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Conceptual Models of the Dixie Valley, Nevada Geothermal Field

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ABSTRACT

Many conceptual models of Dixie Valley and its geothermal field have been developed over the past 32 years. These document academia's and industry's struggle to understand what appears to be one of the simplest geothermal systems in the world. The first geological model in 1967 hypothesized nested grabens in the valley with multiple buried 60° dipping normal faults taking up much of the offset between the valley and the Stillwater range. A variety of geothermal models, mostly involving convection cells, were superimposed on the 1967 geological model for the next 16 years. In the mid 1980s the nested graben and convection cell concepts were discarded in favor of a single range-front fault model dipping about 53°. Interestingly, recent seismic and gravity studies have reverted toward the original concept that a significant portion of the offset between the valley and mountain range is associated with buried piedmont faults.

For a number of years it was believed that the development of permeable fractures in the reservoir was largely controlled by lithology with offsetting brittle rocks across the Stillwater fault being the preferred geometry. In the late 1990's regional in-situ stress studies led to the development of a permeability model wherein the highly permeable fractures forming the reservoir are oriented subparallel to the Stillwater fault and are critically stressed for normal faulting. Although not yet fully tested, this model would downplay the importance of offsetting granitic and gabbroic lithologies in controlling the location of large permeable fractures.

Introduction

No person has ever seen an active geothermal reservoir. Like the blind men and the elephant, it can be sensed from differing perspectives with a wide variety of tools or measurements. Models must then be created to give meaning to the measurements. Even before a specific reservoir is first sensed a conceptual model, even as simple as envisioning open space in hot rocks filled with hot water, may already exist.

Over the lifetime of a geothermal project various disciplines will develop progressively more complex models to explain the characteristics of the reservoir and surrounding geology. The first conceptual model will be geological in nature. It may consist of as little as two lines, one representing an inclined fault, the other representing the surface of the earth, and a single arrow showing fluid flow direction. Even this very simple model is based on a simpler geologic model of a fault without fluid movement. Many additional layers of geological and engineering concepts are later added to the model.

During the exploration and drilling phases of a project the single most important challenge is to develop a conceptual understanding as to why hot, high permeability wells can be found in some locations and not others. As engineers take over testing and production of wells and reservoirs, modeling needs change from geologic to numerical but a conceptual model still forms the foundation for the numerical models.

Overview of Dixie Valley Model Development

In the late 1970's and early 1980's Dixie Valley in west-central Nevada was the scene of the most competitive geothermal leasing and exploration in the Basin and Range province. At least eleven different companies engaged in geothermal exploration along the active Stillwater normal fault which separates the Stillwater Mountains from the Dixie Valley graben. Seven of these companies actually located and drilled exploratory wells, but only three of these companies drilled wells supporting the existing 62 MWe power plant. An extraordinary number of explorationists were able to develop and test exploration strategies and models. In the past few years much Dept. of Energy sponsored research has occurred at Dixie Valley, giving another generation its opportunity to develop and test new concepts here which have revised and improved the fundamental understanding of this resource (Barton *et al.*, 1998; Hickman *et al.*; 1998, Rose *et al.*; 1998, Plank *et al.*, 1999).

When Oxbow Geothermal Corp. consolidated the Dixie Valley holdings in 1985 several unpublished reports from the period 1976 to 1984 were obtained and preserved. These now offer a unique and sometimes entertaining history of the geothermal industry's evolution in visualizing what on the surface appears to be one of the simplest geothermal systems in the world; a straight normal fault. To avoid unnecessary embarrassment of various authors, the unpublished models will simply be identified by the year in which they were reported.

1967 Geological Model

Geothermal systems are superimposed on preexisting geology. The first modern geological model of the subsurface of Dixie Valley was published by Stanford University researchers (Thompson *et al.*, 1967) as a result of interest in trying to understand why four large earthquakes occurred in or near Dixie Valley in 1954 (Thompson, pers. comm 1997). This was a major research effort and the stature of the Stanford University authors resulted in unquestioning acceptance of this geological model by the first generation of geothermal explorationists. It would be almost two decades before aspects of the 1967 interpretations would be publicly revised.

This geological model was based primarily on results of seismic refraction lines with additional support from gravity, aeromagnetics, and photogeology of fault scarps. There was no drillhole information and no interest in geothermal exploration at the time so this model did not address aspects of geothermal interest.

The major thesis of this model was that Dixie Valley contains buried grabens nested within the main valley graben and that a significant fraction of the total vertical offset has occurred on buried normal faults with little or no surface expression (Figure 1). These faults were interpreted to have dips near 60°. The 1954 Dixie Valley earthquake produced small fault scarps in alluvium as much as a mile or two east of the Stillwater range front about 30 miles southwest of the present Oxbow power plant. This is where the majority of the Stanford research was conducted. Although the buried normal faults were not actively incorporated in the geothermal models, and no new information was generated to support this interpretation for many years, the nested graben concept dominated most geothermal models until 1984. Conclusively proving or disproving the existence of these buried faults and documenting their offsets remains difficult due to the presence of many large landslide blocks along the front of the range, poorly known densities of valley fill, and surprisingly limited drillhole information on the dips of the fault(s) at depth.

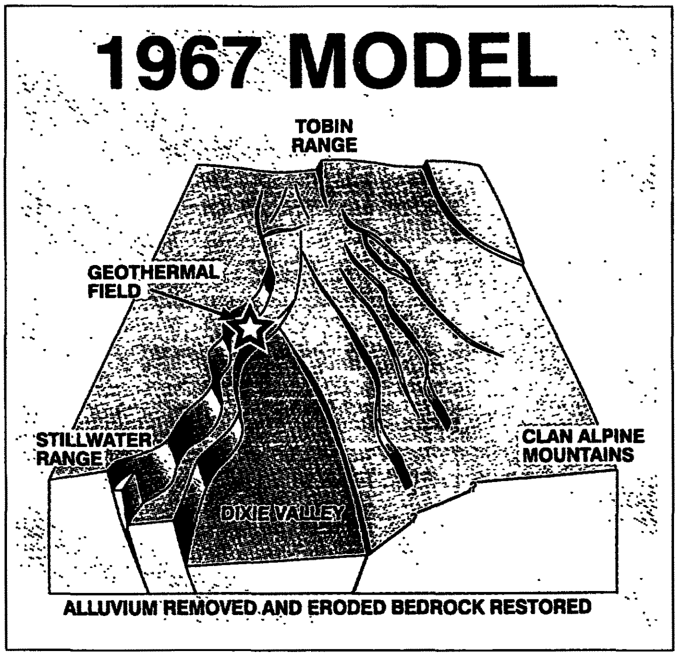

Figure 1. Generalized block diagram of central and northern Dixie Valley. (Figure 3 from Thompson *et al.*, 1967.)

1976 Conceptual Geothermal Model

In December 1976 the first conceptual geothermal model of Dixie Valley was presented in an unpublished report. It was largely based on results from 15 temperature gradient holes up to 300' deep, primarily located along the western edge of the valley and the 1967 geological model. It has both amusing and almost prophetic aspects.

The conceptual model (Figures 2 and 3) showed hot fluid flowing laterally from near the center of the valley and rising up through apparently unfractured bedrock in the block between two normal faults. The fluid then cools and descends along the range-front fault to a depth of 3 or 4 km and then migrates back horizontally toward the middle of the valley to complete a boomerang shaped convection loop. The buried normal fault (Figure 2) has no impact on the fluid flow and therefore was not a active or critical component of this model. The cross section

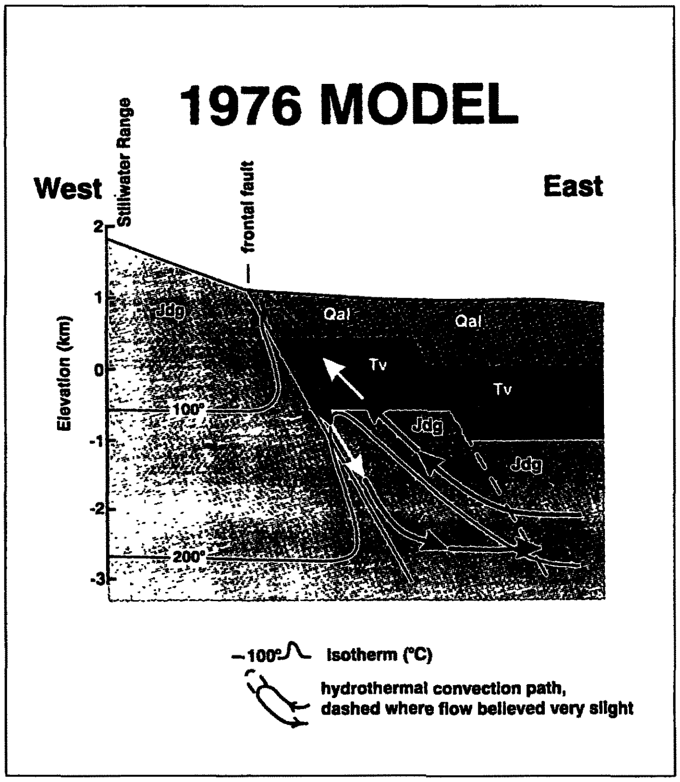

Figure 2. Schematic model of hydrothermal convection and temperature gradient, Dixie Valley, Nevada. Section transverse to plant of frontal fault.

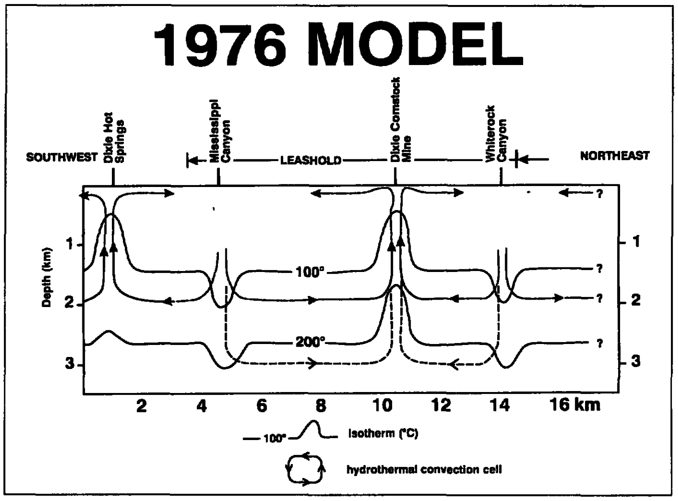

Figure 3. Schematic model of hydrothermal convection and temperature gradient, Dixie Valley, Nevada. Section in plane of frontal fault.

along the plane of the range-front fault (Figure 3) suggested a series of convection cells within the range-front fault with downflows suspiciously coinciding with the mouths of major canyons discharging year round streams. Figures 2 and 3 were not merged into a coherent three dimensional diagram. This model shows the strong influence of closed convection systems popular in the mining industry at the time.

The more credible aspects of this model include text stating "convection probably is most pronounced within the frontal fault zone." and "a reservoir is to be sought in brittle, fractured metamorphic and/or igneous rocks of Mesozoic age underlying the western part of the stepped-down Dixie Valley graben." Deep circulation of meteoric water was the preferred heating mechanism. Lastly, an unsupported conclusion was that hydrothermal convection is not likely to occur within the fault's footwall or range-block. So far this has generally held true.

1979 Conceptual Model

Occasionally a model is developed that is ahead of its time but coverage of the advancement is so limited that its significance is not recognized until years later. A model can also be a significant advancement by questioning previously accepted concepts. The 1979 model is such an entity . It was prepared by individuals not closely associated with the geothermal industry and was based on extensive mapping and results from the two southernmost wells in the area, 45-14 and 66-21.

This model was the first to note that recurrent movement along the "primary range-front fault" favors the maintenance of permeability. It also introduced the concept that rocks with favorable primary or secondary permeability characteristics needed to be juxtaposed across the fault for significant permeability to develop. The exact formations were not defined. This requires that high productivity wells intersect the range-front fault zone at specific depths to intersect the appropriate formations. The very extensive Triassic slate formation in the area was fingered as unlikely to have sufficient permeability, and no well in Dixie Valley has yet encountered significant permeability in this formation.

This model also questioned the importance and reality of the postulated interior graben faults, describing them as hypothetical and questioned the existence of a major fault and associated major convection cell in the middle of the valley. It was also the first time that the location of the range-front was noted crossing a deep well. (At this time at least one other unpublished report showed most postulated faults to be vertical and a few were even shown as high-angle reverse faults.) A dip of 50° for the range-front fault was shown which is significantly different from the approximately 60° of the 1967 geological model. In the vicinity of the power plant the dip appears to be 52 to 54° for a single fault model.

As the 1979 model covered an area where two nonproductive wells had been drilled, an expected conclusion was a recommendation for future well locations. This recommendation was to drill in areas where other faults intersect the range-front fault. While drilling at the intersections of faults has long been a favored ploy of geologists, it tends to offer relatively small targets and recent in-situ stress work suggests that other factors may be more important in controlling large-scale permeability.

1980 Integrated Model

This model was prepared by graduate students and professors with very limited geothermal experience (Bell *et al.*, 1980) and the highly simplistic model represents a substantial regression from concepts developed by 1979 (Figure 4). Of particular interest is the fact that it includes spherical local heat sources, about 2 kilometers in diameter, along both edges of the valley at depths of 6 to 8 km, based primarily on interpretation of MT data. Presumably these represent magma bodies, but nothing in the published literature suggests the presence of such shallow features in Dixie Valley. No fluid flows are shown on this model.

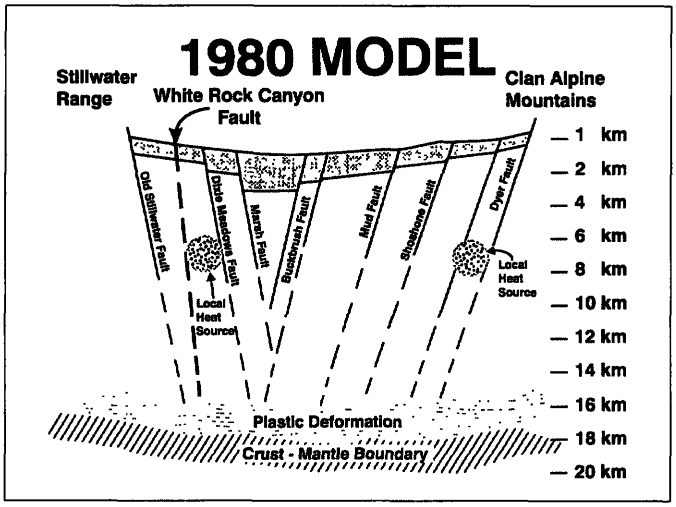

Figure 4. Generalized east-west cross-section of the integrated model of the Dixie Valley geothermal system. (Figure 8 from Bell *et al.*, 1980.)

1981 Model

In June 1981 SUNEDCO, the discoverer of the geothermal field, published its only paper on the exploration effort (Parchman and Knox, 1981). Perhaps Figure 5 was constructed prior to making the discovery, as there is substantial disagreement with actual results from the #1 S.W. Lamb discovery well drilled in 1978. Depths to tops of formations and thicknesses are highly erroneous. However, given the highly competitive conditions in Dixie Valley in 1981 one can speculate that this published information might have been an attempt at spreading disinformation. Unfortunately, there appear to be no unpublished SUNEDCO reports to shed further light on their concepts at the time. This model also contained multiple convection cells in bedrock beneath the central part of the valley (Figure 5 in Parchman and Knox, 1981).

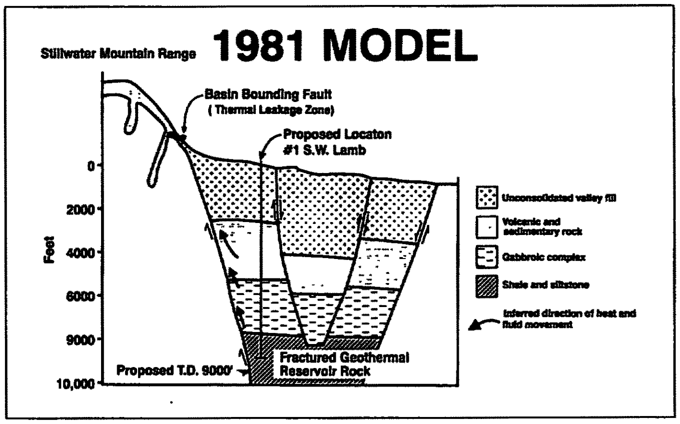

Figure 5. Cross section of the subsurface geologic model relative to the location of the proposed #1 S. W. Lamb exploratory well. (Figure 5 from Parchman and Knox 1981.)

1983 Model

By 1983 SUNEDCO had drilled 8 wells, but data from these wells were very well guarded. Therefore, this model is based on more-or-less the same information as the three previous models. The 1983 model made a rather extreme attempt to conform to the 1967 geological model (Figure 6) and tried to answer most questions with fault-based solutions. Consequently, the dip of the faults were increased to 70°. The temperature contouring on Figure 6 is also quite distorted as the two control wells are located about 6$^1/_2$ miles apart and attempts were made to explain limited permeability in these wells through a "volcanic aquifer." It is interesting to note that no thermal fluid is shown rising up any of the faults between offsets in the aquifer segments even though the isotherms are clearly at shallow levels near the range-front fault. This model also resulted in the postulation of a fault immediately west of the production wells within the geothermal field.

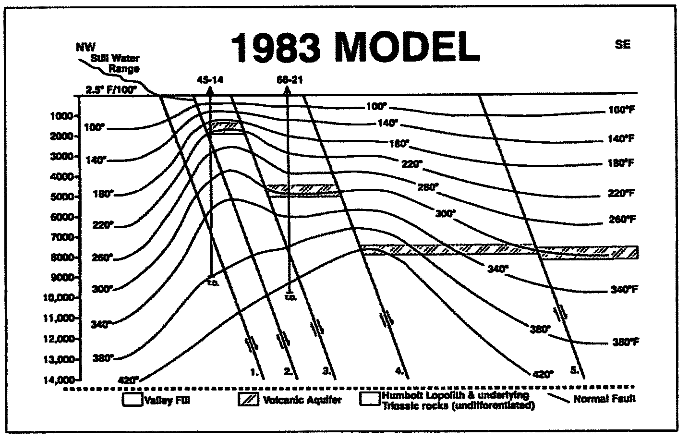

Figure 6. Schematic geologic and temperature cross-section of the western side of Dixie Valley, Nevada.

Evidence for this fault remains very limited. This was the last geothermal model in the 1980's to be superimposed on nested grabens.

Much geophysical exploration occurred between 1974 and 1983 yet little or none of these results was actually incorporated into this conceptual model.

1984 Conceptual Model

The year 1984 marked the first time that the subsurface data from the SUNEDCO wells were seriously analyzed and put together in a coherent model (Figure 7). The buried normal faults are missing and the dip of the range-front fault is now shown at 52°. The convection cells in solid bedrock are also now missing. The dominance of the range-front fault in controlling thermal fluid flow is shown by the temperature contours. Since 1984 changes to this basic model have been slight refinements, generally adding only finer details.

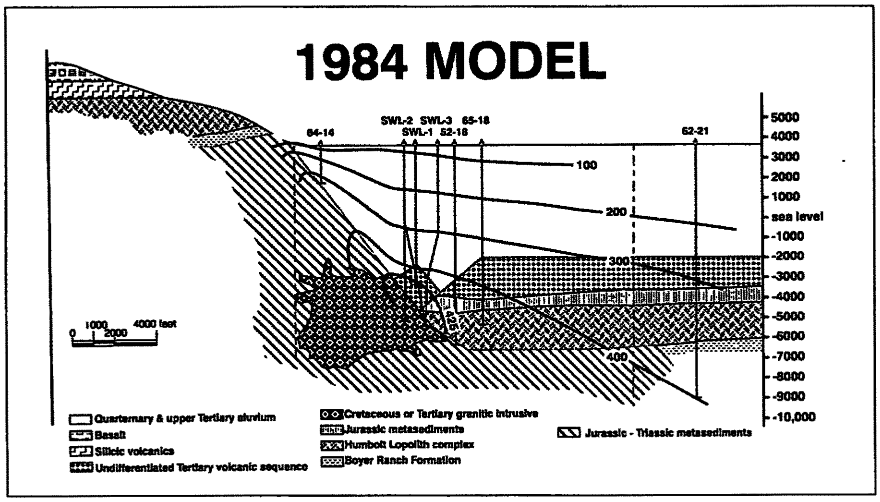

Figure 7. Geologic and temperature cross-section of western portion of Dixie Valley at Sun properties.

1985 Geological Model

It may not be coincidental that the greatly improved 1984 model is consistent with a paper published in January 1985 and coauthored by the principal author of the 1967 geological model. The 1985 model shows a single normal fault defining the margin between Dixie Valley and the Stillwater range in the immediate vicinity of the geothermal field (Okaya and Thompson, 1985) (Figure 8). This study was based on a seismic reflection line, SRC-3, and gravity data. It should be clearly pointed out that the 1967 model was largely based on seismic refraction data. Different density contrast assumptions between the intermingled alluvial fan material and lacustrine sediments in the western part of the valley (Blackwell and Kelley, 1994) were also used in the 1985 gravity analysis to develop the single fault model. The fundamental cause of this substantial change in the geologic model appears to be an inherent ambiguity in uniquely interpreting even multiple geophysical data sets.

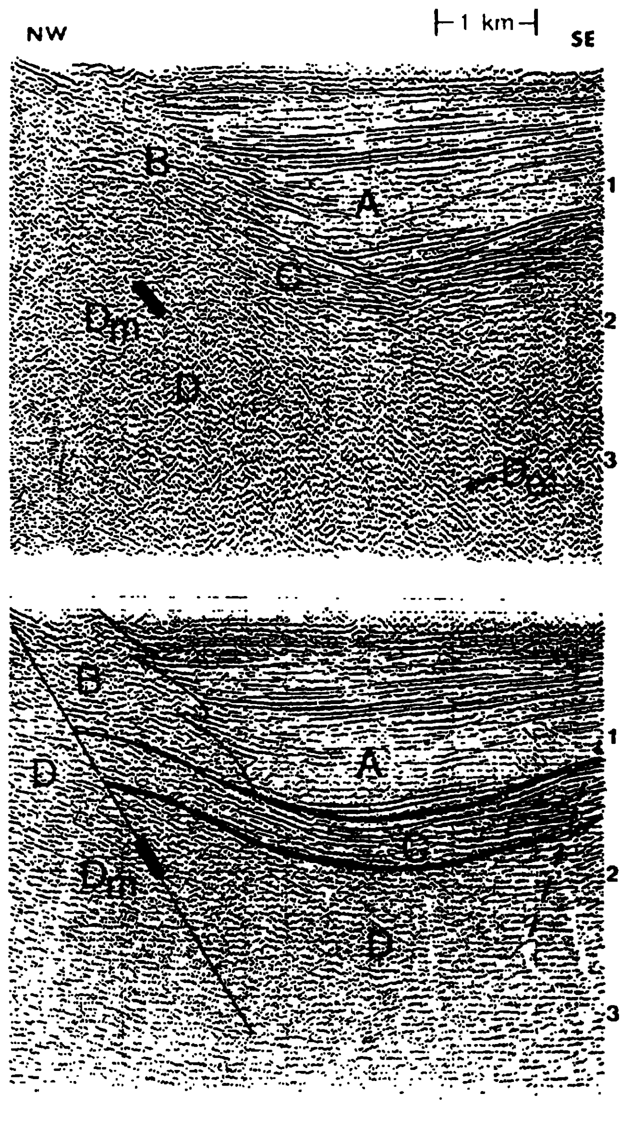

Figure 8. Seismic line SRC-3, (top) stacked and (bottom) interpreted finite difference migration. Reflection symbols: A, lacustrine and playa deposits; B, alluvial fan; C, Tertiary volcaniclastic sequence; D, Mesozoic basement; D_e, steeply dipping fault plane reflections: D_m, hand migration of event D_e. Calculated fault dip from the hand migration is 50°. (Figure 3 from Okaya and Thompson, 1985.)

Recent Geological Modeling Considerations

The nested graben concept at the geothermal field has recently been resurrected with the reprocessing of several reflection seismic lines (Hongas *et al.*, 1997; Plank *et al.*, 1999). An unpublished report by Hongas *et al.*, shows both the range front fault and a buried normal fault to have dips well in excess of 60° in the geothermal field.

Recent seismic reflection lines located about 30 miles south of the geothermal field have "unequivocally" defined the range front fault to dip at 28° to a depth of 1.5 km (Louie *et al.*, 1999). Interestingly, this is the same area where most of the work was performed for development of the 1967 geological model.

A detailed gravity survey run in 1996 in the vicinity of the geothermal field has shown zones of high gravity gradient 5000 to 7000' away from the range-front fault which may be interpretable as buried normal faults (Blackwell *et al.*, 1999). These gravity data and a reinterpretation of the seismic reflection lines shot in the early 1980's has produced an interpretation of three faults splaying off the range front fault into the valley, giving an appearance of nested grabens. It is also possible that these high gradients are outlining buried landslide deposits. There are several easily visible large landslide deposits along the front of the Stillwater Range. A water exploration well drilled in 1997 near the toe of the Senator alluvial fan at the north end of the geothermal field produced cuttings of mixed quartzite and shale at depths thousands of feet shallower than predicted by the 1984 model.

The most recent published geological work by Plank, *et al.*, (1999) offers a different interpretation, that the dip of the range-front fault may not be constant with depth and that recently active splays of the range-front fault are actually located within the Stillwater Range near the geothermal field.

Obviously, this new information has the potential to substantially modify the basic conceptual geological and geothermal model of the Dixie Valley geothermal field.

1986 Numerical Model

By 1986 the modeling focus had shifted from geology to predicting future reservoir performance. The largest geothermal flow test in the United States was conducted at Dixie Valley in mid 1986 with up to six wells flowing at one time and pressure monitoring in eight idle wells (Desormier, 1987). Understanding the pressure interactions between wells and overall reservoir dynamics had become important parameters for modeling future productive characteristics of the reservoir. A conceptual model of the reservoir flow and connectivity (Bodvarsson and Doughty, 1987) was developed for a numerical

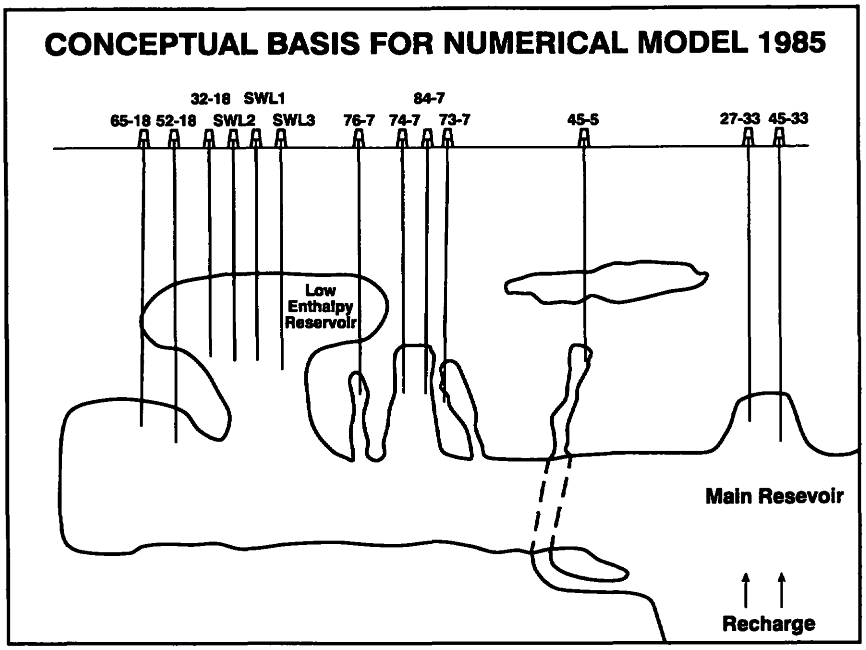

Figure 9. Schematic reservoir model.

model (Figure 9). This unconventional looking conceptual model is based on well interference data, enthalpy considerations and the basic geology. Figure 9 can be roughly viewed as a map of permeability in the plane of the Stillwater fault.

Interference testing responses suggested that the main recharge area is in Section 33 at the north end of the geothermal field and that thermal flows were toward the south and shallower depths where the low enthalpy reservoir was located. Wells in Section 7 showed limited pressure interference which results in the hypothesized vertical channels. The unique character shown near well 45-5 is an attempt to rationalize anomalous pressure responses in Section 5. This numerical model reliably predicted the behavior of the field during its first decade of operation. Recent tracer testing has documented some unpredictable flow paths within the reservoir (Rose *et al.*, 1998). Incorporating these paths into a numerical model will result in additional conceptual complexity.

Permeability And The 1997 Stress Model

From the latest 1970's to the mid 1990's several explorationists, including this author, believed that certain rock types had to be intersected in the immediate vicinity of the range-front fault for a well to have adequate permeability (Waibel, 1987). The juxtaposition of rocks of the Mesozoic Humboldt Lopolith in the hanging wall and Cretaceous granite in the footwall has certainly been very successful at the operating geothermal field. Wells which have encountered Triassic shale on either or both sides of the fault have been consistently unsuccessful. However, these two factors alone are not sufficient to explain all variations observed in reservoir permeability as they represent only a very small sampling of the entire length and depth of the range-front fault. They certainly do not explain the occurrence of a number of impermeable legs of wells in the immediate vicinity of the reservoir.

The first reasonably detailed explanation of localized permeability in the Dixie Valley geothermal field was presented in 1987. The concept was that high permeability resulted from the interaction of extensional features associated with localized rhombograbens (rhombochasms) and various brittle litho/mechanical units (Waibel, 1987). This important and little noticed advancement preceded the recent in-situ stress studies by almost a decade.

The in-situ stress studies, begun in late 1995, have shown that the orientations of the highly permeable fractures are distinct from the overall fracture population and are subparallel to the Stillwater fault (Barton *et al.*, 1998; Hickman, *et al.*, 1998). Hydraulic fracturing stress measurements in the productive wells indicate that the magnitude of the least horizontal principal stress is low enough to lead to frictional failure (normal faulting) on the Stillwater fault and these highly permeable fractures. Similar measurements in two wells located along the Stillwater fault 8 and 20 km south of the geothermal field indicate that shear stresses on

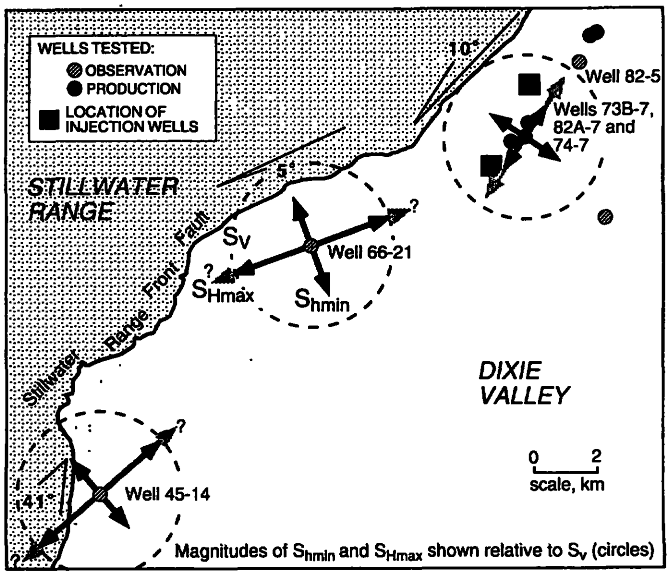

Figure 10. Orientations and relative magnitudes of the least horizontal principal stress, S_{hmin}, and the greatest horizontal principal stress, S_{Hmax}, at Dixie Valley. The length of each arrow is proportional to the magnitude of the corresponding stress, normalized to the magnitude of the vertical stress S_V (dashed circle) appropriate for that well and test depth. Lower and upper bounds of S_{Hmax}, determined through analysis of conditions for breakout formation, are depicted as dark and light gray arrows, respectively. Stresses shown for wells 73B-7 and 82A-7 are average values from three measurements at 1.7 to 2.5 km depth. Also shown is the extent (in degrees) to which the Stillwater fault is locally deviated from the optimal orientation for normal faulting. (Figure 10 from Hickman *et al.*, 1998.)

the Stillwater fault and any sub parallel faults at these locations are too low to lead to frictional failure. Thus, fault zone permeability is high only when individual fractures as well as the overall Stillwater fault zone are optimally oriented and critically stressed for frictional failure (Figure 10). While small rhombograbens may be present within Dixie Valley they may not be a necessity for localized high permeability.

Conclusions

The development of conceptual models of the geology and the geothermal reservoir beneath Dixie Valley has provided a unique and long running case history of academia's and industry's struggle to understand what appears to be one of the simpler geothermal reservoirs in the world. Geological and geophysical interpretations have repeatedly proven to be ambiguous and been repeatedly revised, in some aspects strongly resembling the original nested graben concept. Workers have tended to show a considerable reluctance to both incorporate new information into conceptual models or to revise basic assumptions. With over 20 years of exploration and dozens of geophysical surveys and deep wells there still remains considerable uncertainty and legitimate debate about the basic structure of the Stillwater range-front fault(s).

Reservoir engineering information such as interference test results and tracer tests indicating anomalous pathways adds another layer of complexity to our efforts to visualize pressure responses and fluid movement within the fractures defining the Dixie Valley reservoir.

Much new and recent information has been generated at the Dixie Valley geothermal field in terms of basic geology, seismic line reprocessing and interpretation, gravity modeling, tracer testing, and in-situ stress measurements. All of these need to be integrated into the next generation of the Dixie Valley geothermal field conceptual model.

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