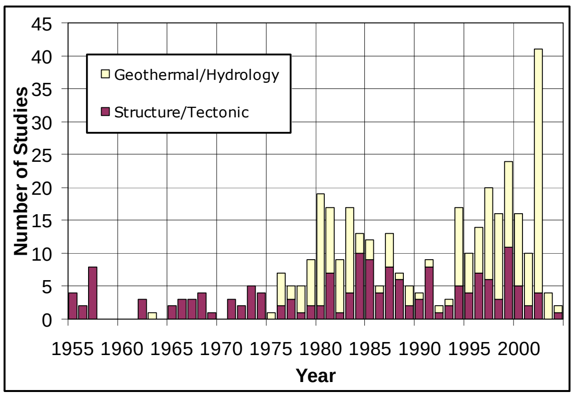

Figure 2. Histogram of Dixie Valley Studies vs. Time

Objectives of this Synthesis

Blackwell et al. (2007), as summarized here, presents available information for Dixie Valley in enough detail to allow inter-comparison and interpretation of multiple data sets, and to draw conclusions that allow revision of the conceptual understanding of the Dixie Valley geothermal system (and by inference other geothermal systems in the Basin and Range Province). From the full Department of Energy report the following summary discusses portions of the Geophysics, Geochemistry, Thermal Regime, and Remote Sensing. In general only the most recent literature is cited here. Complete references to the sources of data, ideas and original papers and reports are included in the Nevada Bureau of Mines report (Blackwell et al., 2007).

GEOPHYSICS

High-Resolution Aeromagnetic Survey

High-resolution aeromagnetic surveys of basins represent a tool that can provide two kinds of information useful for geothermal exploration in basins. First, they can be used to delineate intrabasin fault patterns (Grauch, 2001), which is useful for outlining potential channel-ways for geothermal fluid flow. Second, the occurrence of small low-amplitude negative anomalies might provide clues as to the size and distribution of channels used by hot fluids in the subsurface, especially in areas of strongly magnetic volcanic and mafic intrusive rocks. In 2002 a high-resolution aeromagnetic survey was conducted over a 940 km^2 area extending from Dixie Meadows northeastward to the Sou Hills, and from the eastern front of the Stillwater Range to the western edge of the Clan Alpine Range. The resulting aeromagnetic map is described and discussed by Smith et al. (2002) and by Blackwell et al. (2007) (Figure 3). The main distinguishing feature of the Dixie Valley survey, compared to other Basin and Range surveys, is the extreme topographic relief at the east front of the Stillwater Range, which dictated the use of a helicopter to acquire data near the range-front fault.

The complete pattern of shallow faults revealed by the aeromagnetic data and surface mapping (Figure 3) shows that intrabasin faults with a strong surface expression also have a strong aeromagnetic signal. However, in addition there are many magnetic anomaly identified faults in the valley that exhibit no surface expression on air photos; some of the faults with surface expression are actually sections of longer faults. The set of faults defined by magnetic anomalies at shallow depth (the 100 m fault set determined by Grauch (2002) in Figure 3) must be very young, late Pleistocene or Holocene, and thus must be part of the presently active Basin and Range system of extension faulting. The aeromagnetic data does not show a big piedmont fault on the west side of the valley as expected.

Gravity Interpretation

After removing the regional field, the residual Bouguer gravity anomaly shows generally negative values in the valleys and positive values in the ranges because of the density contrast between the poorly consolidated valley fill and the bedrock of the ranges. On a basin-wide scale the gravity low in Dixie Valley is strongly asymmetrical from east to west. The west side is relatively well-defined by rapid horizontal changes in the gravity anomaly value, whereas along the east side horizontal changes are more subdued and often consist of several steps.

The horizontal gradient of the gravity field is very useful in identifying the surface projection of subsurface contacts of greatest density contrast, (Blackwell et al., 1999). Thus where the contact is sharp and large the gravity shows a high value, but in areas with shallow features or small density contrasts, the gravity gradient high represents the midpoint over that feature. The terrain slope is the slope of the

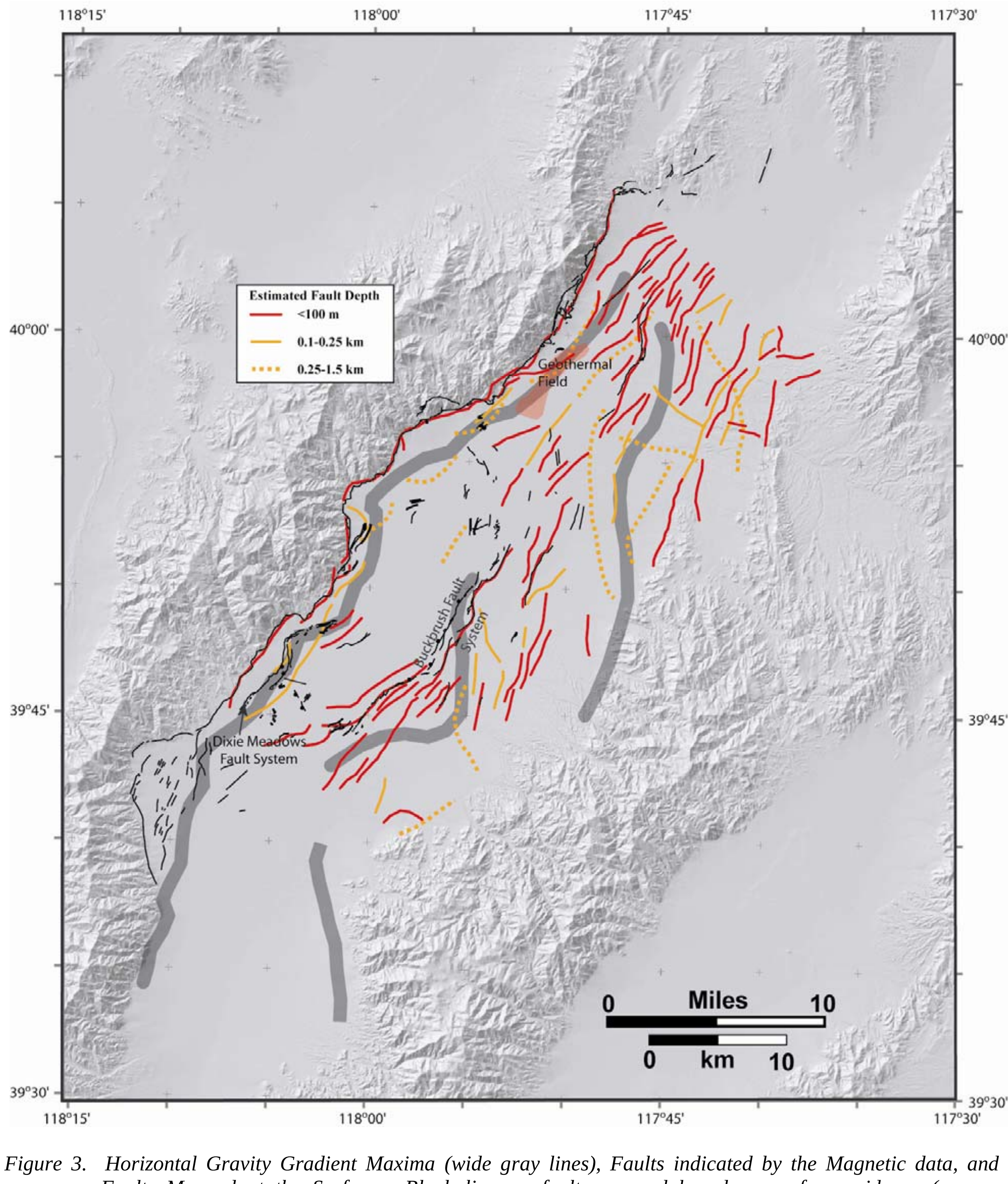

Figure 3. Horizontal Gravity Gradient Maxima (wide gray lines), Faults indicated by the Magnetic data, and Faults Mapped at the Surface. Black lines = faults mapped based on surface evidence (scarps, lineaments); Red and Orange colored lines = faults indicated by high-resolution aeromagnetic data. Surface evidence of piedmont faults & intrabasin faults occurs on or near gravity gradient maxima.

contours in the direction of steepest descent so it locates the magnitude and direction of the steepest gradient in any area of the map. Two-dimensional modeling of the gravity data (Blackwell et al., 1999) shows that along much of the steep east side of the Stillwater Range, piedmont faults in the valley accommodate most of the displacement between the range front and the valley bottom.

Based on the gravity pattern, the Dixie Valley basin is about 10 to 20 km wide from Pirouette Mountain northward. The deepest part of the basin, based on the minimum residual gravity values, is far west of the geographic center of the basin and thus emphasizes the asymmetry of the basin. The pattern of the residual gravity and the gravity gradients along the eastern side of the basin is complex and in general not parallel to the edge of the valley. In that area the presence of the dense Jurassic mafic complex (Humboldt lopolith) complicates the pattern and combined magnetic and gravity interpretation is needed to analyze the structure. Details of the analysis are described in Blackwell et al. (2007). The Jurassic mafic complex rocks are an important reservoir unit in the DVPF because the Humboldt igneous complex tends to be more highly fractured than the remainder of the basement rocks, (Waibel, 1987; Benoit, 1999) and thus is of geothermal interest.

Stress Measurements

Borehole imaging and hydraulic fracturing experiments have been carried out in several Dixie Valley wells. Wells 45-14 and 66-21 to the south, and production wells 37-33, 62-21, 73B-7 and 74-7 in the DVPF have been the subjects of fracturing and borehole imaging experiments by Barton et al. (1998) and Hickman et al. (1998). They concluded that the producing wells had permeable fractures in an orientation that is optimally oriented and critically stressed in the current stress field. The current stress field is defined by a N45°E least horizontal principal stress. The nonproducing wells (all of which have some flow) have permeable fractures of more varied orientations. The dip of the permeable fractures in the productive wells is about 60° to the SE. This orientation, based on fracture analysis, represents planes optionally stressed for rupture in the ESE extensional stress regime in Dixie Valley.

In addition, the presence of well bore breakouts in wells 45-14 and 66-21 (Hickman et al., 1998) was taken as evidence that the maximum horizontal stress is greater in the vicinity of those two wells than for either the producing wells studied or the well in the middle of the valley (62-21). Therefore, they argued that the higher ratio of maximum horizontal stress to vertical stress acts to decrease the shear stress that can drive fault slip. In this situation, even optimally oriented fractures for normal faulting are not critically stressed for frictional failure. So at the location well 45-14 they argued that there is no production because: 1) the direction of the range-bounding fault is so misoriented with respect to the regional stress directions that it is not optimally oriented for movement; and 2) the high horizontal differential stress results in a fault that is frictionally stable and fluid flow is suppressed. However, there is evidence for active shallow flow at some location nearby based on the high temperatures in the Dixie Comstock mine.

GEOCHEMISTRY

Mountain Versus Basin Hydrogeochemistry

Stillwater Range waters have higher Mg and Cl and generally lower Ca than Clan Alpine Range and Augusta Range waters, which are lower in HCO_3 (Nimz et al., 1999). These variations reflect the corresponding lithologic differences in the ranges. Basin waters compositionally overlap those of the mountains, which is expected because the basins contain detritus of bedrock units present in both ranges. But the basin waters tend to have higher Na and K, typical of waters with input of geothermal fluids, than most waters from the ranges.

Stable Isotope Geochemistry

Local meteoric water lines for inland desert basins commonly have smaller slopes and more enriched oxygen-18 isotope values than the world meteoric water line and Dixie Valley is no exception. Water data were collected for δD vs. $\delta^{18}O$ from the Stillwater Range, Clan Alpine Range, Dixie Valley basin, and Dixie Valley production zone. Significantly cold waters from the ranges are isotopically enriched relative to cold waters in Dixie Valley basin. This is the opposite of what would normally be expected because, within a given region, waters of high elevation show depleted isotopic compositions compared to those of lower elevation. The only reasonable explanation for this anomaly is that the basin waters are older and were recharged in the past when isotopic compositions of meteoric recharge fluids were more depleted. Such discrepancies are common in basins of the Basin and Range Province and are ascribed to Pleistocene recharge.

Waters of the pre-production Dixie Valley geothermal reservoir do not isotopically resemble cold waters in the adjacent ranges indicating that the ranges are not recharge sources for the reservoir. Instead, fluids from the reservoir have similar δD values to Dixie Valley basin waters but are enriched in $\delta^{18}O$ by about 2.5 ‰. Production has substantially changed the present isotope compositions of production fluids by evaporation and mixing as discussed below. Positive oxygen isotope shifts with no deuterium shift are common in fluids of geothermal systems in which meteoric water is the only recharging fluid.

Local Helium Isotope Trends

Helium isotopic compositions were determined in several springs, wells, and fumaroles through out the Dixie Valley area, including samples from the DVPF. The study was conducted in conjunction with a Dixie Valley regional geochemistry study of surface fluids (Goff et al., 2002). Preliminary results were presented in Kennedy et al. (2000) and Kennedy and Van Soest (2006).

The helium associated with the productive geothermal reservoir fluid has an isotopic composition of 0.70 - 0.76 Ra, representing the highest ratios measured in the valley and are consistent with a mantle helium component in the Dixie Valley reservoir fluid. These values are also high with respect to the surrounding areas, which identifies the DVPF as a "He-spike" in the regional trend. If it is assumed that the magmatic source has a helium isotopic composition of 9 Ra, then as much as ~7.5% of the reservoir helium is mantle-derived. Dixie Valley has a significantly stronger mantle helium signal compared to similar non-magma hosted geothermal reservoirs in the Basin and Range, such Beowawe (~0.4 Ra) and Ruby Valley (~0.2 Ra) to the east.

The mantle signature, however, is weak when compared to geothermal systems that are known to be associated with recent igneous activity. For instance, at Steamboat Springs, Nevada, $^3He/^4He$ ratios of ~6 Ra have been measured, providing strong evidence for an active or recently active magmatic system. High ratios reflecting active magmatic systems have also been reported for Long Valley and the Coso geothermal systems. The much lower Dixie Valley ratios are consistent with a non-magmatic heat source and confirm the lack of geologic and geophysical evidence for a mid-level to upper crustal magma system.

The DVPF samples, which have the highest helium isotopic compositions, are from the production wells where 245°C fluids are produced from fractures along the valley bounding range-front Dixie Valley fault system. The helium compositions of springs and wells throughout the valley are mixtures of this mantle derived fluid with younger, less He and ^3He-enriched, groundwater [R < 0.4 Ra, $F(^4He)$ < 10]. The exceptions to the simple mixing trend are fumaroles (Section 10 and Senator) and Dixie Hot Springs (30 km southwest of the DVGS), which are apparently not affected by shallow groundwater and are directly connected to the deep system. This result implies that the Dixie Valley fault is a fast path for vertical fluid flow that is unencumbered by local hydrology. Thus, the He data suggest that the entire Dixie Valley fault may be a geothermal target.

Geochemical Evaluation of Springs & Fumaroles

During the initial phases of U.S. geothermal development in the 1970's, Dixie Valley was not a primary focus as none of the features in Dixie Valley have high chemical geothermometer temperatures based on the Na-K-Ca or the SiO_2 systems. However, more is now known about the chemistry of geothermal systems. Geochemical data information can be found in Goff et al. (2002) and in the Blackwell et al. (2007). Compared to other types of groundwater, high-temperature geothermal fluids (HTGF) generally display reservoir pH between 6 and 9, are often characterized as Na-K-Cl waters, and contain relatively high SiO_2, As, B, Br, and Li. Gas analyses invariably reveal that dissolved CO_2 is another major component, often exceeding the concentrations of Cl. HTGF are also characterized by relatively low concentrations of divalent cations (Ca, Mg, and Sr) and extremely low concentrations of trivalent cations (Al and Fe).

DVPF production fluids meet all the chemical criteria described above, but most other thermal/mineral waters in the Dixie Valley region do not. As a result, these waters either have not equilibrated at high-temperatures (as verified by chemical geothermometers) or are mixed fluids - possibly of high-temperature fluids and cooler groundwater. Mixed fluids, however, leave fingerprints of their high-temperature parentage, usually as relatively high concentrations of SiO_2, Cl, Na, K and the key trace elements (As, B, Br, and Li). In particular, mixed fluids generally retain constant ratios of the conservative species such as B/Cl and Li/Cl. The geochemical data show that DVPF production fluids and other regional thermal/mineral waters display different ratios of conservative components, and that the other regional thermal/mineral waters display different ratios among themselves.

For example Bromide versus chloride concentrations have increased in the southern production wells (in Section 7) due to steam loss and reservoir concentration during heat extraction in the power plant. Steam loss in the northern production zone (Section 33) has been less dramatic. Thus, Br behaves conservatively during production of geothermal fluids in the reservoir, similar to B. Thermal/mineral well waters generally lie on the same mixing trend as the production fluids. This behavior is likely caused by similar types of reservoir rocks between reservoir fluids and other geothermal well fluids. On the other hand, these thermal/mineral spring waters have exceptionally low Bromine with respect to chloride and are not related to production fluids (Figure 4). Thus, it appears that each thermal system has a different geochemical history.

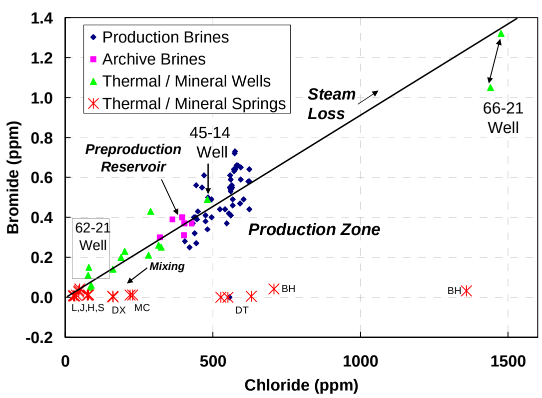

Figure 4. Bromide versus Chloride. Thermal and nonthermal waters of the Dixie Valley region. Labels: DX= Dixie Hot Spring, MC = McCoy Hot Spring, DT = Dead Travertine Spring, BH = Big Horn Spring, H = Hyder Hot Spring, S = Sou Hot Spring, J = Jersey Hot Spring, L = Lower Ranch Hot Spring.

Time Behavior of Reservoir Chemistry

By the late 1990s, the chemistry of the reservoir fluids had changed noticeably with respect to their preproduction compositions. Chloride contents in the south (Section 7) wells had risen to as much as 625 ppm, while those in the north (Section 33) wells had risen to as much as 570 ppm. The primary reason for the increase in Cl content is the water loss from steam removed during the process of generating electricity. Very little Cl goes into the vapor phase during steam separation; thus the residual brine became progressively enriched in Cl through time. This is often referred to as “conservative” geochemical behavior.

On the other hand, key trace elements enriched in high temperature geothermal fluids displayed nonsystematic behavior. The elements B and Br behaved conservatively. When Cl contents increased, so did B and Br. Arsenic concentrations decreased substantially while Li contents decreased moderately. The implication is that these two elements have precipitated during recycling of the reservoir fluid as a result of steam flash or some other process or combination of processes. The loss of arsenic is rather easy to explain. Arsenic can drop out as a sulfide in the steam pipelines and steam separator by reaction with H_2S. A mechanism for loss of Li is not known.

The detailed behavior of silica as a function of time is much more complex. When the data are differentiated by sampling year, the Section 7 production well fluids are gradually losing SiO_2 even though Cl content is rising. The silica loss is attributed to slight cooling of the reservoir whereas the Cl increase is caused by steam loss. In contrast, the north wells showed more erratic behavior. Chloride and silica contents actually decreased slightly from 1997 to early 1998 suggesting both dilution and cooling by other groundwater marginal to the reservoir. From 1998 to 1999 both Cl and SiO_2 contents went up suggesting steam loss and slight heating of the fluids, possibly resulting from less dilution by cooler groundwater.

Contributions of cooler groundwater into the geothermal reservoir, either by reinjection of mixed fluids or by dilution from reservoir margins, are traceable by dramatic increases in Ca contents (Figure 5). In 1986, preproduction geothermal fluids contained only 1 to 2 ppm Ca but by the late 1990s average Ca values had risen to roughly 7.5 ppm in the north wells and 9 ppm in the south wells. Calcium contents of high temperature geothermal fluids are usually quite low due to the inverse solubility of divalent metal carbonates and sulfates (Goff and Janik, 2000). Reinjection fluids during the late 1990s commonly included some shallow well waters (Domestic and Goerenger wells) containing as much as 62 ppm Ca (Goff et al., 2002). Increased Ca in production fluids over time may have increased the potential of the production wells to form $CaCO_3$ scales.

Ages of Spring Deposits

The oldest known spring deposits in the Dixie Valley region are those currently associated with the Dead Travertine (Cottonwood Travertine) springs about 2 km upstream of the mouth of Cottonwood Canyon. A sample of dense, honey-colored calcite from a

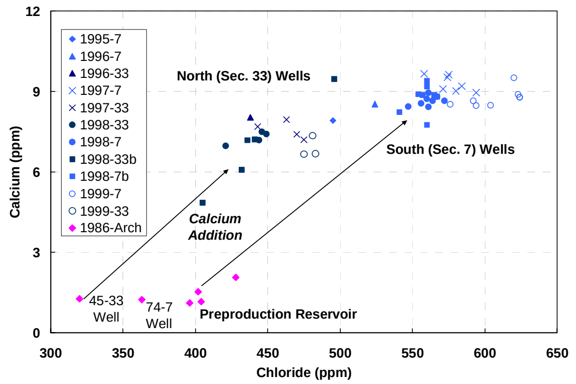

Figure 5. Calcium versus Chloride. Changes in calcium over time shown with respect to chloride.

calcite vein yielded U/Th disequilibrium and protactinium-231 ages of 182 ± 4 ka and 161 ± 15 ka, respectively (Goff et al., 2002). More recently, Dixon et al. (2003) reported a preliminary U/Th isochron age of 100 ka from four layered travertine samples obtained throughout the deposit.

Another large deposit of travertine and subordinate siliceous material occurs at the Lower Ranch Hot Spring area on the east side of Dixie Valley about 20 km northeast of the producing geothermal field. A sample of mixed calcite and chalcedony was obtained from the base of the deposit in a ravine on the northeast part of the uplifted block. The siliceous fraction was separated and yielded U/Th disequilibrium and protactinium-231 ages of 54 ± 4 ka and 39 ± 2 ka, respectively. The siliceous material near the base suggests that the springs may have once been hotter, although this speculation requires much more evaluation.

The Dixie Valley fault zone from behind the Dixie Hot Springs to northeast of the Senator fumaroles displays dispersed varied alteration, active fumaroles, and fossil sinter deposits over a strike length of at least 40 km. A few of the hot spring deposits along the fault have been dated. A sample of siliceous fault gouge within fractured Jurassic gabbro exposed at The Mirrors yielded a preliminary U/Th disequilibrium age of 287 ± 16 ka.

The Dixie Comstock Mine is an epithermal gold deposit hosted in quartz-rich gouge and breccia along the Dixie Valley fault zone (Vikre, 1994). Eroded sinter deposits occur on the upthrown (west) side of the fault zone. Within the mine area, clasts of the sinter are incorporated in lacustrine beach gravel and diatomite associated with pluvial Lake Dixie. Lutz et al. (2002, 2003) dated a concentrate of pollen and organic material within a clast of sinter in the lacustrine deposits, obtaining a ^{14}C age of 10, 722 ± 70 years BP. According to Lutz et al. (2003), this provides a maximum age for the diatomite and an age for hot spring activity and gold mineralization.

Sections 10 and 11 Altered Areas and Sinters

A brightly colored zone of altered Triassic metasediments (mostly shale) underlies Jurassic quartzite, gabbro and volcanic rocks along a northeast-trending thrust fault about 4 km west of the DVPF and 1.5 km southwest of the mouth of Cottonwood Canyon. One alteration deposit consists of horizontally banded hematite, dolomite, and barite cut by more recent calcite veins. A ^{14}C age of 5,040 ± 60 years BP was obtained from material in the banded deposit (Lutz et al., 2003). A U/Th disequilibrium isochron age of 3.75 ± 0.33 ka was obtained on two samples from a white calcite vein cutting black, hematite-rich spring deposit nearby. In Section 10 a series of sinter deposits described by Lutz et al. (2003) near an active boiling point in the Section 10 Fumarole group have ages of 3±1 ka. The Dixie Valley fault zone cuts the deposits and the present fumaroles are fault controlled.

THERMAL REGIME OF DIXIE VALLEY

The regional temperature gradient and heat flow distribution for the valley is shown in Figure 6. Most of the values lie between 40-50°C/km and the Gaussian fit peaks at 63°C/km (average gradient). The high value for the average is probably due to the positive contribution of ground water into the valley. Taking these into account, the valley gradient is calculated as 54±5 °C/km. Based on thermal conductivity measurements of valley-fill types of rocks in Dixie Valley, and elsewhere, the average thermal conductivity is 1.4 ±0.2 W/m/K. Therefore, the estimated background heat flow for the valley is calculated as 76 mW/m^2. The deepest well, 62-21 is in the middle of the valley away from geothermal systems and has a conductive gradient to a depth of almost 4 km. The estimated heat flow for that well is 84 mW/m^2, similar to estimates from the shallower wells.

Thermal Sections of Production Areas

Models from the initial exploration data generated for the DVPP area depicted a single range-bounding fault with a dip of about 54°. Drilling of the 62-23, 62-A23, and 36-14 wells demonstrated the range-bounding fault dipped at an angle of 65° or steeper and fault geometry more varied than previously thought.

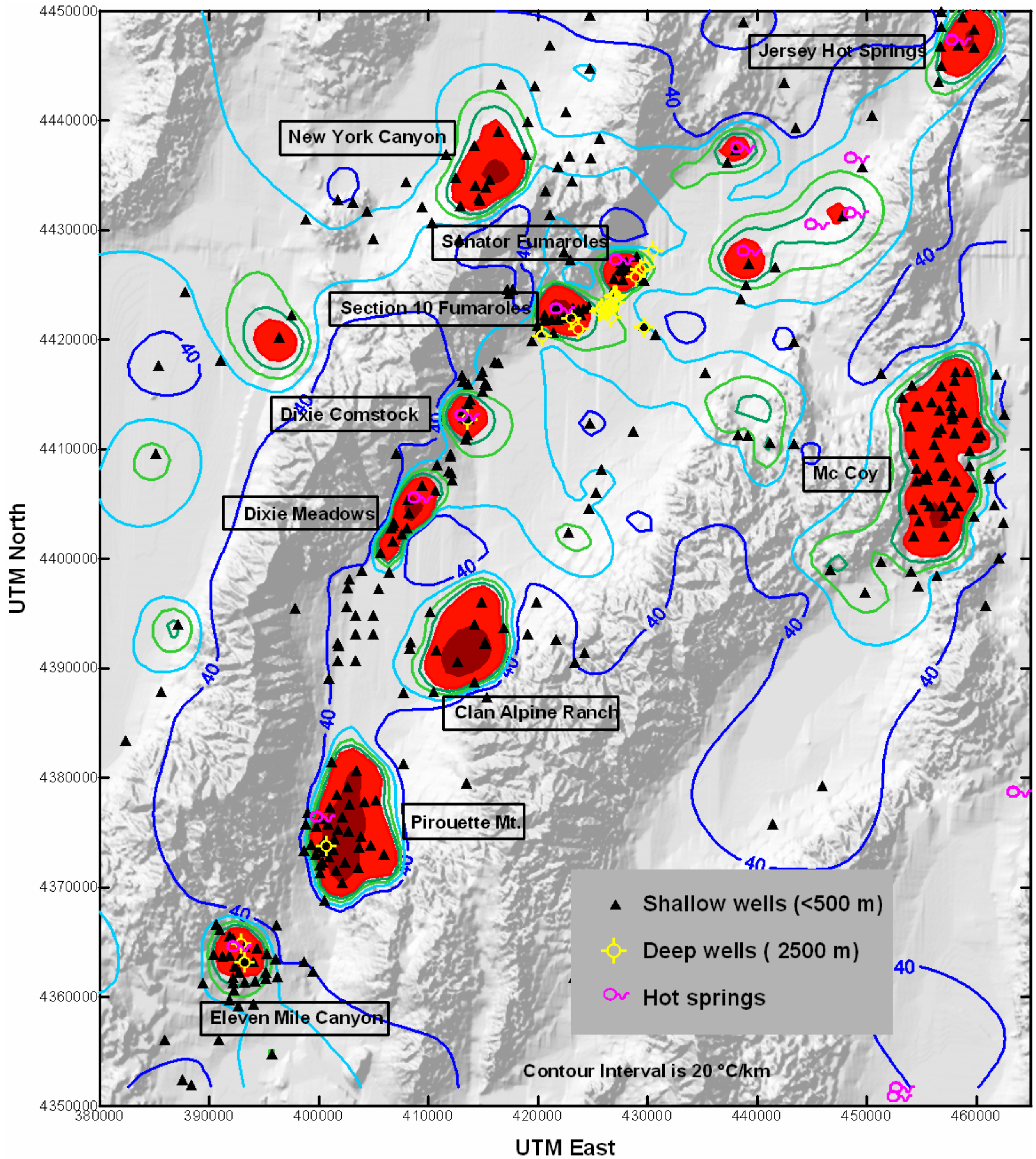

Figure 6. Dixie Valley Area Thermal Gradient and Well Locations. Contour intervals are 20 °C/km. From 120 – 250 °C/km the contours are a red fill and 500°C/km+ the contours are a dark red fill. Contours in the ranges are diagrammatic due to the lack of data. Well gradient locations are shown as black triangles for shallow wells (<500 meters) and as yellow circles for wells > 500 m.

A two-fault finite difference numerical model (Blackwell et al., 2002) for the DVPP area was then developed based on the temperature and geological constraints from the wells (McKenna and Blackwell, 2004) (Blackwell et al., 2007). The geometry inferred is shown in Figures 7a. The boundary conditions included a surface temperature of 15°C, an assumed background heat flow of 80 mW/m^2, with thermal conductivity values for the Cenozoic units (1.25 W/m/K) and for the PreCenozoic rocks (2.5 W/m/K), and a period of existence of the system of 70,000 y. Heat transfer was assumed conductive except for convective flow along the fault zone. The cross-section shown in Figure 7 is somewhat generalized because the strikes of the fault structures in the area are not constant.

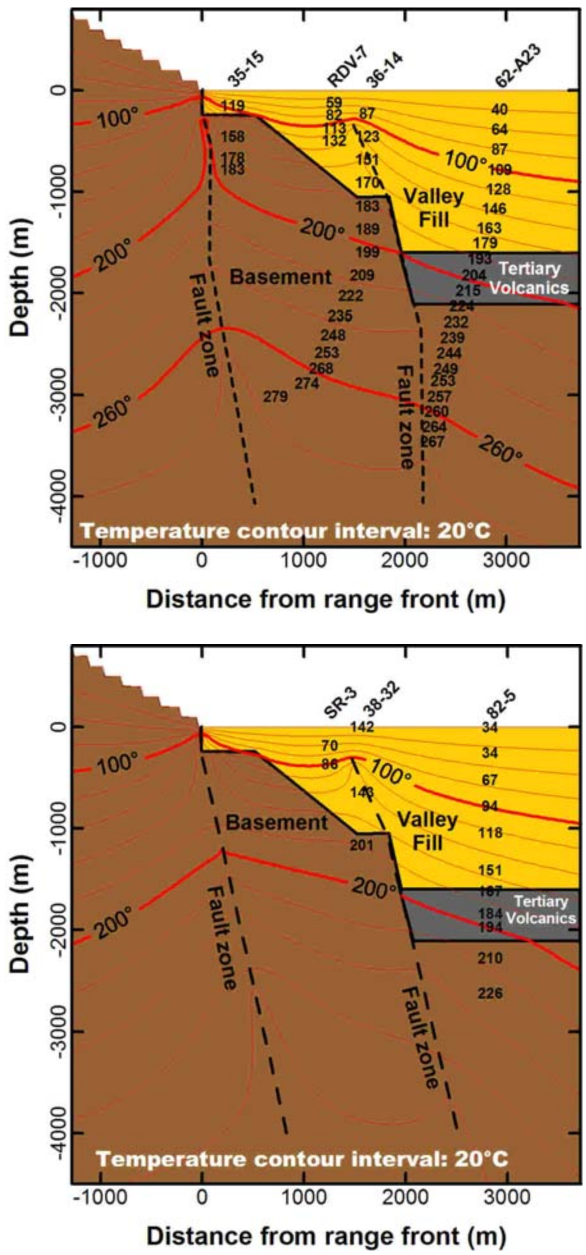

Figure 7. a) Thermal model for the DVPP area based on temperature matching in the deep wells (Blackwell et al., 2002). b) Thermal model for the DVPF in section 32/33 based on temperature matching in the deep wells.

With the drilling of well 38-32, a model of the DVPF area was possible using the detailed gravity survey (1996), and the formation of Senator and Section 33 fumaroles (1997). The structural and thermal cross-section covered Section 32/33 area of the DVPF in the same way the DVPP thermal section was constrained (Figure 7b). Based on the data, the existing thermal model from the DVPP area required almost no modification to match the 38-32 conditions in the DVPF area.

The two areas at least 5 km apart and 2 km wide have similar temperatures of 225 to 245°C at depths of 2500 m and over 265°C below 3000 m. The fluid flow in this area has operated over a long enough time that the thermal regime is locally near equilibrium in the 1 to 3 km depth range. There is a major variation in the hydrologic situation with the present flow paths numerous, but discrete. Some paths are not connected or barely connected on the time scale of pressure and temperature measurements in the field (almost 20 years). Hence, the geochemical interpretation that emphasizes the differences of the fluids reflects the 20 year time frame, whereas the thermal data apparently reflect much longer times (but still short geologically). Much of the loss of fluid in the system is apparently via leakage from the piedmont faults directly into the valley fill with little or no surface of shallow indications of its presence. This behavior must also complicate the chemistry of the water in the valley fill and probably is at least partly responsible for the highly variable water geochemistry in the valley groundwater and springs. The degree of connection between the transition is not known as there are no drill data in the gap near the range front.

By contouring data from gravity, seismic, and drilling the valley geology is modeled as a perspective diagram of the basement shape with the valley fill removed. This is in the area of Stillwater Range/Dixie Valley around the DVPP and DVPF areas, (Figure 8). These results illustrate that the range/valley surface topographic break does not coincide with the position of the fault representing most of the valley offset, except possibly at the north end of the area studied.

Heat Loss

Determination of the total anomalous heat loss is useful in order to determine the long term potential of the geothermal field. In the calculation of the anomalous heat loss, the regional heat flow of 82 $m\text{W/m}^2$ was removed from the general heat flow distribution and the residual distribution was used for

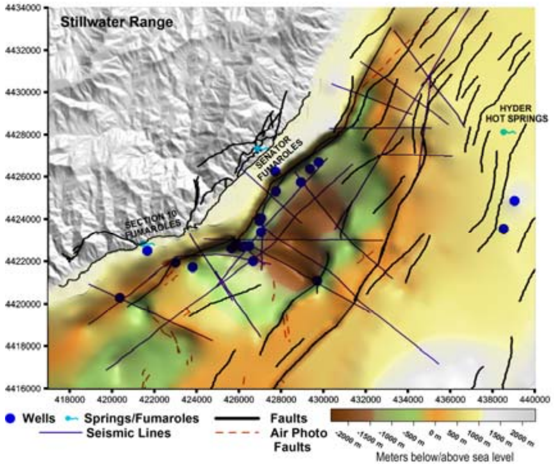

Figure 8. Dixie Valley Basement Diagram (valley fill removed). Based on seismic, drilling data, and fault lines to limit contours.

the anomalous heat loss. By numerically integrating the residual heat flow distribution with the total area inside the valley, the total heat loss of 73.8 MW was calculated for the Dixie Valley geothermal system. Based on the analysis of Wisian et al. (2001) and Richards and Blackwell (2002) this heat loss figure implies an electrical generation potential of 74 to 740 MWe, depending on the rate of production. However, this calculation does not determine if this heat is extractable by current technologies.

Heat loss became a real concern when surface subsidence occurred in the northern part of the producing area from subsurface discharge of geothermal fluids from the Senator and Section 10 fumaroles area into the valley-fill sediments created two thermally hot plumes with temperatures of over 150°C. During 1997-1998, a number of test wells ranging in depth from 60 m to almost 400 m were drilled between the producing DVPF wells and the range front. The temperature-depth curves of these wells are described by Allis et al. (1999). It was determined to be more cost effective to repressure the reservoir with shallow groundwater flow than to drill new production wells (Benoit et al., 2000). The excess heat flow associated with the created plumes in the valley can be used to estimate the heat loss due to the flow of hot water. Based on the thermal gradient anomaly contoured of the plumes, the rate of deep geothermal fluid upflow discharging into the valley aquifer along the approximately 1.5 km of range front in Sections 10 and 15 in the DVPP area is a minimum of 0.2 l/s.

The wells between the DVPF and the Senator fumaroles also have temperature-depth curves showing shallow leakage of very hot water as just described. In this case, the approximate discharge is about 5 l/s (Allis, 1999). The heat loss calculated from this previously unknown flow system is about 56 MW. The existence of flow systems like this one appears to be a common feature of Basin and Range geothermal systems (Richards and Blackwell, 2002).

Temperature Modeling Conclusions

The 285°C temperature in the 36-14 well at 3 km is associated with Quaternary normal faulting and the water and heat are non-magmatic in origin. Meteoric water enters via the ranges or through valley fill, warms during deep circulation, and ascends along the nearest, highest permeable pathway, usually an active range-bounding fault. Wisian and Blackwell (2004) and McKenna and Blackwell (2004) examined numerically the conditions necessary for a reservoir temperature near 280°C to occur in the upper crust in a deep circulation system. The characterization of the reservoir utilizes several parameters, including temperature along the producing fault, and the predicted surface heat flow. The geometry of the models investigated is similar to the typical geometry of a basin and range extensional geothermal system.

The most important observations obtained from these simulations are that temperatures in Basin and Range geothermal systems can be highly time-dependent and the geologic history can dramatically modify the maximum reservoir temperature and the time frame of occurrence. The maximum fault temperature of about 245–275°C obtained utilizing a bulk rock permeability of 5×10^{-16} m^2 does not occur at steady-state, but rather at 50,000–60,000 years, and is about 110–160°C hotter than at steady-state. The 1×10^{-16} m^2 bulk rock permeability model behaves in a similar way. The temperature is not a function of the fault (high permeability) extent. A fault extending 2 km deeper than the 4 km of the standard model yields similar behavior and temperatures. The modeling shows that the high temperatures needed to match the observed fault temperature, flow rates, and heat flow require a regional permeability that allows significant flow to persist to depths of 6 to 8 km or more. The modeling results suggest that the best initial conditions for high-temperature system development are an actively convecting porous medium, and not an essentially conductive thermal regime. Deep drilling in the ranges adjacent to active geothermal systems would help identify the appropriate regime for modeling.

The heat present in the system is naturally “mined” over time causing the system to cool significantly; nonetheless, the system may persist for millions of years at commercially exploitable temperatures, especially for binary systems (~150°C). Hence, the problem of reconciling higher observed reservoir temperatures with the lower temperatures modeled at steady-state becomes the problem of determining where in the temporal-evolution history the geothermal system production is situated. If higher temperatures are observed, the implication from the models is that the present thermal and flow regime is early in the system's cycle. In fact, the present-day temperature and heat loss from the Dixie Valley geothermal system suggests that the system is not at steady-state, rather earlier in the temporal evolution, perhaps only a few hundred thousand years as suggested by the dating of the spring systems in the area.

For specific application to Dixie Valley, the modeling shows that the age of the present thermal flow must be on the order of 50,000 to 500,000 years to generate the high temperatures seen in the DVPP area. This age is much shorter than the age of the Dixie Valley normal fault system and so a periodicity is implied. The age range is supported by the age dating on spring deposits, at least on deposits not related to the flow initiated by the last earthquake event (i.e., The Bend event). The presence of a variety of thermal systems as implied by the geochemical analysis is comparable with diffuse flow in general with focusing of deep upwelling in the hottest systems. The models are not compatible with recharge of the systems through the valley or at the margins. The model results corroborate the postulated link with young faulting and higher temperature geothermal systems.

REMOTE SENSING

Air Photo Interpretation

Several workers have made interpretations of various aspects of Dixie Valley geology and structure using aerial photographic interpretation. In addition, various kinds and scales of aerial photographs have been used. A complete suite of large scale, "low sun angle" aerial photographs of the valley is archived at the Nevada Bureau of Mines and Geology office on the University of Nevada, Reno campus, and has been used by most authors since the mid-1970's. Another useful type of aerial imagery is color infrared photography, which enhances vegetation anomalies associated with springs and geothermal features. Small-scale (high altitude) photography and satellite imagery are useful tools for analysis of regional structures and lineaments, and for contextual understanding of local features in relation to those in surrounding areas.

Hyperspectral Studies of Dixie Valley

HyVista HyMap hyperspectral imagery of the Dixie Meadows area has proved useful for mapping geology, alteration, and hydrologic features (Kennedy-Bowdoin et al., 2003). The spatial resolution of the imagery (3m) is sufficient to reveal many of the same features visible on aerial photographs (locations of springs and flowing wells, some of the intrabasin faults, the shoreline features of Lake Dixie, the salt marsh thrust belt, and many details of the current surface hydrology), but without the large distortions present on aerial photographs. Because of this, and because it covers an area much larger than any one aerial photograph, the hyperspectral imagery provides an integrated picture with sufficient detail to map important features and with features in proper geometric relationship with one another (Martini et al., 2003; Pal and Nash, 2003; Kennedy-Bowdoin et al., 2003).

AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) hyperspectral data were acquired in the general area of the power plant in an effort to detect buried faults and buried geothermal phenomena and have been described by (Nash et al., 2004). Analysis of the AVIRIS data led to mapping soil calcium carbonate and kaolinite anomalies that are spatially related to and likely associated with the buried piedmont fault.

InSAR

Interferometric synthetic aperture radar (InSAR) images (Foxall and Vasco, 2003) reveal a WNW-trending lineament that passes through the geothermal field, crosses the Clan Alpine Range to the east, and possibly the Stillwater Range to the west. It intersects a NNE trending lineament near the gravity gradient maximum on the east side of the geothermal field. It is considered significant that a Landsat lineament, an InSAR lineament, two of the most prominent intrabasin faults, and the gravity gradient maxima along the western margin of the basin all coincide and intersect in the area of the Dixie Valley geothermal system between the DVPP and DVPF areas.

InSAR has also been used to map subsidence related to production in the Section 33 wells. Synthetic aperture radar interferograms spanning several time intervals between 1992 and 1997 were used to investigate ground subsidence in Dixie Valley (Foxall and Vasco, 2003). The interferogram for a 10.5 month period between April 1996 and March 1997 shows rapid subsidence locally reaching about 10.5 cm/yr. This subsidence is centered slightly NE of the Section 5 injection wells, in the northern part of the field, between the Section 33 and Section 7 production areas. The area of most rapid subsidence is about 1.2 km southeast of Senator fumaroles at the toe of the Senator alluvial fan.

CONCLUSIONS

Dixie Valley, Nevada has been the subject of extensive geoscience studies since the large earthquake events of 1954. The presence of large geothermal energy resources in the area has led to an intensification of these studies. As a result, the geometry of a large displacement normal fault zone (>5 km vertical displacement over ~ 8 to 15 My) between the Stillwater Range and Dixie Valley is probably the most thoroughly explored large normal fault zone in the world, penetrated by over 20 deep drill holes, several thermal gradient surveys, numerous seismic reflection profiles, gravity surveys, electrical sounding surveys, three levels of aeromagnetic surveys, and detailed geologic mapping. Dixie Valley differs from other well-known areas, such as Railroad Valley, in that the target for geothermal activity is the fault zone itself.

At Dixie Valley, the present production within the DVPF consists of two distinct areas (Section 33 and Section 7) each about one to three kilometers long. The average thermal anomaly though is over 20 km long. These two areas are hydrologically separated from each other at depth, and from the third production area - DVPP, even though all three areas are thermally similar at depth as shown in Figure 6 by the area of deep wells near the fumaroles. Thus, the geologic model that best fits the results is not a single fault plane or set of parallel fault planes, but a complex interfingering system of fractures that host a variable (in time and space) flow system confined to the most open parts of the system at a particular point in time. This type of model is similar to the model of vein structure associated with ore deposits. In fact, gold mineralization has been found associated with the geothermal systems at the Senator fumaroles (Johnson et al., 2000) and at the Dixie Comstock Mine (Vikre, 1994).

An example of a plan view of a vein system is shown in Figure 9. The figure shows the typical vein structure associated with an ore body in the El Bronce mine in Chile (Camus et al., 1991). The complex effects of the superimposition of many different events lead to a pattern that is neither easily understood nor simply described. Furthermore, the location of the permeability necessary for a large,

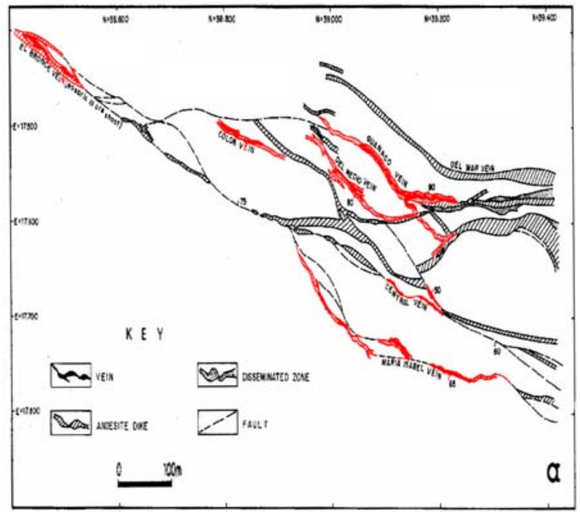

Figure 9. Ore Bodies at El Bronce, Chile. Zones of permeability are shown in red. The area shown is 0.5 km square, about the size of the production zones in Sections 7 and 33.

long-lived system of this type varies with time and as a result the ore bodies are not uniformly nor logically distributed along the vein system in its final configuration. Many types of models for locating permeability may be useful in a given situation, i.e., the orientation of the fault, the position in time relative to the last large earthquake, etc. These are probably less relevant though than directly locating the shallow thermal anomalies associated with the active flow paths at a given moment in the evolution of the system by using thermal gradient drilling, very shallow (1 m) temperature surveys, or airborne infrared surveys. The results in Dixie Valley show that the position of the permeable pathways will not necessarily be obvious, but that they are not hard to find with thermal techniques.

Structural models of Basin and Range normal faults predict a wide variety of dips from high angle to low angle, with the two end members possessing strong support within the scientific community. The techniques utilized in geothermal exploration, particularly drilling, are critically dependent on the expected dip of structures related to the reservoir. So the uncertainty in the structure, based on the extremes of the generally accepted models, is a major drilling factor and ultimately adds to the risk involved in geothermal exploration and development. In the case of the Dixie Valley/Stillwater Range fault zone structural models, the "fault" has been determined to be a complex zone of faults and fractures.

Hence using the knowledge gained from the Dixie Valley Producing Field (DVPF) and the Dixie Valley

Power Partners (DVPP) is critical to our understanding of normal fault systems, because the geometry of the fault zone in these two areas is now well understood from numerous drilling and geophysical surveys. The results are:

1. A 20+ km strike length of the fault zone between the Stillwater Range and Dixie Valley is presently the locus for fluid(s) circulating at temperatures over 200°C (up to 285°C) at 2 - 3 km depth.

2. Geothermal systems along the fault zone have been intermittently to continuously active for a long time with the present systems in existence for approximately 100,000 years.

3. The fault zone is complex, 1-2 km wide with multiple strands in the range (footwall) and in the valley (hanging wall), in addition to the exposed range/valley bounding fault.

4. Individual fault strands dip 70-80° or greater to a depth of at least 3 km. The dip of layering in the exposed Stillwater Range reflects deep-seated shear deformation imparted layering. Theory predicts near vertical extensional fracturing at the surface, which is actually observed.

5. As a consequence of point #4, *none* of the production wells in the field (located 2-3 km into the valley) produce from the exposed main strand of the fault zone (the *Dixie Valley normal fault* as commonly defined), but from blind valley (piedmont) segments.

6. The surface expression of the fault zone (range-valley contact) does not reflect the subsurface structure in any simple way, so its segmentation has little relevance to locating the specific position of the geothermal resources.

7. In general, the exposed fault along the topographic range front does *not* accommodate the majority of the vertical displacement in the areas of large vertical displacement. The seismic reflection profiles of the range front structures are difficult to interpret, as shown in the-classical section by Okaya and Thompson (1985) the range-bounding fault is not imaged in their study as they proposed.

8. The extensional strain in the Dixie Valley area is not only accommodated by the range bounding surface trace, but also by the multitude of other range and valley structures. Synclines in the valley fill, clearly imaged in the reflection sections, delineate areas where buried extensional accommodations are focused and antithetic faults are prominent.

9. Vertical and low angle structures can explain the complex surface shapes of the mapped scarps, but low angle faults cannot explain the thermal structure.

10. The Bend event (2 - 2.5 ka) probably affected the area of the power plant and to the north for several kilometers, but the scarps were confined to the range and have been erased by erosion or are not recognized because they do not cut Quaternary materials. The thermal regime in the range may have affected the style of faulting there.

The five primary geophysical characterization techniques (gravity, magnetic, seismic, electrical, and thermal) have contributed information in the Dixie Valley area as described in the discussions above. Of all of the techniques, gravity is the most cost effective. The data are three dimensional, which is very important in the complicated extensional settings of Dixie Valley. The results obtained utilizing gravity are particularly useful in the Basin and Range setting where the low-density valley fill is juxtaposed against the higher densities typical of range lithologies. In the case of Dixie Valley, the technique is especially helpful because of the large displacement between the range and the valley. In areas with less basement relief or lower density contrasts the results might be less definitive.

The high-resolution aeromagnetic survey also provided very useful results for situations in which three-dimensional analysis is required. The technique has been used in the Albuquerque Basin (Grauch, 2001) and Dixie Valley for locating young intrabasin faults. It helped to define the detailed surface pattern of faulting in both cases. The presence of detritus from the highly magnetic basic rocks of the ophiolite in the valley fill at Dixie Valley probably contributed to the success in detecting the distribution of the young faults in the valley fill.

Probably more money was spent on the reflection seismic studies than on the other geophysical techniques. The reflection data are only two-dimensional and are thus of limited use in interpreting structures in Dixie Valley because of the three-dimensional velocity setting. There are many off the line reflection features in the data that complicate the interpretation, and even if the data were of modern vintage the two-dimensionality would still be a problem. The SRC-1S and SRC-1N lines are particularly affected. The setting of very abrupt, high velocity contrasts also causes problems for the reflection technique, even if 3-D data are collected. The approach of generating velocity maps has been extremely useful in the interpretation, however. If the Dixie Valley fault were not such a large displacement fault zone, the technique would be more useful. In the case of line 106, where the basement structure has a ramp geometry, the imaging of the details of the structure was very successful. In a contemporary application of the technique, there are ways to increase the usefulness of the results. Considering the high costs of reflection surveys, it would make sense to use other low cost geophysical techniques first so that potential problems can be identified and addressed before reflection surveys are deployed.

ACKNOWLEDGEMENTS

The objective of the report summarized here was to describe in one location U.S. Department of Energy (DOE) supported studies in the Dixie Valley geothermal area over approximately the last 10 years in the context of other studies in the area during the past 40 or 50 years. This study attempted to comprehensively compile references to the studies and surveys published, unpublished, or incompletely published in the gray literature. The focus of the report is on the basin geology and structure, thermal regime, and geothermal system geochemistry. Reservoir studies are briefly discussed. The individual investigators are responsible for the sections of the report as follows: David Blackwell and Richard Smith are the overall editors and also focused on the geology and geophysics of the area. Steve Bergman prepared the regional summary and regional discussion of Basin and Range structure. Fraser Goff prepared sections on aspects of the system geochemistry and contributed pictures of the various geothermal systems. Mack Kennedy prepared the sections on the He studies and the reservoir geochemical behavior with time. Jason McKenna contributed the sections on natural state flow modeling and aspects of the thermal regime, and magnetic and gravity modeling of the basin structure. Maria Richards contributed to the thermal data analysis, to the editing of the whole report, and to appendix preparation. Al Waibel contributed the details of the range and reservoir geology and the geothermal system hydrothermal alteration. Philip Wannamaker contributed the section on the electrical studies. A number students contributed to the preparation of the report, including especially Mark Leidig (geophysical analysis), Kamil Erkan (thermal regime), and Patrick Stepp (index figures and structural model figure design).

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