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**Case History on Geothermal-Well-Log
Interpretation, Surprise Valley, California**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

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Case History on Geothermal-Well-Log Interpretation; Surprise Valley, California

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G. P. Zebal*

Prepared for
Los Alamos National Laboratory

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SYMBOLS

B	Coefficient multiplying the cation exchange capacity (Q_v) in the Waxman-Smiths formulation (page 63) for the resistivity of a shaly formation.
D	Formation density value recorded by the density log.
D_0	Apparent matrix density.
E_s	Streaming potential.
f	Filter loss factor used in the calculation of streaming potential.
F	Formation factor from Archie's Law relating formation resistivity and pore fluid resistivity.
F^*	A modified formation factor for dealing with shaly formations assumed to depend on POR* (see below) rather than POR.
F'	A modified formation factor used in the Waxman-Smiths formulation (page 63) for the resistivity of shaly formations.
IP	Induced polarization.
k	A constant.
POR	Porosity, the fraction of the volume of the formation filled with formation fluids (generally water or steam, in a geothermal formation).
POR(D)	The porosity calculated from the density log reading and the apparent matrix density.
POR(N)	The porosity (on the limestone scale) indicated by the neutron porosity log.
POR*	A modified porosity for use in shaly formations representing POR plus the volume fraction of shales or clay minerals formed by hydrothermal alteration in the formation.
PSP	Pseudostatic self-potential, the self-potential opposite a shaly formation.
P	Pressure difference between the borehole and the formation.
q	Shale (clay) fraction, the fraction of POR* filled by shale or clay minerals.
Q_v	Cation exchange concentration of the shale or clay minerals in the pores of a formation.

R	Resistivity, used in general formulas that may apply to more than one part of the formation (i.e., flushed zone or univaded zone).
R _d	Resistivity measured by a device that senses the formation far from the borehole, the induction log resistivity values.
R _f	Pore fluid resistivity, used in formulas when the nature of the pore fluid is not specified (mud filtrate or formation water).
R _{LL8}	Resistivity values recorded by the Laterlog 8 (Schlumberger) device.
R _m	Mud resistivity.
R _{mc}	Mud cake resistivity.
R _{mf}	Mud filtrate resistivity.
R _s	Shallow resistivity, resistivity measured by a device sensitive to the formation near the borehole; in this report this may mean a Laterlog 8 or an 18 inch normal log.
R _{sh}	Resistivity of the shale or clay minerals formed by hydrothermal alteration in the formation.
R _t	True resistivity of the undisturbed formation
R _w	Resistivity of the formation water (geothermal fluid).
R _{xo}	True resistivity of the flushed zone near the borehole.
SP	Self-potential.
t _{mc}	Mud cake thickness.

CASE HISTORY ON
GEOTHERMAL WELL LOG INTERPRETATION
SURPRISE VALLEY, CALIFORNIA

by

F. A. Rigby and G. P. Zebal

ABSTRACT

This report discusses well logs from a 1972 geothermal well drilled in California's Surprise Valley. The well is in an igneous formation, primarily basalt in the logged interval, and had a bottom-hole temperature of about 170°C at a total depth exceeding 1400 m. It produced good flow rates from what is presumably a formation with predominately fracture-related permeability. The well has special interest because fractures could be located approximately by the appearance of well-defined secondary crystallization in the drill cuttings. The original use of the log data in evaluating the well when it was drilled is discussed. In addition, the log data are reviewed and valuable data are obtained on log response in basalts, the effects of secondary mineralization, fracture detection, and aspects of the resistivity logs. The Surprise Valley well gives a clear demonstration of the value of thorough logging in geothermal exploratory wells, especially in the identification and location of potential production zones.

I. INTRODUCTION

A. Surprise Valley

Surprise Valley is located in the extreme northeastern corner of California and is partly included in the Surprise Valley-Lake City Known Geothermal Resource Area defined by the U.S. Geological Survey. Several hot springs and "mud volcanoes" occur on the western margin of the valley. Geologically, Surprise Valley is in the westernmost part of the Basin and Range Province. This logging case history for Surprise Valley discusses several of the major concerns encountered in geothermal reservoirs of the Basin and Range, the most extensive of the western U.S. geologic regions in which substantial geothermal potential has been identified. A specific feature of the Surprise Valley resource is a fault-dominated convective system in igneous rocks, with fractures providing most of the reservoir permeability.

Surprise Valley is a long, narrow, typical Basin and Range Province valley formed as a block-faulted graben and formerly occupied by a Plio-Pleistocene lake, which was not connected to Lake Lahontan. The major north-south fault forming the western margin of the valley is concealed by talus derived from the steep eastern face of the Warner Range. Its location can be approximated by projecting the two planes forming the break in slope between the steep face of the layered volcanic strata of the range and the flat lake bed sediments of the valley floor. The Warner Range volcanics dip to the west at 20 to 25°. The Surprise Valley fault is a broad zone, on the order of a kilometer wide, containing major fault lines and literally hundreds of minor faults, which is a characteristic that supports the inference of subsurface fracture porosity in the area.

B. Geothermal Wells

Two wells (one by Magma Energy, Inc., and one by the Gulf Oil Corporation) have been drilled to investigate the geothermal potential of Surprise Valley. These companies have supplied log data from their wells for study. The well drilled by Magma produced a good flow of hot water and steam in igneous formations and represents a reasonably successful geothermal well, although lack of a local demand for hot water or electricity has prevented

further development efforts to date. Although the Gulf well, located less than a mile from Magma's well, was less successful in terms of flow rate and temperature, it was anticipated that the logs from the Gulf well would provide valuable comparisons with the Magma well. Surprisingly, when the logs were obtained, Gulf's well was found to be in a completely different formation, penetrating sedimentary material to total depth at more than 2000 m. The Gulf well did not appear to be particularly interesting because of having only a few logs (self-potential, resistivity, and acoustic velocity), being in sedimentary formations, and lacking interesting geothermal features or useful comparisons with the Magma well. A brief discussion of the Gulf well is given in Appendix B (microfiche in pocket on inside back cover). This report is a study of the Magma (Phipps No. 2) well. Appendix A (also microfiche in pocket on inside back cover) gives details on the drilling, completion, and testing of the Phipps No. 2 well.

The Phipps No. 2 geothermal well is located on the Phipps Ranch in Section 23, T.44N., R.21E., Mt. Diablo B and M, Modoc County, California. The precise site is 364 m south and 8 m west of the northeast corner of Section 23. The well lies at the base of the Warner Range, which is the western boundary of Surprise Valley, approximately 2 miles due north of the town of Lake City. Figure 1 shows the location of the well in relation to the local geology. The ground-level elevation of the well is 1481 m above sea level. The elevation of the kelly bushing when the well was originally drilled was 1488 m.

Geologically, the well is located adjacent to the major graben-forming fault bounding the west side of Surprise Valley. The Parman Ranch Hot Springs lie one-half mile southeast of the well site. A major fault, trending northwest-southeast, crosses Surprise Valley between Upper and Middle Alkali Lakes. The hot springs emanate from this fault line several hundred yards from its intersection with the major graben-forming fault. Therefore, the well is critically located to take advantage of nearby surface geothermal manifestations and the junction of two fault zones at a site where lacustrine sediments were not encountered.

Drilling History. The Phipps No. 2 well was drilled to 30 m by an auger rig. Fifty-one-cm (20-in.) conductor casing was set to that depth and cemented in place before the arrival of the Beeline Drilling Co. rig. The

Fig. 1. Location of the geothermal wells in Surprise Valley (in relation to the geology of the area).

well was spudded on 13 November and temporarily completed at a depth of 1375 m on 26 December 1972. In October 1974, the well was plugged back and redrilled to a total depth of 1508 m. The kelly bushing during the drilling of the original hole was 3 m (10 ft) greater, so there was a difference in the data elevations of the original hole and the redrill. This is reflected in the depths recorded on the logs run in the well. All depths referred to in the main body of this report (exclusive of the appendices) are in terms of the data elevation of the redrilled hole because more logs were run in the redrill. References to the logs from the original hole have been converted to the data elevation of the redrill. However, a few of the figures reproduce portions of the original logs on which the original depth scale (in feet) appears; the captions of these figures make note of the difference in depth scales in each case for the reader's convenience.

For the original drilling, 34-cm (13-3/8-in.) casing was set to 37.8 m. A 20-cm (7-7/8-in.) hole was then drilled to 1280 m and Welox induction-electric and temperature logs were run. Nonperforated casing was hung to a depth of 815 m. Drilling was discontinued at 1372 m due to increasing problems with lost circulation and bad weather.

The subsurface temperature gradient was monitored as drilling proceeded by recording the temperature of the drilling fluid at the flow line at 10-ft intervals. Bottom-hole temperatures were obtained at irregular intervals by means of a wireline temperature sonde containing two armored maximum recording thermometers. Figure 2 reproduces a plot of the flow line temperature gradient, the approximate gradient reconstructed from six bottom-hole temperature measurements, and a subsurface temperature survey conducted by Agnew and Sweet 29 days after drilling had ceased. The Agnew and Sweet static temperature and pressure gradient surveys were run on 24 January 1973. Before running these surveys, the open hole between 815 m and total depth had bridged over and a depth of 1165 m was the maximum that could be attained.

Because of the mechanical problems enumerated above, the well was redrilled in October 1974. A cement plug was placed in the original hole at 1164 m. A 20-cm (7-7/8 in.) hole was drilled to a total depth of 1508 m. Schlumberger Dual Induction-Laterolog (DIL), gamma-ray compensated neutron, and formation density logs were run at total depth over the open interval (a bridge prevented logging sondes from descending below 1320 m). The well was completed by hanging slotted, 16.8-cm (6-5/8-in.) liner to total depth.

Fig. 2. Subsurface thermal gradients.

Temperature measurements were made, indicating maximum temperatures around 170°C. Appendix A contains these data. Figure 3 summarizes the drilling and logging program outlined above.

A formal production flow test was conducted on 18 June 1974. Static temperature and pressure gradient data were recorded by Agnew and Sweet before flowing the well. Water recovered amounted to 204 037 kg/h; the additional flashed steam vented amounted to 25 504 kg/h, representing a total volume of 229 541 kg/h, which equates to a production rate of 3831 /min. Bottom-hole flowing temperature was 168°C, and the flow temperature at the surface was 118°C.

C. Quality of Logs

Log data used in this report were taken from analog recordings made as the logs were run. The quality of the logs was generally good. The records were free of breaks or discontinuities, and there was little sign of extraneous noise. With the exception of a few substantial washed-out sections, borehole diameter was quite uniform, which contributed to log quality. The well logs from both wells drilled in Surprise Valley are on microfiche in the pocket on the inside back cover (Appendix C).

The resistivity tools were calibrated at the well with test voltages before and after logging. There was no indication of drift or other problems from these calibrations. As shown in Fig. 3, the Schlumberger resistivity log run in the redrilled hole also covered a considerable portion of the original well above the level at which the redrill was kicked off. The deep induction logs (which would not be strongly affected by different mud properties) for the original hole and the redrill show good quantitative agreement for the overlapped section in areas in which invasion was not extensive, which provides an interesting cross check for the resistivity logs. Details on the mud characteristics are in Sec. V.

Repeat sections were included in the density and neutron logs as a check on the performance of these tools and indicated reasonably consistent performance by the logging tools. These tools were calibrated according to standard procedures for petroleum operations; interpretation of the measurements for igneous formations must therefore be approached with care. Unfortunately, no cores were taken from the well to provide known points at which log values could be related to measurements made in the laboratory.

Fig. 3. Summary of the casing and logging operations in the Phipps No. 2 well.

II. ANALYSIS OF WELL AT TIME LOGS WERE MADE

A. Stratigraphy

Appendix A reproduces in full the geologist's report of the original log of the well. The well penetrated a sequence of Miocene volcanic rocks of the Cedarville formation, which make up most the Warner Range. Volcanic sequences ranging in composition from olivine basalt to quartz-rich rhyolite were encountered. Above 408 m, rhyolitic volcanics predominated. A mixed olivine basalt, andesite, and quartz latite assemblage exists from 408 to 1100 m. From 1100 to 1508 m, olivine basalt and andesite agglomerates, massive flows, and breccias were drilled.

The major zones of porosity appeared to be fault-induced fracture zones occurring within massive basalt sequences. Minor zones of porosity are exhibited by some basalt breccia beds. In the cuttings these fractured zones are characterized by abundant examples of chips exhibiting slickensides (polished and scratched surfaces resulting from fault movement), the presence of copious amounts of putty-like fault gouge, thin plates of quartz and calcite (secondary vein-filling minerals), and small clusters of well-formed, singly terminated quartz and calcite crystals (secondary void space coatings).

B. Porosity

Two types of porosity were encountered in the Phipps No. 2 geothermal well: distributed porosity (intergranular or vesicular) and fracture porosity. In the analysis made of the cuttings and logs at the time the well was drilled, it was assumed that the fracture porosity is wholly fault induced because of the proximity of the well to the junction of two major faults. Based on an examination of samples, loss of mud, loss of circulation, and rapid drilling rates, a number of porous intervals were identified during the drilling of the well. Table I summarizes the depths, thicknesses, and lithologies of porosity zones established in this manner in the original hole. Table II shows similar data for the redrilled hole.

There is a substantial degree of inaccuracy inherent in estimating from drill cuttings the relative amount of porosity and the precise interval of this porosity. Inaccuracies can be introduced by the following effects.

TABLE I
DESCRIPTION OF INDIVIDUAL POROUS ZONES IN ORIGINAL HOLE

<u>Depth (m)</u>	<u>Thickness (m)</u>	<u>Lithology</u>	<u>Criteria</u>
108-130	22	Fractured agglomerate	Abundant calcite vein material; lost circulation.
771-783	12	Fractured basalt	Gouge; some calcite vein material.
841-857	16	Basalt breccia	Some slickensides, much thermal alteration; some loss of mud.
942-957	15	Basalt breccia	Much thermal alteration, much gouge.
1006-1015	9	Basalt breccia	Much gouge; some loss of mud.
1044-1094	50	Fractured basalt	Abundant gouge.
1192-1283 (limit of logged in- terval)	91	Fractured basalt	Many slickensides, much calcite vein material; some loss of mud.
1283-1305	22	Fractured	Abundant slickensides, much gouge, much quartz and some calcite vein material; severe loss of mud.
1305-1318	13	Fractured agglomerate	Same as above.
1318-1372	54	Fractured basalt	As above, intense thermal alteration; lost circulation

- Broad interval sampled (10 m per sample).
- Influence of lag time (time between actual drilling and return of sample to surface) as a function of rapid vs slow drilling.
- Influence of secondary mineralization on porosity.
- Possible contamination of the cuttings samples with material sloughed from uphole.

Sample examinations showed that each porous interval is characterized by an increase in the number of chips exhibiting slickensides and secondary vein material, culminating in a zone of intense thermal alteration. In several of these zones, the volcanic material had been replaced by kaolinite and chlorite or the unit had been brecciated. Below the zone of intense thermal alteration, the number of slickensides and the volume of secondary mineralization decreased. These factors represent fracturing adjacent to a steeply dipping fault trace. The thermally altered zone spreads in fractures related to the plane of the fault. Therefore, faults are interpreted to exist at the following depths in the original hole: 777, 844, 950, 1010, 1074,

TABLE II
DESCRIPTION OF INDIVIDUAL POROUS ZONES IN REDRILLED HOLE

<u>Depth (m)</u>	<u>Thickness (m)</u>	<u>Lithology</u>	<u>Criteria</u>
1234-1294 (limit of logged in- terval)	60	Fractured basalt	Microbreccia; abundant slickensides, abundant gouge, much quartz and calcite vein material.
1353-1356	3	Fractured agglomerate	Abundant quartz vein material.
1356-1394	38	Fractured quartz latite	As above, much gouge.
1394-1399	5	Fractured basalt	Intense thermal alteration.
1394-1408	9	Fractured agglomerate	Much quartz vein material.
1436-1445	9	Fractured agglomerate	Abundant slickensides and gouge.

1279, and 1371 m. In the redrilled hole, faults are interpreted to exist at 1268, 1396, and 1445 m.

When electrical logs were run in the original hole, a correlation of porous zones, noted on the lithologic log with the electrical logs, showed that the best indicator of porosity was the self-potential curve. (Drilling in the original hole was carried out with a clay- and water-based mud; mud resistivity at 28°C was 7.25 ohm-m.) Negative self-potential kicks of 5-mV magnitude appeared to represent porous intervals on the lithologic log. A reinterpretation of porous and permeable intervals was made on this basis and the following more restricted intervals were designated.

<u>Interval (m)</u>	<u>Thickness (m)</u>	<u>Remarks</u>
108-126	18	Behind casing
681-686	5	Behind casing
708-710	2	Behind casing
716-718	2	Behind casing
835-840	5	Producing
928-939	11	Producing
1042-1047	5	Producing
1055-1065	10	Producing
1079-1090	11	Producing
1194-1197	3	Plugged off
1232-1238	6	Plugged off

When this reinterpretation was made, the samples were re-examined, and the following intervals were interpreted to be permeable in the original hole below the electrically logged depth.

<u>Interval (m)</u>	<u>Thickness (m)</u>	<u>Remarks</u>
1280-1283	3	Plugged off
1359-1372	13	Plugged off

In the redrilled hole and based on similar evidence, the following porosity zones and fracture permeability exist.

<u>Interval (m)</u>	<u>Thickness (m)</u>	<u>Remarks</u>
1197-1200	3	Producing
1235-1239	4	Producing
1283-1286	3	Producing
1362-1375	13	Producing (below logged interval)

Therefore, the producing intervals in the Phipps No. 2 geothermal well were found to amount to 65 m of fractured volcanic rocks. It should be noted that the fracture porosity and permeability is not equal on a meter-by-meter basis because of the plugging effect of secondary minerals.

C. Relationship between Original and Redrilled Holes

Examination of the samples and correlation of the electric logs from the original and redrilled holes showed that similar volcanic sequences of rocks were present; but the intervals in which they appear differ. Correlations between the two holes can be made by matching possible fault zones, white welded tuff marker beds, and zones of maximum thermal alteration. Brick red basalts exist down to 1279 m in the original hole and to 1266 m in the redrilled hole. White tuff was logged from 1286 to 1295 m in the original hole, but in the redrilled hole these tuffs extended down to 1317 m. Figure 4 shows these correlations. The degree of deviation is exaggerated and the portrayal of the original hole as being vertical is not accurate; the intent of the figure is to graphically demonstrate the relationship between the two holes as inferred by analysis of the samples and logs.

III. ADDITIONAL ANALYSIS: LITHOLOGIC PROPERTIES

A. Introduction

To improve log interpretation from geothermal wells requires greater knowledge of lithologic responses of logging instruments to igneous and metamorphic formations. Thickness and physical properties of the interval from which a well is producing are required to make a good well-performance projection. Good lithologic logs obtained during the drilling of the well are of major importance. However, quality of lithologic logs can vary, and a

Fig. 4. Correlation between original hole and redrilled hole.

lithologic log prepared from the drill cutting returns is less precise than can be attained by wireline logging. A reverse pomposity problem, however, is that accurate quantitative interpretation of log data is greatly enhanced by prior knowledge of the lithology. This well case demonstrates that a good lithologic log may be essential to logging data interpretation.

B. Lithologic Column

The Phipps No. 2 well was drilled almost entirely in igneous formations. The deeper portion of the well is primarily in basalt and basalt breccia, with small sections of andesite, tuff, and agglomerate. Figure 5 shows a lithologic column for the portion of the well for which extensive logging data exist. The depths are as recorded for the redrill.

To investigate the responses of the logging tools to rock type, it was necessary to identify the intervals on the logs that contained the various rock types. The gamma ray, porosity (compensated neutron), density (gamma-gamma), and resistivity logs were examined, and points were found on the logs where changes in properties occurred. All the major lithology changes recorded on the lithology record were found on the various well logs. Changes in log readings corresponding to lithologic changes are readily identified, but the log values corresponding to various rock types are not consistent through the well. Table III shows the intervals that were identified as containing equivalent rock types. These intervals will be important in the discussions that follow. Most contacts derived from well log analysis are not at the same depths as contacts derived from cuttings analysis. In some cases, interval revision in the determination of the thickness is 5 m or more.

The logs were digitized from the analog traces contained in the logging books. Gamma ray, density, neutron porosity, and sections of the resistivity logs were digitized. The digitized surveys were then smoothed by averaging on 0.61-m (2-ft) centers.

C. Histograms

The gamma-ray log proved valuable in differentiating igneous formations. Sanyal, Juprasert, and Jusbasche (1979) give an example in which major rock types show characteristic gamma-ray values. Figure 6 is a histogram of gamma-ray values for the Surprise Valley well.

Fig. 5. Lithologic column for the Phipps No. 2 well below 823 m (the portion of the well covered by density and porosity logging).

TABLE III

INTERVALS CONTAINING EQUIVALENT ROCK TYPES BASED ON
ANALYSIS OF CUTTINGS AND WELL LOGS

<u>Rock</u>	<u>Depth (m)</u>
Basalt	832-866 942-963 1001-1027 1042-1052 1263-1266
Basalt Flow	892-924 963-1001 1027-1042 1117-1155 1197-1263 1266-1300 1304-1311
Agglomerate	866-892
Andesite	924-942
Tuff	1056-1067 1079-1094

Note: Washed-out sections of log data are not included.

Figures 7 and 8 are histograms of the porosity and density log readings. Washed-out intervals in which the caliper of the density-porosity tool reached full extension (40.6 cm) and the log values ran off scale have been omitted. Neutron porosity is presented using the limestone porosity scale. The presence of negative values is of interest and will be discussed in the section on fracturing and porosity.

D. Crossplots

More detailed examinations of rock properties can be made by the use of log properties crossplots. Plots of gamma-ray values against density and neutron porosity values were made to reflect the exact lithology. Figures 9a and 9b, respectively, show the crossplots of gamma-ray vs density and gamma-ray vs log values for agglomerate, andesite, and tuff intervals.

Fig. 6. Histogram of gamma-ray log for non-washed-out intervals, 832 to 1311 m.

Fig. 7. Histogram of neutron porosity log.

Fig. 8. Histogram of density log for 832-to 1311-m interval.

Figure 9b shows that the gamma-ray/density plot separates the rock types best, but that they are still not easily separated. Figure 10 shows the gamma-ray/density crossplot for the basalt flow intervals. There is a great deal of scatter, and it is clear that the tuff, andesite, and agglomerate would not be readily identifiable as discrete units on a plot without differentiation of the various depth intervals.

Two unusual intervals can be noted. First, the interval from 1117 to 1155 m forms an obvious unit, with values that overlap the andesite unit in Fig. 9a. Second, there is a noticeable scattering of points in the basalt interval from 1197 to 1263 m that are isolated from the general basalt

Fig. 9a. Agglomerate, andesite, tuff depth intervals-- gamma-ray vs bulk density.

grouping and are near the values shown by the higher density of the two tuff intervals (Fig. 9a). Figure 11 shows the gamma-ray/porosity crossplot for the basalt intervals, and the same relationships occur among groups. The interval from 1242 to 1247 m accounted for the circled grouping of points in Fig. 10 resembling the characteristics of the tuff layers. A thin tuff layer encountered in that interval probably was not identified during the cuttings analysis. The lithologic log does refer to the existence of occasional streaks of tuff in the basalt flow near the bottom of the well. Such tuff streaks may contribute to the scatter in the plots for the basalt, but are hard to identify with certainty because of their very limited extent.

Fig.9b. Agglomerate, andesite, tuff depth intervals-- gamma-ray vs neutron porosity.

Plots of the brecciated intervals fell in the same intervals as the plots of the basalt flows and are not shown. No tendency toward higher neutron porosity values or different density values was found either for the brecciated intervals as a whole or for those intervals noted as "fractured" or "probable fault zones" on the lithologic log. A general trend for higher gamma-ray readings to be associated with both lower density and lower neutron porosity values was observable in the brecciated intervals, perhaps indicating infilling with materials of lower density and greater radioactivity than the basalt.

Fig. 10. Basalt flow depth intervals-- gamma-ray vs bulk density. Circled points may be thin tuff layers.

Crossplots of the density vs the neutron porosity were also made. The limestone porosity scale was used because the values produced were reasonable, and the data on neutron log response of various rocks collected for the Geothermal Log Interpretation Program in Sanyal, Wells, and Bickham (1980) was in terms of the limestone porosity scale. In this well, the density/porosity plots were less effective than the plots using the gamma-ray log for separating the rock types. Density/porosity crossplots, however, can also be used to determine an approximate value for matrix density (density at zero porosity).

Fig. 11. Basalt flow depth intervals-- gamma ray vs neutron porosity.

Figures 12a and 12b, respectively, show the crossplots for the basalt flows and the intervals of basalt breccia. The plot for the brecciated intervals is essentially the same as that for the massive basalts. There is a clear trend, with low density corresponding to high-porosity values; it is also clear that the slope of the trend is much too steep. For comparison, the line representing the change in density with increasing porosity for a material with a matrix density of 2.74 g/cm^3 and porosity filled with water at 1.0 g/cm^3 is shown in Fig. 12a.

This phenomenon has been observed in other geothermal wells in igneous formations, such as Roosevelt Hot Springs (Glenn and Hulen, 1979). The most

Fig. 12a. Basalt flow depth intervals-- bulk density vs neutron porosity. Line shown represents plot appropriate for a material with matrix density (zero porosity) of 2.74 g/cm³ and pores filled with fluid of density 1.0 g/cm³.

likely explanation is the presence of clay minerals formed by hydrothermal alteration of the original rock. Adsorbed water and OH⁻ radicals associated with these minerals would give limestone porosity readings from 37 to 51 percent and 26 to 32 percent, respectively (for 100 percent concentrations of these materials). The density log responses for these minerals, however, are given as being on the order of 2.7 g/cm³, which is about the same as the apparent density of the basalt matrix. Thus, the density log response will be virtually unaffected by the presence of these alteration products, whereas the neutron porosity value is strongly affected. This may account for much of the

Fig. 12b. All breccia depth intervals-- bulk density vs neutron porosity.

scatter in the density/porosity plot. In addition, as true porosity of a section of rock increases, there will be more percolation of water through it, resulting in an increased degree of hydrothermal alteration. This accounts for the steepening of the slope of the density/porosity trend. Because the density log is virtually unaffected by the presence of the alteration products, the apparent matrix density will not be represented by a single point at minimum porosity and maximum density. Instead, it will appear as a vertical (constant density value) line of points marking the right-hand (high-density) margin of the distribution of points on the plot. This gives an apparent matrix density for the basalt of about 2.74 g/cm^3 . Whereas a few points occur to the right of this line (higher-density values), these may

represent inhomogeneities in the rock. Sanyal, Wells, and Bickham give data for basalt indicating a wide range of density values but showing that 2.74 g/cm^3 is not unreasonable. On the plots in Figs. 12a and b, the greatest frequency of porosity values occurs around 7 or 8, but a number of lower values occur, minimum porosity log values being close to zero.

The slope of the general trend of the basalt density/porosity crossplot is about -66 porosity units per g/cm^3 . The slope of the line representing change in density with water filled porosity is -57 porosity units per g/cm^3 . Based on the neutron log responses for kaolinite and chlorite quoted earlier, and assuming that the alteration products produce about one-third the porosity response of a water-filled pore, then the difference in slope can be accounted for by an increase in the volume of hydrothermal alteration products of about 0.3 porosity units for each one porosity unit increase in true porosity. Certain intervals, however, show a much greater degree of hydrothermal alteration.

Figure 13 shows the density/porosity crossplots for the andesite, agglomerate, and tuff intervals. The agglomerate interval is similar to basalt with little porosity. The andesite is recorded on the lithologic log as having microvesicular porosity. The porosity of the andesite layer is clearly reflected in the crossplot. The tuff intervals also display a variable porosity. The lithologic log describes these tuffs as densely welded. Each interval, however, displays some fairly porous sections and also appears to have a different matrix density. The slopes of the general density/porosity trends of the andesite and the tuff intervals in Fig. 13 are less steep than is the case for the basalt. This suggests that these intervals may contain smaller amounts of hydrothermal alteration products than the basalt intervals, which is of interest because the alteration products may clog pores and reduce permeability. The high scatter of the points for the andesite layer nonetheless suggests that some degree of alteration may be confusing the neutron porosity values. The tuff intervals give little evidence of the presence of alteration products.

Comparing Fig. 13 with Fig. 12a, it can be seen that the andesite has a slightly lower apparent matrix density than the basalt, about 2.69 g/cm^3 .

In the two more extensive tuff intervals, reasonable apparent matrix density values can be obtained by extrapolating to zero porosity. When this

Fig. 13. Agglomerate, andesite, tuff depth intervals-- bulk density vs neutron porosity.

was done using linear regressions of the data, apparent matrix densities for the two intervals were found to be 2.82 and 2.87 g/cm³. The third tuff interval is too limited in vertical extent and shows too much scatter to allow a good linear fit. A value of 3.0 g/cm³ was obtained by using the maximum density log value and minimum porosity log value (which were coincident).

IV. FRACTURES AND POROSITY

Wells in igneous formations generally produce from fracture systems. The Surprise Valley well is in a formation with many fractured zones and apparently drew most or all of its production from some of these zones. Both the extent of invasion of the formation by mud filtrate provided by the DIL and the SP log indicate that the best permeability is encountered in isolated, narrow intervals that are apparently fractured. (Mud properties and resistivity log response are discussed in Section V.) Most of the rock, however, including the massive basalt flows that occupy the greatest part of the well, show some degree of porosity. Separation of deep and shallow resistivity traces over much of the well also indicates that these rocks have at least a small degree of pore space that mud filtrate was able to invade. Throughout most of the well, the logs give evidence of extensive pore filling with clay minerals that probably formed by hydrothermal alteration. In these same intervals, evidence of invasion is limited, and it is assumed that the clay minerals in the pore space limit matrix permeability over most of the well.

A. SP and Resistivity

At the time the well was drilled, penetration of an open fracture could be detected by the presence in the cuttings of well-formed crystals of quartz and calcite resulting, presumably, from secondary crystallization in the open fracture. Examination of the well logs indicated that the location of each such open fracture corresponded to a SP deflection on the order of 10-15 mV, these being the largest deflections present in the log. Figure 14 shows the Welex SP and resistivity log trace for several such cases. The sharply delineated SP deflection is readily apparent. The resistivity logs at these points show large increases in resistivity with evidence of invasion by mud filtrate. The Welex induction log characteristically showed wild oscillations, perhaps in response to the broken character of the rock. This feature made it difficult to obtain a coherent deep resistivity value for these intervals.

Figure 14 shows, however, that the resistivity log response was not unique to the open fractures. Other intervals, including locations within intervals identified on the lithologic log as basalt flows, also show sudden increases

Fig. 14. Section of the Welex electric log for the original hole showing SP deflections. Depth scale (in feet) reads depths 10 feet greater than depth figures used in text due to different datum elevations of original hole and redrill.

in resistivity and violent oscillations on the Welex induction log. An example is the basalt interval from 963 to 1001 m (3159 to 3283 ft) in Fig. 14. The density/porosity crossplot for this interval in Fig. 12a shows a wide range of porosity. The sudden resistivity peaks are marked by small SP deflections of a few millivolts, suggesting a small amount of permeability, which would allow some invasion.

The SP trace was used in the original evaluation of the well to refine the inferred size and location of the fractured intervals. As can be observed in Fig. 14, the SP deflection often identifies only a portion of a fractured zone as open and permeable. This fact was used by the consulting geologist to obtain a value for the net producing interval for the well.

The SP deflections opposite the fractures are presumably the result of streaming potentials. Negative SP deflections from this phenomenon have been observed in other fractured reservoirs (Aguilera and VanPoolen, 1978). This effect results from flow of an electrolyte through a membrane that is not equally permeable to the ions of opposite charges in the electrolyte. In well logging, the membrane may be supplied by mudcake forming on the borehole wall at a permeable zone such as a fracture. A fracture that is large enough so that mud particles can enter it will form mudcake on its walls. As fluid flows out of the main fracture into lesser fractures, or from the matrix porosity, a streaming potential will again be produced. Even without mudcake, a streaming potential may be produced as the borehole fluid enters the pores of the rock matrix. Because cations such as Na^+ penetrate mudcake more readily than anions such as Cl^- , a negative potential develops on the side of the membrane with the higher pressure. The mud pressure usually exceeds formation pressure in logging, thereby producing negative SP deflections. The streaming potential is dependent on the characteristics of the membrane and the pressure differential. Telford, et al. (1976) give an empirical formula, where E_s is the streaming potential, ΔP the pressure difference, R_{mc} and t_{mc} are the resistivity and thickness of the mudcake, and f is a filter loss factor. In this well, the caliper log did not show consistent signs of mudcake opposite fractures; however, this caliper log was the caliper of the neutron and density log, which is not a good mudcake indicator. It is a single arm caliper with a spring strong enough to cut through, rather than

$$E_s = 0.039 \Delta P R_{mc} t_{mc} f, \quad (1)$$

ride over, mudcake. Because membrane characteristics cannot be determined, the values of SP deflections opposite permeable zones have only qualitative significance.

Whereas streaming potentials seem to be the obvious explanation for the SP log in the Surprise Valley well, the fact that substantial quantities of clay minerals are present in the rock does raise an important question. Could the SP value result from the situation more common in oil well logging in which the SP is generated from electrochemical potentials at the contact of a shale layer with a permeable zone? Electrochemical potentials in clean sands are usually expected to be much larger than streaming potentials and also much larger than the SP deflections noted in this well. Few, if any, intervals in this well appear to be completely free of hydrothermal alteration products. Test calculations were made of SP values for various intervals in the well, using several different formulas (Schlumberger, 1972) for electrochemical SP. The lowest values were given by the laminated shaly sands model (not necessarily a good model for this well),

$$\text{pseudostatic SP} = k \log R_{xo}/R_t \quad (2)$$

at 100 percent water saturation. R_{xo} is resistivity of the flushed zone and R_t is deep resistivity; $k = 91.5$ at 111°C , the recorded temperature in the borehole at the time the Welex log was run. Calculated SP ranged from 18.9 mV for the interval 931 to 933 m (based on Welex resistivities) up to 47.8 mV for the zone at about 1090 m (for which deep resistivity values from the DIL had to be used), while the recorded SP deflections had a maximum of 20 mV at 933 m and were more commonly about 10 mV. The cleanest intervals in the well, based on the density/porosity crossplots, are apparently the tuff intervals at 1056 to 1066 to 1094 m. These intervals should show the largest SP deflection if the electrochemical effect is applied; whereas, in fact, the SP deflections for these intervals are similar to, and in some cases smaller than, the deflections elsewhere. Thermoelectric effects and mineralization potentials can also produce SP effects. However, thermoelectric effects are generally too small to account for the observed voltages and would probably require the presence of pure metals, while mineralization potentials tend to be far larger (two orders of magnitude) than those observed and would indicate the presence of metallic minerals, which were not recognized during cuttings analysis. The

assumption that the SP effects are related to streaming potentials from fractures would thus seem to be a legitimate one.

B. Density and Neutron Log Response

The microvesicular andesite from 924 to 942 m, and the two layers of welded tuff from 1056 to 1066 and 1079 to 1094 m have more true porosity and less evidence of pore-filling clay minerals than much of the rest of the formation and, therefore, these intervals show some permeability. However, the nature of the SP trace and the behavior of the resistivity suggest that permeability, although possibly not porosity, is fracture controlled.

Figure 15 shows several sections of the neutron porosity and the density log for intervals having fractures. An unusual feature is that each fracture coincides with a low reading for the neutron porosity, generally a local minimum for the porosity log reading. The apparently large fracture at about 1229 m shown in Fig. 15 is certainly the most obvious case. This fracture is of such size that it creates an enormous dip in the density reading, whereas the neutron porosity value actually takes on a negative value. For some other fractures, such as those shown in Fig. 15, the drop in the density log is not sufficient to make the fracture noticeable against the surrounding irregularities, apparently resulting from the natural inhomogeneities of the formation. The discrepancy between a low-density reading and a low-porosity reading with no change in rock type appears at these fractures as well. Disagreements between the density and porosity logs also occur in the andesite and tuff intervals.

The explanation of the behavior of these logs opposite the fractures is perhaps to be found in the observed presence of crack-filling quartz and calcite crystals at the open fractures. For most of the rock, the neutron log gives a substantial apparent porosity reading, in part due to the presence of hydrothermal alteration products, but also because the basalt itself may characteristically have a small positive apparent neutron porosity value. Calcite gives a neutron porosity value of zero on the limestone scale and quartz gives a value of negative four. The density response for these minerals (about 2.65 g/cm^3 for quartz and 2.7 g/cm^3 for calcite) is slightly less than the apparent matrix density found for the basalts (Sanyal, Wells, and Bickham, 1980). An open fracture could have a high degree of filling due to secondary crystallization and yet maintain high permeability,

because the remaining porosity would be expressed as passages between the secondary minerals instead of being distributed as small matrix pores. The open fracture thus appears as a minimum on both logs: density (due to true porosity and the low density quartz filling material), and neutron porosity (due to displacement of clay minerals by quartz or calcite). Fractures that are not open or do not connect to other fractures, so that they do not circulate fluids have not developed secondary crystallization, will not give the low apparent porosity reading. Fractures that have become clogged with clay minerals will produce at most only a small density deflection. This is due to the excess of slightly lower density quartz crystals in the fracture.

Figure 16 is a plot against depth of the difference between the neutron porosity value, POR(N), and the porosity value computed from the density log,

$$\text{POR(D)} = \frac{D_0 - D}{D_0 - 1}, \quad (3)$$

where D_0 is the apparent matrix density of the various rock types, D is the density log value, and the density of water is taken to be 1 g/cm^3 . This quantity, $\text{POR(N)} - \text{POR(D)}$, was regarded as a possible indication of the degree of hydrothermal alteration in the rock. A value of zero should indicate an absence of pore filling clay minerals. The several washed-out intervals between 1050 and 1200 m were assigned a value of -1 and are easily identified (there is also a small wash-out near 1300 m). The plot gives a general indication of greater alteration in the upper part of the logged interval (above the washed-out sections) than in the lower part. Much more striking, however, is the comparison with the location of the SP deflections. A one-to-one correspondence exists between the SP deflections marking permeable zones, and places where the $\text{POR(N)} - \text{POR(D)}$ plot approaches zero. Furthermore, the extent of the minimum in the $\text{POR(N)} - \text{POR(D)}$ plot appears to be an indicator of the magnitude of the fracture.

The interval between 1128 and 1143 m represents a local minimum in the $\text{POR(N)} - \text{POR(D)}$ plot and has strong SP deflections, the $\text{POR(N)} - \text{POR(D)}$ is not the same as it is for the other fractured zones. Re-examination of the gamma-ray log shows that the readings for this interval are low, appearing to be more characteristic of tuff than of the basalt in this portion of the well.

Fig. 15. Similar section of logs showing fracture response at about 1051 meters (3448 feet).

Fig. 16. Difference in porosity value from the neutron log and porosity calculated from the density log. Washed-out intervals are set to -1 to render them easily identifiable. The position of SP deflection is shown by bars along the bottom of the plot. One bar corresponds to a deflection greater than 5 mV; two bars, greater than 10 mV; and three, greater than 15 mV. Below 1200 m location of the SP deflections depends on correlation of the electric logs from the original hole and the redrill and is somewhat less precise.

Whereas the density log between 1128 and 1143 m never shows the high values that identified the other tuff intervals in the well, it may be that there is a sufficient degree of porosity throughout this interval to explain the lower density values. The very extensive alteration of the basalt above and below this interval makes it difficult to determine if a contrasting rock type rather than a change in degree of alteration is responsible. If a value for apparent matrix density appropriate for the tuff intervals was used for the interval from 1128 to 1143 m, it would show near zero and negative values of $POR(N)-POR(D)$ as do the other tuffs.

Figure 17 shows the density and neutron traces corresponding to the SP deflection at about 1280 m. It seems clear that there is a fracture here and it apparently lacks the secondary crystallization that produces the negative $POR(N)-POR(D)$ values. Whether this fracture is merely clogged with clay

Fig. 17. Density and neutron log responses near 1280 meters (4200 feet).

minerals and produces an SP deflection only because of a strong membrane effect, or whether this fracture is in fact a good producer, is impossible to determine. We should note that the lithologic log for the portion of the well below 1310 m, for which we have no logs, states that the degree of hydrothermal alteration rapidly increased to such a point that it was impossible to determine the original nature of the rock near fractured zones. It is possible, therefore, that the fracture at 1280 m represents the beginning of a change in the appearance of the fractures in the well, although the small fractures 6 m below it again show negative POR(N)-POR(D) values.

For the most part, the POR(N)-POR(D) plot bears out the original interpretation of permeable intervals from the SP log with the following modifications.

- Some degree of permeability may exist between about 971 and 975 m.
- The identification of a fractured interval from 1283 to 1286 m in the redrill may not be accurate. In fact, two fractured sections seem to be present. The first (~1277 to 1281 m) has a SP deflection but also has low neutron porosity values, which may indicate either a very large fracture or a very high degree of hydrothermal alteration. The evaluation of the fracture is problematic. Second, there are two lesser fractures in the interval from 1286 to 1290 m that show signs of permeability.

C Porous Intervals

We have demonstrated that the neutron log is not a reliable indicator of true porosity throughout much of the well. The calculation of porosity from the density log and the apparent matrix densities determined earlier must therefore be relied upon. Whereas permeability is apparently strongly dependent on the absence of clay minerals in the rock, and permeable zones can be identified accordingly, the location of such zones is not the only problem encountered in evaluating of the well. Although the role of porosity in the evaluation of a geothermal reservoir is somewhat different than it is for oil and gas reservoirs, knowledge of the porosity is still important. Reservoir life will be significantly affected by the total pore volume drained by the fractures. Without a reinjection program, total production is obviously limited by the total fluid storage; however, even with a reinjection program, the optimum rate of production and ultimate field life is dependent on the volume of rock with which the reinjected fluid comes in contact.

As stated earlier, no logs are available for the bottom hundred meters or so of either the original hole or the redrill. We cannot know how much of the production from the well is coming from the logged interval and how much is coming from deeper in the well.

In the logged interval below about 1200 m, the rock is primarily basalt. Porosity calculated from the density of the unfractured basalt intervals appears to be only 1 or 2 percent. Major fractures and occasional tuff streaks however may raise the average porosity to 2.5 percent or greater. Several significant fractures can be identified, located at 15- to 30-m intervals. Low porosity and the presence of hydrothermal alteration products suggest that the basalt between fractures may have low permeability, so the long-term production rate from this zone may be well below initial flow rates.

Above 1200 m in the well, basalts appear to have somewhat greater porosity (about 2 to 3 percent). However, these basalts appear to be extensively altered resulting in very limited permeability. The greatest permeability and porosity appear in the andesite and tuff intervals. The andesite layer near 930 m and the two dense welded tuffs about 1060 and 1080 m appear to have 5 to 10 percent porosity and limited alteration. If, as seems likely, the permeable interval near 1130 m, identified in the lithologic log as basalt, actually includes a low-density tuff, this interval would represent the highest porosity in the well, 10 to 15 percent, depending on the apparent matrix density. The tuffs located between 1000 and 1200 m in the well thus represent the greatest storage volume in the logged interval. In addition, there are extensive washed-out intervals, surrounding the welded tuff layers, for which there are no reliable data. Judging by the lithologic log and high gamma-ray log values in the washed-out zones, these are mostly highly altered basalts or soft siltstone from old weathering surfaces. These intervals might make some additional contribution to the total porosity between 1000 and 1200 m, especially if they include any soft ash layers.

V. RESISTIVITY AND FORMATION WATER

The resistivity logs in the well responded to the permeable zones with local maxima in the recorded resistivities. Clay minerals in the rock, which filled pores and reduced permeabilities, also lowered resistivity.

Qualitatively, therefore, maxima in the resistivities and in the separation of deep and shallow resistivity traces provided some assistance in recognizing open fractures and porous intervals. The resistivity logs were also useful in the initial step of locating the limits of the different lithologic intervals given in Table III. Although the resistivity logs did not give data useful for identifying the rock type (because resistivity values are apparently dominated by the degree of hydrothermal alteration), the transitions from one rock type to another were often evident on the resistivity logs. However, the response of resistivity logging tools to fracture porosity is not fully understood. Also, the presence of conductive hydrothermal alteration products in this well complicates the interpretation of resistivity data. Therefore, to obtain useful quantitative data from the resistivity logs, some theory describing the resistivity response is required.

A. Formation Water and Mud Filtrate Resistivities

Two sets of resistivity data were obtained. Welex 18-in. normal and induction resistivity logs were run in the original hole. Mud characteristics, specifically mud filtrate resistivity, were recorded for this logging run. In the redrilled well a Schlumberger DIL run was made, but no mud characteristics were recorded, apparently because samples were not available after the lost circulation event that led to the termination of drilling. It was, however, established that the redrill was made with a clay base mud similar to that used in the original well.

The resistivity log from the original well, of which some examples were shown in Section IV, was of limited quantitative value over many interesting intervals because of the extreme oscillations of the induction log. The DIL, recorded on a logarithmic scale, gave more stable data.

In the original well, bottom-hole temperature was 111°C. The temperature log (taken immediately following the electric logs, 4 hours following the end of circulation) shows that the temperature is almost constant, between 110 and 115°C, from about 700-m depth on down. The only exception is a dip, in three steps, to a minimum of about 105°C between 1000 and 1200 m (the interval with the large wash-outs and the deeply invaded tuffs). Mud filtrate resistivity at 111°C was 3.27 ohm-m). Based on the small temperature variation below 820 m (the portion of the well under discussion), filtrate resistivity was treated as constant.

One formation property to which the resistivity logs are sensitive is the resistivity of the water in the pores of the rock. Sanyal and Jubasche (1979) argue that in a porous zone, resistivity of the invaded zone (R_{xo}) will be proportional to the mud filtrate resistivity (R_{mf}), while resistivity of the formation beyond the invaded zone (R_t) will be proportional to the formation water resistivity (R_w), according to the standard formula

$$R = FR_f \quad , \quad (4)$$

where R is the formation resistivity, R_f is resistivity of the fluid in the pores of the formation, and F is formation factor. Thus, if the invasion is such that the resistivity is measured with a deep resistivity tool (R_d) such as a deep induction log that can be regarded as approximating R_t , and if resistivity is measured with a shallow sensing tool (R_s) that can be taken to approximate R_{xo} , a plot of R_s against R_d will have slope R_w/R_{mf} , allowing the determination of R_w . Sanyal and Jubasche apply this approach to data from deep induction and Laterolog 8 (LL8) logs in a well at Raft River and show that the plots do indeed give linear trends.

There is, however, a difficulty with this application. According to published charts for the interpretation of DIL data (Schlumberger, 1978), the LL8 provides a reasonable approximation of R_{xo} only if $R_{mf} = R_w$ or if invasion is so deep that the induction log cannot be regarded as a reasonable approximation of R_t . The LL8 reads a combination of invaded zone and uninvaded zone resistivities determined by the depth of invasion, R_{xo} and R_t , and the geometrical factors describing the response of the LL8 to material at various radii from the borehole. If the depth of invasion is about constant in an interval with various resistivities, and if R_{LL8}/R_d does not vary too widely (more than about a factor of 2), the Schlumberger charts show that R_{LL8} will vary approximately proportionally to R_{xo} . Thus, under these conditions, a plot of R_{LL8} against R_d should give a linear trend with a slope proportional to, but not equal to, the ratio of R_{mf} and R_w (assuming that R_{xo} and R_t vary as R_{mf} and R_w).

The depth of invasion as estimated using the DIL data, is fairly constant over substantial portions of the well. From 845 to 945 m, the depth of invasion estimate (based on the published charts, Schlumberger, 1978) is

about 125 cm. Below that, down to the washed-out intervals, it appears to be somewhat smaller (~80 to 100 cm), but is relatively constant over several intervals. Below the washed-out zones (below 1200 m), depth of invasion is apparently smaller, generally less than 70 cm except at the isolated fractures. Figures 18, 19, and 20 show crossplots of R_{LL8} against R_d for three sections of the logs recorded in the redrill. For the intervals plotted, borehole corrections are negligible, because there is little variation in borehole size in the plotted intervals, and the mud is not highly conductive. All three plots clearly display linear relationships between R_s (R_{LL8}) and R_d ; the slope of this relationship is approximately the same in Fig. 18 and Fig. 19, but differs in Fig. 20. Figure 21 is a similar plot for the resistivity logs from the original drilling. It shows the resistivity recorded by the 18-in. normal tool vs the induction log resistivity for the interval 844 to 924 m (this was the only interval for which the induction log from the original drilling could be digitized). Figure 21 also gives a linear trend, demonstrating that this phenomenon is not an artifact of the DIL. The difference in the slope between Figs. 18 and 21 may be the result of tool differences or of a difference in mud filtrate resistivity. This cannot be determined because mud characteristics are not known for the redrill.

The intervals dealt with in Figs. 18, 19, and 20 are not clean, porous intervals (as can be seen from the crossplots in Section III). The minimum resistivity values on each plot are points at which invasion was minimal and both R_s and R_d are primarily affected by the conductivity of the clay minerals in the rock (with the result that $R_s \approx R_d$). It is clear, however, that the plots do not show a gradual transition. If they did, R_s would approximate R_d in zones of limited invasion, followed by a transition to a portion in which R_s more closely approximates R_{xo} . Such a plot would show a section of line at 45° (slope of one) and then a transition to a slope depending on R_w/R_{mf} . Therefore, the plots presented by Sanyal and Jubasche from RRGE No. 1 in Raft River were re-examined. It was found that, selecting two intervals of a reasonable depth in RRGE 1 such as those identified by Sanyal and Jubasche as Zone 5 (sandstone and siltstone above about 1000-m depth) and Zone 6 (tuffaceous siltstone between about 1000 and 1300 m), minimum resistivity (R_{LL8-9}) of about 8 ohm-m are shown for $R_{mf} = 2.1$ ohm-m and 1.8 ohm-m in the two zones. Applying the paper's premise,

Fig. 18. Crossplot of deep and shallow resistivities (in. ohm-m) for the interval 844 to 924 m. Least squares line has slope 0.35 and intercept 2.0. (Differing symbols for plotted points are not significant.)

Fig. 19. Crossplot of deep and shallow resistivities (in ohm-m) from 942 to 1042 m. Least squares line has slope 0.34 and intercept 5.2.

Fig. 20. Crossplot of deep and shallow resistivities (in ohm-m) from 1222 to 1290 m. Least squares line has slope 0.40 and intercept 9.0.

Fig. 21. Crossplot of deep and shallow resistivities (in ohm-m) from logs for the original hole, interval 844 to 924 m. Least squares line has slope 0.42 and intercept 2.2.

$R_{LL8} = FR_{mf}$, and using one of the common versions of the Humble Formula for F (Schlumberger, 1972),

$$F = \frac{0.81}{(POR)^2} , \quad (5)$$

porosity (POR) must exceed 45 percent in the sandstone and 40 percent in the tuffaceous siltstone. It seems more likely that, rather than being determined by Eq. (4), the linearity of the plots for RRGE No. 1 result from phenomena similar to those for the Surprise Valley well, in which the presence of clay minerals is affecting the resistivity.

B. Resistivity in Shaly Formations

We are still left with no satisfactory explanation for the linear relationship of R_x and R_d . Clearly, the resistivity response of a formation containing dispersed, conductive clay minerals is a crucial factor.

One approach that has been suggested is to treat the conductivity of the formation as that which would be found if the clay and water acted as a mixture of electrolytes. A quantity, POR^* , which is the sum of the fluid filled porosity and the volume fraction of shale or clay, will then fill the role of the porosity in a clean formation. Also, a factor, q , representing the fraction of POR^* filled by the clay or shale is required. If F_f is the resistivity of the fluid and R_{sh} is the resistivity of the shale or clay, the formation conductivity will be given by (Schlumberger, 1972)

$$\frac{1}{R} = \frac{1}{F^*} \left(\frac{1-q}{R_f} + \frac{q}{R_{sh}} \right) , \quad (6)$$

where F^* is the equivalent of a formation factor and will depend on POR^* . Then

$$R_{xo} = \frac{F^* R_{mf} R_{sh}}{(1-q)R_{sh} + qR_{mf}} \quad (7)$$

and

$$R_t = \frac{F^* R_w R_{sh}}{(1-q)R_{sh} + qR_w} \quad (8)$$

Whereas this formulation will reduce to Eq. (4) in the case of a clean ($q = 0$) formation and will give $R = F^* R_{sh}$ for a pore clogged ($q = 1$) formation, it will not give a linear relation between R_{xo} and R_t for $0 < q < 1$.

Equation (6) is formulated with additive conductivities and is, of course, effectively a formulation for a circuit with parallel conduction paths, one in the clay and one in the pore fluid. In view of Figs. 18 through 21, one might postulate that a continuous clay conductor does not exist and that current must be carried in series through the clay and pore fluids. This would give rise to a formulation

$$R = (1 - q) F^* R_f + qF^* R_{sh} \quad (9)$$

Although Eq. (9) has been written with a single F^* , it would not be impossible to suggest that a distinct F^*_{sh} should be introduced because the conduction mechanism in the clay is different from that in the pore fluid. Equation (6) is also equivalent to Eq. (4) whenever $q = 0$ and provides a basis for a linear relationship for R_{xo} and R_t with slope equal to R_w/R_{mf} . Intuitively, however, it is difficult to accept the assumption that no continuous conduction path exists for the clay conductivity when q is near one (since the fluid resistivity exceeds the shale resistivity, the effect of a continuous fluid conduction path is negligible). Further, because resistivity is low when q is near one despite the fact that POR^* will, in general, also be small, it follows that $F_f \gg R_{sh}$. Then when q is near one, a small change in q will produce a large change in $1 - q$ and thus a large change in R , whereas when q is near zero, the sensitivity of R to q should be much less. In fact, the logs show that R is relatively stable in zones with q near one as indicated by low R values and high values of $POR(N)$ - $POR(D)$ and R is highly variable in intervals with more open porosity (low q).

Another theory that has been advanced for conductivity in shaly formations (Jennings and Carroll, 1979) is the Waxman-Smiths formulation

$$\frac{1}{R} = \frac{1}{F'} \frac{1}{R_f} + BQ_v \quad (10)$$

Here F' is a formation factor approximately equal to the formation factor that would apply to a clean formation of equivalent porosity; Q_v is the cation exchange concentration of the clay content; and B is a parameter that may be dependent on the availability of ions to fill the exchange sites at the clay surfaces. Thus, B may be constant in the case of a high salinity pore fluid, but with fresher fluids and high portions of clays, B will vary as $1/R_f$. If that is the case, R will be proportional to R_f and the plot of R_{xo} against R_t will be linear with slope R_w/R_{mf} . Equation (10) does not allow a totally pore-clogged formation to be treated as having no pore fluid, however.

Using Eq. (10), a hypothesis regarding the effect of invasion can be developed. Equation (10) indicates that when conductivity is dominated by the clays, the dependence on fluid resistivity results simply from the availability of ions to the cation exchange sites on the surface of the clay particles. Thus, it would seem that when the formation is largely pore-filled with clay minerals, the change in resistivity, which we call invasion, could result from surface diffusion on the clays and would not necessarily be related to bulk permeability. This could explain the fact that the resistivity logs seem to indicate considerable invasion even in intervals with very little open porosity or bulk permeability.

In an attempt to further investigate the behavior of resistivity in the well, a number of efforts were made to isolate the formation factors by taking the difference of deep and shallow resistivities (or conductivities) and dividing by fluid resistivities inferred from the plots of R_s against R_d . Log-log plots were made of these quantities vs porosity and vs a number of possible formulations for POR^* based on two-mineral models using the neutron porosity and density logs and assuming the neutron log responds to the clays with one-third and one-half the response for water. None of these efforts produced useful results. Not enough data are available for the Surprise Valley well to provide conclusive evidence for the selection of a formula for resistivity log response.

C. Conclusions Derived from the Resistivity Plots

The lack of a complete explanation for the behavior of the resistivity does not rule out that some benefit can be gained from the data. On the contrary, in the preceding sections, it has been shown that the Surprise Valley well is not the only geothermal well in which a linear relationship of

R_s and R_d has been observed. It has been demonstrated that some hypotheses exist, which would support the obvious assumption that this linearity has slope dependent on R_w/R_{mf} . It is unfortunate that no water sample data are available currently that might give empirical evidence of this dependence.

On this basis, and assuming that temperature for the redrill was approximately constant as was the case in the original hole, Figs. 18, 19, and 20 provide a potentially useful piece of information. Specifically, these plots indicate a change in the character of the formation water below 1200 m. Resistivity of the formation water appears from Figs. 18 and 19 to be constant in the upper part of the well. Below 1230 m, however, the resistivity is apparently greater, indicating lower salinity formation water. Figures 18 and 19 do not include the andesite interval and the interval of washouts and tuffs between 1000 and 1200 m, because fractures and other inhomogeneities in these produce noise on the short reading resistivity log, and also because the higher maximum resistivities in these zones would tend to dominate the scale of the plots. However, omitting fractures and the effects of wash-outs and thin, impermeable layers, the ratio of shallow to deep resistivity values in these relatively porous intervals is greater than or equal to three, in keeping with the slopes of Figs. 18 and 19, and not Fig. 20. (Figure 21, taken from the log of the original hole, is not quantitatively comparable to Figs. 18, 19, and 20 because of the differences in mud characteristics and tool geometry.)

The conclusion is that the well penetrates two potentially distinct hydrologic systems, the separation being the washed-out intervals that have their base about 1200-m depth in the well. The lithologic log notes that at least one of these washed-out zones was an interval of soft siltstone that may have been an ancient soil resulting from weathering of the basalts at some time when they were exposed at the surface. This contact also represents a change in the character of the basalts in the well; the gamma-ray counts being higher, and the porosity and content of hydrothermal alteration products (as indicated by Fig. 17) being smaller, below 1200 m. Because the soft, clayey siltstones would not support fractures (fractures caused by faulting would tend to close) and may be otherwise relatively impermeable, it is not unreasonable that this layer should separate two different salinity zones.

This should be of some interest in development of the field. It has already been pointed out that the pore storage volume may differ between these

same two sections of the well. Analysis of water produced from the well could be used to indicate which level was dominating production and would also indicate any change in the partition of production with time. There may also be differences in temperature or pressure between the two systems. If so, it would be undesirable to allow a single well to be open at both levels. A lower pressure in one level could lead to a loss of flow from the well, whereas a temperature difference in the two levels would make it undesirable to mix the two flows because this would reduce the maximum fluid temperature. Static temperature surveys for the well shown in Fig. 22 indicate a temperature increase of 15°C around 1200 m (4000 ft) with constant temperature above and below these levels. This supports the conclusion that there are two distinct convective systems, and also shows the importance of separating production from the two levels.

VI. CONCLUSIONS AND RECOMMENDATIONS

The Surprise Valley well was originally drilled in 1972 and redrilled in 1974. Logs were run each time. This case history reviewed the data of the original log interpretation study and showed that valuable information could be obtained from further analysis of the logs. Originally, the log data were used for correlation between the original hole and the redrill for identification of permeable zones from the SP deflections. We have extended the original study to obtain additional information on logging response in volcanic terrains, refined the location of fractured intervals (probably producing zones) and dealt with the problems of resistivity logging and interpretation of the data in fractured, altered volcanic material. It should be pointed out that this extended log analysis stems from increased experience in dealing with igneous formations and especially geothermal reservoirs that have become available only in the last few years. Experience with the effect of hydrothermal alteration products and discussions of fractured reservoirs have been of specific value.

A. Data Obtained on Reservoir Characteristics

One significant fact that this study demonstrates is the value of a good lithologic log made with attention to the properties of igneous formations.

Fig. 22. Static temperature survey for the well showing break in temperature about 1200 m. Additional temperature data is in Appendix A.

Information on structural characteristics, minor constituents, and specific minerals, as well as rock type, was most valuable. The downhole logging data made possible the revision of the lithologic log and more exact location of major transitions. Identification of specific rock types solely from the logging data was not easy. However, using the logs together with the original lithologic record, it was possible to separate the logs into lithologic intervals and show that two sections originally recorded as part of a basalt section, probably contain welded tuff with significant porosity. Crossplots of the gamma-ray and density logs seemed to be the most effective for separating rock types.

Crossplots of density and neutron porosity values revealed the presence of hydrothermal alteration products that seriously affected the neutron log response. Values for apparent matrix density were therefore deduced and calculations of porosity were made from the density log. Due to the hydrothermal alteration and secondary deposition of quartz and calcite vein material in fractures, an unusual log response to open fractures was found. Opposite fractures, density log values were low, reflecting the existence of void space; but paradoxically, neutron porosity values were also low as a result of the presence of crystalline vein-filling materials (which produce low or negative neutron log responses) displacing the basalt and alteration products that produce a greater neutron response. Because fractures represent highly localized features, conventional crossplot techniques were of limited use in evaluating them. A porosity difference plot for the well showing the difference between porosity values drawn from different logs (in this case the neutron porosity and the density log) against depth was found to be a useful tool--pinpointing fractures and porous intervals and also isolating problem intervals, such as intervals in which the apparent matrix density estimate was uncertain. Negative deflections in the self-potential log also appear to indicate permeable fractures, apparently as a result of streaming potentials.

Interpretation of the resistivity logs was complicated by the hydrothermal alteration products that apparently were the controlling influence on formation conductivity. A satisfactory formulation for the resistivity of the formation could not be established from the data available, thereby limiting the quantitative applications of the resistivity logs. Comparison of deep and shallow resistivities, however, strongly suggested the existence of two separate hydrologic regimes in the reservoir separated by

soft, low-permeability material near 1200 m in the well. Temperature log data support this possibility.

The effect of hydrothermal alteration was evident in virtually all aspects of the log interpretation for this well. The hydrothermal alteration products distort the neutron porosity log response and complicate lithologic identification, determination of matrix density, and estimation of true porosity. In addition, the impact of the alteration products on the neutron log is directly related to the unusual fracture signature found from the neutron and density logs. The presence of hydrothermal alteration products seemed to be a controlling factor in formation permeability. Finally, formation resistivity is dependent on the alteration products as well as the pore fluids.

B. Potential Applications to Further Exploration or Development

If, or when, interest is again focused on Surprise Valley's geothermal potential, data from the well logs may be of interest for more than reservoir evaluation. It has been estimated that advances in the application and interpretation of well log data could produce benefits of millions of dollars through improved well siting and reduced drilling costs (Rigby and Reardon, 1979). The possibility of the existence of two distinct hydrologic systems may be of considerable interest in any development plans. It is unfortunate that none of the logging tools were able to reach total depth, which limits the evaluation of part of the deep system. Judging by temperature surveys and lost circulation during drilling, the deeper system is likely to be the more important. Distinguishing between the two systems may be important for several reasons. If the shallower system has significant production it would seem undesirable to mix it with the flow from the deeper system. The soft material that washed out about 1200 m in this well apparently separates the two systems and might be of use as a geologic marker in drilling other wells. The expected depth of the soft layer(s) will also be of interest in making bit plans for drilling. If communication does prove to be poor between the two systems, it will also have a major impact on planning for reinjection.

If the washed-out layer does mark the separation of distinct portions of the reservoir, the well log data may also dictate some future geophysical studies. The well logs indicate that the zone between 1050 and 1200 m is quite distinctive. Although a sonic log is not available, it would certainly

seem that this section of alternating dense tuffs and looser material should be detectable seismically. Thus, the logs indicate that a seismic survey would be worthwhile because we could expect to locate an identifiable marker of the top of the hotter, deeper system. This would be desirable in siting and planning additional wells. Data from an acoustic velocity log for the interval in question would obviously be desirable in planning and interpreting a seismic survey.

Another possibility would be resistivity sounding data. The transition to higher resistivity formation and less porosity in the lower system causes the resistivity in the lower portion of the well to be greater than it is in the upper portion. Above 1050 m, large portions of the basalt flows have resistivities of 8- to 10- m, whereas below 1200 m, resistivity is seldom much below 20 m. Resistivity may drop again as a result of increasing alteration at depths greater than the bottom of the logged portion of the well. Even so, the top several hundred meters of the lower convective system will provide a high-resistivity layer. Such a resistivity contrast involving layers of a few hundred meters thickness is a feasible target at the depths involved, although high levels of injected current would be necessary because of the generally low resistivities.

The soft material that washed out in the well between 1050 and 1200 m is soft siltstone and highly altered basalts, so the resistivity of this layer should be low. Resistivity cannot be exactly determined because corrections for the borehole effect in the washed-out zones where well diameter is unknown cannot be made. However, mud resistivity was fairly high (in the original hole, it was 3.27 m at bottom-hole temperature), and even for a 51-cm (20-in.) or larger hole, the borehole correction will only be 50 to 100 m (Welex Charts for the Interpretation of Well Logs (1968)). The induction log conductivity values in the extensive washed-out intervals exceed 1000 m indicating that the formation resistivity is very low and that borehole correction is probably of limited significance. Nearly two-thirds of the section from 1050 to 1200 m in the well is washed out. Although the remainder is composed of high-resistivity tuffs, the mean conductivity of this 150-m-thick layer will still be very high. By using data from the logs to model the thickness and resistivities of the near surface layers in the area, it might also be possible (given fairly horizontal layering) to detect this high-conductivity layer by surface-resistivity soundings. Variations in the

resistivity of this zone could be indicative of the thickness of the porous tuff layers included in it (more tuff and less siltstone would increase the mean resistivity). If it seems desirable to produce from the upper system, the tuff layers will probably dominate such production.

C. Additional Logging

The review of the log interpretation for the Surprise Valley well naturally suggests additional log data that could have been gathered and would have been valuable in the log interpretation. A multi-arm caliper log would have been useful in the washed-out intervals. The single-arm caliper associated with the neutron and density tools did not have sufficient capability to measure several washed-out intervals. Borehole corrections to the log data in the washed-out intervals might reveal some additional useful facts, such as whether or not soft ash layers occur as part of any of the washed-out intervals. A more sensitive caliper log might also have given some information regarding mudcake formation opposite the permeable zones.

The lack of an acoustic velocity (sonic) log has been pointed out several times in this paper. Porosity calculations utilizing acoustic velocity data could have been compared with both the neutron and the density log data, effectively tripling the amount of information available on the distribution of hydrothermal alteration products and porosity. In this well, porosity, degree of alteration, secondary crystal growth in the fractures, and occasionally, rock type were all unknowns; yet only two knowns, density and neutron porosity log values, were available.

There are unanswered questions associated with the resistivity logs. A microlog or other flushed zone resistivity tool would have been a useful addition, especially to the Welex induction and 18-in. normal logs for which mud and mud filtrate resistivities were recorded. If such a log were available, we might be able to make somewhat more confident and quantitative statements regarding formation water characteristics. Another point that should be emphasized with regard to the resistivity data is that a temperature log was made along with the electric logs in the original hole, which established that temperatures were relatively uniform below 800 m. A temperature survey should always accompany resistivity measurements in geothermal wells because of the large temperature differences that are possible.

Another interesting type of logging, which could not have been run at the time the well was logged because tools suitable for the conditions involved were not available, is induced polarization (IP) logging, now used primarily as a mineral exploration technique. Obtaining IP logging services for geothermal wells may be a problem at present, but for the future it is worthwhile taking note of the technique. The IP response is sensitive to the presence of the dispersed clay minerals in a formation. It has been pointed out that virtually all aspects of the log interpretation for this well were affected by the clay minerals forced by hydrothermal alteration. It would certainly be interesting to have an IP log for this well.

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