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HYDROLOGIC PROPERTIES OF THE DIXIE VALLEY, NEVADA, GEOTHERMAL RESERVOIR FROM WELL-TEST ANALYSES

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ABSTRACT

Temperature, pressure, and spinner (TPS) logs have been recorded in several wells from the Dixie Valley Geothermal Reservoir in west central Nevada. A variety of well-test analyses has been performed with these data to quantify the hydrologic properties of this fault-dominated geothermal resource. Four complementary analytical techniques were employed, their individual application depending upon availability and quality of data and validity of scientific assumptions. In some instances, redundancy in methodologies was used to decouple interrelated terms. The methods were (1) step drawdown, variable-discharge test; (2) recovery analysis; (3) damped-oscillation response; and (4) injection test. To date, TPS logs from five wells have been examined and results fall into two distinct categories. Productive, economically viable wells have permeability-thickness values on the order of 10^5 millidarcy-meter (mD-m) and storativities of about 10^{-3}. Low-productivity wells, sometimes located only a few kilometers from their permeable counterparts, are artesian and display a sharp reduction in permeability-thickness to about 10^1 mD-m with storativities on the order of 10^{-4}. These results demonstrate that the hydrologic characteristics of this liquid-dominated geothermal system exhibit a significant spatial variability along the range-bounding normal fault that forms the predominant aquifer. A large-scale, coherent model of the Dixie Valley Geothermal Reservoir will require an understanding of the nature of this heterogeneity and the parameters that control it.

INTRODUCTION

The Dixie Valley Geothermal Field is located within the western Basin and Range in west central Nevada, USA. The area is marked by high localized heat flow (Williams et al., 1997) and late Cenozoic extensional faulting and volcanism (Okaya and Thompson, 1985). The regional hydrologic system is comprised of over 5000 km^2 of surface drainage (Parchman and Knox, 1981), with groundwater recharge occurring primarily from infiltration of meteoric water through permeable channels within the consolidated rocks of the surrounding mountain ranges. The Stillwater Fault is a major range-bounding normal fault that dips moderately ($\approx 52°$) to the east-southeast and forms the predominant aquifer in the region. Most of the geothermal heat and mass transport encountered in Dixie Valley occurs within this fault zone (Benoit, 1992).

Numerous wells have been drilled to exploit this liquid-dominated geothermal resource. In this report, temperature, pressure, and spinner (TPS) geophysical logs obtained from five wells drilled along the fault zone are analyzed to quantify the hydrologic properties of the reservoir. The analytical methods adopted here are similar to conventional groundwater techniques, though the presence of flashing fluid in the wellbore during self-sustaining geothermal discharge introduces additional complications (e.g., Narasimhan and Witherspoon, 1979; Grant et al., 1982). The pertinent wells are identified as 73B-7, 74-7, 62-21, 66-21 and 45-14, and their locations are shown in Figure 1. The results represent reservoir characteristics in the vicinity of the individual wells that

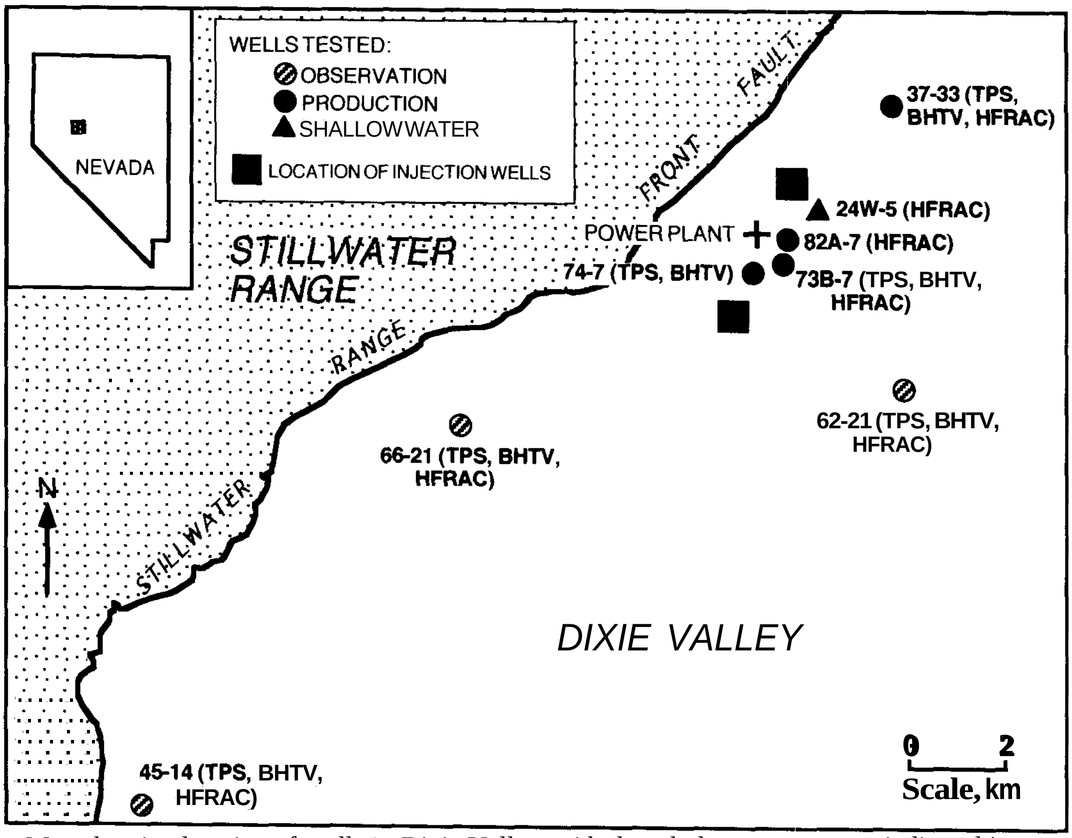

Figure 1. Map showing location of wells in Dixie Valley, with downhole measurements indicated in parentheses. Temperature-pressure-spinner(TPS); borehole televiewer (BHTV); hydraulic fracturing (HFRAC).

together delineate the spatial distribution of hydrologic properties along the fault.

WELL-TEST ANALYSES OF TPS LOGS

Temperature, pressure, and spinner rotation were recorded simultaneously within the wells by means of a multifunctional geothermal logging tool. Data were obtained under a variety of test conditions and were digitized as a function of depth and time. These logs were subsequently analyzed to estimate the hydrologic properties of the aquifer penetrated by the well. Four separate well-test analyses were employed, with each individual application dependent upon availability and quality of data and validity of scientific assumptions. In all methods, the aquifer is considered to be confined, horizontal, of infinite extent, and isotropic along the fault plane. The fault-dominated aquifer appears to be planar to depths below 3 km, with its surface expression appearing as distinct zones of hydrothermal alteration and fracturing (Parry et al., 1991; Seront et al., in press). Since all but one of the wells considered in this report (Well 62-21) intercept the fault at a depth of roughly 2700 meters, the assumptions of hydraulic confinement and infinite extent are reasonable across this spatial scale. It should be noted that the assumption of horizontal fluid flow through an aquifer that is, in reality, moderately inclined will cause transmissivity values to be slightly overestimated (Narasimhan, 1982). Finally, the issue of isotropy is one of continuing research and speculation, and recent laboratory studies by Gentier et al. (1997) indicate anisotropic flow patterns through fractures undergoing shear. Thus, it is not clear to what degree the assumption of fault-plane isotropy is valid in this study.

The hydrologic analyses conducted in this study are derived for fully penetrating, single-well tests and yield estimates of aquifer transmissivity (T) and storativity (S). Interference tests between two or more wells provide additional methods of arriving at storativity values, but these were not performed as part of this particular investigation. Transmissivities obtained in this high-temperature environment are adjusted for variations in fluid viscosity and are presented as permeability-thickness (K-H) in units of millidarcy-meter (mD-m). In order to uniformly compare hydrologic properties from several wells, estimates of K-H and S represent average values integrated across the entire thickness of the aquifer. This reservoir dimension is not yet well constrained at this site. TPS data were also analyzed as a function of depth to locate individual transmissive fractures within the fault and to distinguish them from the general fracture population. These results are discussed in detail by Barton et al. (this volume) in the context of tectonic stress and active faulting, but are not emphasized here.

Application of the four well-test methods to field data from Dixie Valley are systematically presented below. Most of the analytical solutions are extracted from the formulations presented by Kruseman and de Ridder (1994) in their comprehensive hydrologic review.

Step-Drawdown, Variable-Discharge Test

Two of the five wells considered here were successfully stimulated by air lifting to initiate vigorous, self-sustaining geothermal discharge. The TPS tool was initially run in a trolling mode to locate the flash point and to identify transmissive zones in the open borehole. The instrument was then set above the major feedpoint and held stationary while a production test was performed in the flowing well. TPS data were recorded downhole and corresponding volumetric flow rates and lip pressures were monitored at the surface during several stages of discharge. Examples of pressure (in MPa) and spinner (in revolutions per second, rps) data collected during such a test in Well 74-7 are illustrated in Figure 2. The pressure data were subsequently converted to water-level drawdown (in meters) using a fluid density determined from the record of pressure versus depth.

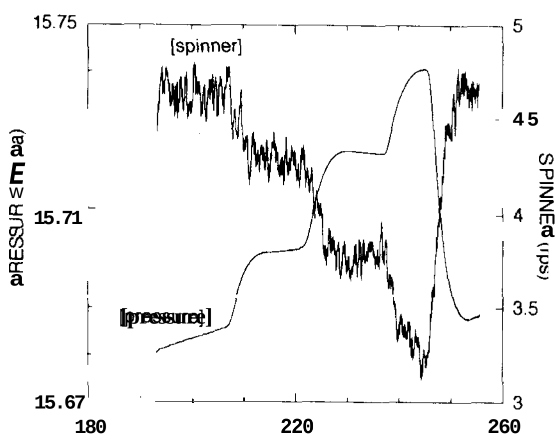

Figure 2. Production data for Well 74-7. Pressure (in MPa) and spinner rotation (in revolutions per second, or rps) were recorded by the TPS tool while held stationary at a depth of 2712 meters.

These log data can be used to quantify aquifer transmissivity based on the following relation (Cooper and Jacob, 1946):

$$s = \frac{2.30Q}{4\pi T} \log\left[\frac{2.25Tt}{r_w^2 S}\right] \quad [1]$$

where s = drawdown (m), T = transmissivity (m^2/min), Q = flow rate (m^3/min), t = time since onset of pumping (min), r_w = radius of well (m), and S = storativity (dimensionless). Using the principle of superposition, Eden and Hazel (1973) devised a graphical method for estimating aquifer transmissivity from a variable-discharge test which accounts for well losses. Another graphical procedure was proposed by Cooper and Jacob (1946) using values of specific drawdown (s/Q) associated with each discharge rate. In this latter analysis, T is computed from the following relation:

$$T = \frac{2.30}{4\pi\, \Delta(s/Q)} \quad [2]$$

where s/Q = specific drawdown (min/m^2), or the drawdown per unit discharge, and Δ (s/Q) is the difference in specific drawdown per log cycle of time t*. The term t* is the discharge-weighted logarithmic mean of t, the time since the onset of discharge [see Kruseman and de Ridder (1994) for computational details]. A value of t* is determined at each production stage and plotted against the specific drawdown; the slope of the best-fit straight line represents an estimate of Δ (s/Q) to be substituted into equation 2. For the production data obtained from Well 74-7 (Figure 2), this graphical exercise (Figure 3) yields a value of transmissivity, T, equal to 0.22 m^2/min. After correcting for fluid viscosity, the permeability-thickness of this well is 5.1×10^4 mD-m (Table 1).

Recovery Test

Once a well has undergone a change in ambient hydraulic pressure conditions, either due to fluid injection, pumping or stimulation, the record of pressure recovery versus time after shut-in can be analyzed to obtain an estimate of aquifer transmissivity. In many cases, this analysis serves as a convenient, independent check on the results of the preceding pumping test. An example of this type of recovery response is presented in Figure 4a with data from Well 73B-7 recorded immediately following a production test. The TPS tool was held stationary at a depth of 2624 meters.

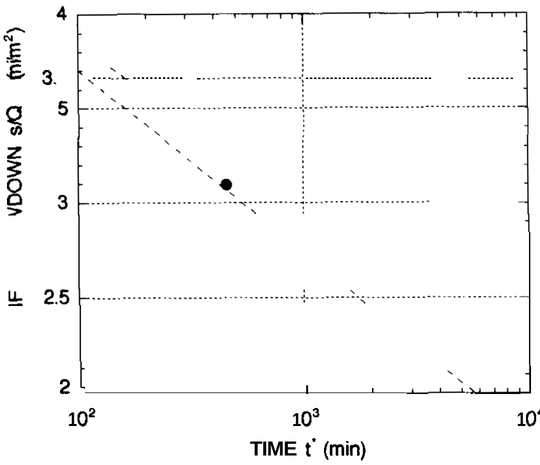

Figure **3.** Step-drawdown graphical analysis of production data for Well **74-7.** Each production stage shown in Figure **2** is represented by one data point and dashed line is a linear best-fit approximation.

Aquifer transmissivity can be determined by examining the pressure recovery record in terms of a Homer analysis (Grant et al., **1982),** which is analogous to the standard groundwater recovery method developed by Theis **(1935).** The pressure build-up is plotted versus the logarithm of Homer time, t":

$$t'' = \frac{t + t'}{t'} \qquad [3]$$

where t is the time since the onset of flow or pumping and t' is the time since shut-in. The slope of the semilog plot provides an estimate of AP, the pressure change across one log cycle of t", and T is determined from a relation analogous to equation **2,** where P replaces the drawdown and Q refers to the time-averaged discharge computed from the preceding production test. Because T is determined from pressure differences rather than absolute pressures, the solution is not influenced by non-linear well losses. This graphical exercise is shown in Figure 4b, where the pressure (in MPa) recorded with the TPS tool has been converted to drawdown (in meters) from fluid-density data. The resulting estimate of T for Well **73B-7** is **1.2** m^2/min, confirming the results determined from the variable-discharge test; the permeability-thickness is **3.0x10^5** mD-m after viscosity corrections. No estimate of storativity is obtained from this method.

Three of the wells included in this study were artesian: Wells **62-21, 66-21** and **45-14.** These wells display no flash point and their discharge is single phase. In each case, flow rate at the surface was measured (rates ranging from ≈**10** to **100** Umin), the TPS tool was lowered to a selected depth, and the logging cable was packed off at the wellhead. The well was subsequently shut-in and the pressure build-up was recorded as a function of time. Occasional monitoring over several months indicated that flow rates at the wellheads were somewhat variable. Thus, a condition of constant drawdown rather than constant discharge was assumed and the flow rate measured just prior to well shut-in was the Q value used in the Homer-type recovery analysis (Rushton and Rathod, **1980).** Viscosity corrections are smaller for these wells than for the producing, self-sustaining wells and permeability-thicknesses, on the order of 10^1 mD-m, are about four orders of magnitude less (Table 1). Well **62-21** has a slightly higher K-H value of about 10^2 mD-m, but this well does not intersect the fault.

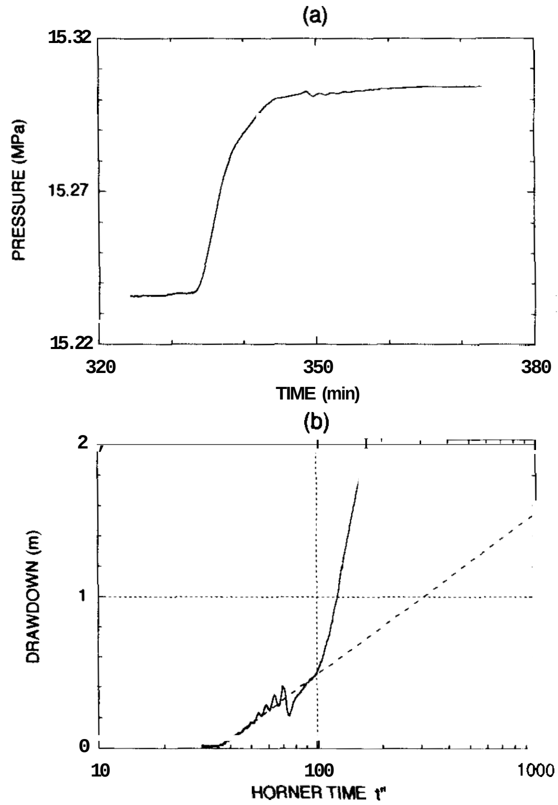

Figure **4.** (a) Pressure recovery record for Well **73B-7** from the **TPS** tool held stationary at **2624** meters and (b) resulting Homer plot with best-fit approximation (dashed line) at early Homer time.

Damped-Oscillation Response

Aquifer tests performed in highly permeable formations often produce water levels that oscillate briefly due to abrupt changes in the momentum of the fluid column. This type of damped oscillatory response was observed in the two producing wells (Wells 73B-7 and 74-7) immediately after they were shut-in. For Well 73B-7, this phenomenon is depicted in Figure 4a. The data are magnified for clarity in Figure 5 and shown alongside the attendant temperature record, which seems to be responding adiabatically to the pressure fluctuations. Oscillating pressures such as these were not detected when the artesian wells were shut-in. The low permeabilities associated with this category of wells produced overdamped hydraulic conditions that suppressed any oscillatory behavior.

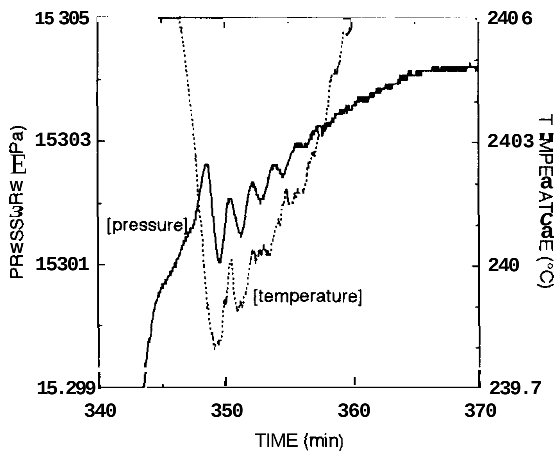

Figure 5. Damped oscillations of pressure and temperature in Well 73B-7 after shut-in. Pressure fluctuations also observed at smaller scale in Figure 4

The evaluation of oscillating water levels resulting from slug tests has been presented by van der Kamp (1976) and by Kipp (1985). Shapiro (1989) used a numerical inversion of a Laplace transform solution to interpret oscillating water levels in observation wells and in wells disturbed by air-pressurized slug tests (Shapiro and Greene, 1995). This work has recently been modified to interpret oscillations observed in a pumped well during recovery, a case which is directly applicable to the producing wells at Dixie Valley. Inertial and storage effects, as well as turbulent head losses, are accounted for, though much of these losses are avoided in practice by recording pressures downhole near the major feedpoints rather than at the surface. However, linear losses at the well due to borehole skin are not considered.

Adapting Shapiro's (1989) solution to conditions evident at the Dixie Valley Geothermal Reservoir, a series of type curves can be generated and presented as log-log plots of dimensionless time t^+ versus dimensionless drawdown s^+:

$$t^+ = \frac{Tt}{Sr_w^2} \quad ; \quad s^+ = \frac{4\pi Ts}{Q} \qquad [4]$$

where t is the time since the well was shut-in (min). An individual curve is associated with each combination of values for the dimensionless parameters α and σ:

$$\alpha = \frac{Sr_s^2}{r_c^2} \quad ; \quad \sigma = \frac{L_e}{g}\left(\frac{T}{Sr_s^2}\right)^2 \qquad [5]$$

where g is the gravitational constant and where the casing radius, r_c, the open-hole or screen radius, r_s, and the effective length of the water column in the well, L_e, can be determined from the well construction and from caliper logs; these are described in detail by Kipp (1985).

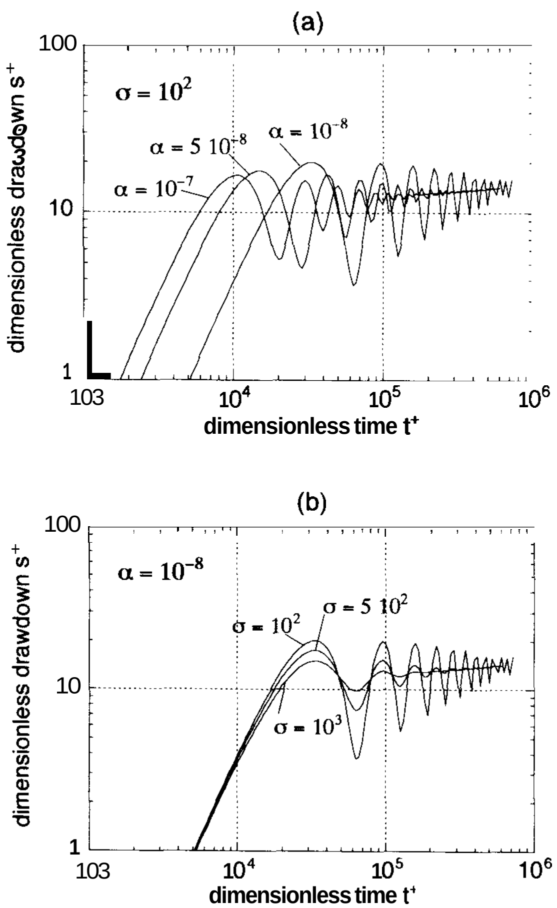

Figure 6. Type-curves illustrating characteristics of oscillating water levels as functions of t^+ and s^+ for (a) constant σ and variable α and (b) constant α and variable σ.

Two series of type curves are presented in Figure 6 as a sequence of ***a*** values corresponding to a single value of σ (Figure 6a) and, conversely, as variable σ curves associated with a common value of ***a*** (Figure 6b). By matching curves such as these with the field data (Figure 5), the one combination of a and σ values that provides the best fit to both the frequency and the magnitude of the damped oscillations may be chosen. These final estimates of a and σ then allow values of T and S to be decoupled (equation 5) and solved individually. From the pressure data obtained in Well 73B-7, this analysis yields values of T and S equal to 1.2 m^2/min and 2.3x 10-3, respectively.

This transmissivity agrees closely with estimates determined from other complementary analyses, thereby lending confidence to this solution and the validity of its inherent assumptions. An added benefit of this method is its ability to estimate aquifer storativity. It should be noted, however, that condensation of steam within the wellbore during the recovery phase amplifies wellbore storage effects (Barelli et al., 1976), in which case estimates of S derived from this analysis are likely to be slightly overestimated. Consequently, storativities obtained for the two production wells at Dixie Valley lose some of their precision and it is assumed that they are each on the order of 10^{-3}, or slightly less than their computed magnitudes.

Injection Test

Injection tests were performed in conjunction with hydraulic-fracturing operations related to the characterization of the local stress field (Hickman et al., this volume). For the artesian wells, water was injected from the surface at rates ranging from about SO to 200 Umin and pressure build-up was recorded with the TPS tool as a function of time. Governing equations that describe this type of test follow along the development of Cooper and Jacob (1946), as shown in equation 1, with Q being the rate of injection. Where recovery analyses have already been conducted and estimates of T obtained, storativity can be solved for directly.

In the early stages of injection, cool injectate introduced from the surface displaces the warm borehole fluid and pushes it back into the formation. Disruptive, non-isothermal effects typically produced when cold fluid permeates hot rocks (Bodvarsson et al., 1984; Benson and Bodvarsson, 1986) can be neglected at early times because of the low injection rates. These slow injection velocities along with the constraint of single-phase flow minimize non-linear well losses and, with no free water surface in the well, borehole storage effects can also be considered negligible.

Values of S are obtained by the graphical method proposed by Rushton and Singh (1983). The pressure build-up data are plotted on semi-log paper and a best-fit match to type curves is used to determine the storativity. Rushton and Singh (1983) provide an S curve corresponding to each order-of-magnitude change in its value, ranging from 10^{-1} to 10^{-6}. This graphical procedure lacks some precision because a shift of one order of magnitude in S does not dramatically change its attendant type curve. Moreover, distinctions among S curves become even less pronounced as the value of storativity decreases. Nevertheless, values of aquifer storativity derived in this manner for all of the artesian wells fall in the range of 10^{-4}, with an estimated error o f f 30%.

RESULTS AND DISCUSSION

Results of the various well tests are summarized in Table 1 and can be separated into two distinct categories. Operational geothermal wells which were successfully stimulated by air lifting have K-H values on the order of 10^5 mD-m. These wells (73B-7 and 74-7) intersect the Stillwater Fault at a depth of approximately 2700 meters and penetrate a very permeable section of the geothermal reservoir. Storativities are on the order of 10^{-3}, which are typical for fractured, confined aquifers.

Well	T (m^2/min)	K-H (mD-m)	S
73B-7	1.2	$3.0x10^5$	$\approx 10^{-3}$
74-7	$2.2x10^{-1}$	$5.1x10^4$	$\approx 10^{-3}$
66-21	$4.3x10^{-5}$	$1.1x10^1$	$\approx 10^{-4}$
45-14	$2.4x10^{-4}$	$6.5x10^1$	$\approx 10^{-4}$
62-21	$5.8x10^{-4}$	$1.6x10^2$	$\approx 10^{-4}$

Table 1. Results of geothermal well-test analyses.

The three artesian wells comprise the second hydrologic category. Although two of these wells penetrate the same fault, their **K-H** values are dramatically lower ($\approx 10^1$ mD-m). The reservoir at these locations appears to show no evidence of enhanced permeability and its hydrologic properties are not significantly different from those of the host rock, as exhibited by Well 62-21 which is located at the valley floor but which does not intersect the fault. Furthermore, associated storativities for these wells are about one order of magnitude less than those of their transmissive counterparts.

Fluid distribution in an aquifer and the particular physical geometry of a reservoir are controlled by a dynamic balance of mass and heat flow which, in turn, is dictated by local variations in hydrologic properties. Some general causes for permeability heterogeneity within a fault zone stem from localized intervals of extensive fracturing, solution transport and mineralization, and gouge formation (Hickman et al., 1995). Laboratory studies (Forster et al., 1994), in situ measurements (Raven et al., 1992), and numerical simulations (López and Smith, 1996) of fault zones indicate that the range of permeabilities encountered in this type of environment spans about 3 to 5 orders of magnitude, in general agreement with the range of values listed in Table 1.

Hickman et al. (this volume) and Barton et al. (this volume) present evidence that the spatial variability in permeability observed at Dixie Valley may be explained, in part, by the local stress field, its orientation to the local strike of the Stillwater Fault, and the favorable alignment of a subset of permeable fractures to this stress field. The alignment produces a highly anisotropic permeability distribution, which may be further amplified through ongoing fault slip (Gentier et al., 1997). The dependence of stress state on the permeability of fractured rocks has long been recognized; recent studies have contributed to this understanding (e.g., Bai et al., 1997) and have some relevance to conditions at this site.

This coupling of tectonic and hydrologic processes may also be inferred from the marked reduction in aquifer storativity that accompanies the reduction in permeability. Storativity is defined as:

$$S = \rho g H [\lambda + \phi\beta] \qquad [6]$$

where ρ = fluid density, g = gravitational constant, H = aquifer thickness, λ = aquifer compressibility, ϕ = porosity, and β = fluid compressibility. Variations in the variables ρ, H, ϕ, and β typically are relatively small and, consequently, may account for slight changes in S. However, changes in λ are the most likely to influence S variations that span an order of magnitude. Aquifer compressibility is a direct function of rock compliance and may vary over several orders of magnitude depending on stress conditions. Thus, some clear correlation between aquifer storativity and compressibility may offer the best evidence of tectonic/hydrologic coupling.

Testing of individual wells reveals small-scale variations in hydrologic properties which must be integrated into any large-scale, coherent model that adequately describes the extent and geometry of the Dixie Valley Geothermal Reservoir. The development of such a conceptual model will require a fundamental understanding of the nature of this heterogeneity and the factors that control it.

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