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ANALYSIS OF PRESSURE INTERFERENCE TESTS FOR WELL S-4 AND SLIM HOLE KY-1: SUMIKAWA GEOTHERMAL FIELD, JAPAN

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ABSTRACT

Discharge of Sumikawa well S-4 in the fall of 1986 was accompanied by *in situ* boiling. In May of 1989, cold water was injected intermittently into well S-4. During both of these tests, a pressure response was observed in KY-1. In this paper, a new interpretation of the latter pressure interference data is presented. While interpretation of the 1989 test is straightforward, *in situ* boiling during the 1986 test creates substantial difficulties in assigning an "effective discharge rate". Because of uncertainties in the "effective discharge rate" history for the 1986 test, the distances to the various reservoir boundaries are not well constrained.

INTRODUCTION

The Sumikawa Geothermal Field is located in the Hachimantai volcanic area in northern Honshu, Japan, about 1.5 kilometers to the west of the Ohnuma geothermal power station operated by Mitsubishi Materials Corporation (MMC). The Hachimantai area also includes the Matsukawa and Kakkonda Geothermal Fields. An extensive well drilling and testing program was initiated in the Sumikawa area in 1981 with the spudding of boreholes S-1 and S-2 by MMC (see Figure 1 for locations of boreholes).

The abundance of drilling logs from the various boreholes in the area has revealed the following geological sequence (see Figure 2):

> *ST formation*. Surficial andesitic tuffs, lavas, and pyroclastics of recent origin.
>
> *LS formation*. Lake sediments; Pleistocene tuffs, sandstones, siltstones, and mudstones.
>
> *DA formation*. Pliocene dacites, dacitic tuffs, and breccias.
>
> *MV formation*. "Marine/volcanic complex"; interbedded Miocene dacitic volcanic rocks and "black-shale" oxygen-poor marine shales and sediments.
>
> *AA formation*. Altered andesitic rocks that apparently are extensively fractured.
>
> *BA formation*. Crystalline intrusive(?) rocks (mainly granodiorite and diorite).

The BA formation is the deepest so far encountered by drilling, but the pre-Tertiary basement, which presumably underlies the above sequence, has not yet been reached.

MMC has performed several multiple-well pressure interference tests in the Sumikawa Geothermal Field. These pressure transient tests have helped in clarifying the permeability structure of the Sumikawa Geothermal Field. Analyses of Sumikawa pressure transient data have previously been presented by Pritchett, *et al.* (1989), Garg, *et al.* (1991), and Ishido, *et al.* (1992). Identification of the "altered andesite" formation as a high permeability reservoir is in large part based on the interpretation of two pressure interference tests (1986 and 1989 tests) between boreholes S-4 and KY-1. In this paper, a new interpretation of the latter pressure interference data (*i.e.*, 1986 and 1989 tests for boreholes S-4 and KY-1) is presented.

Slim hole KY-1 is cased and cemented to 1001 meters depth (−10 m ASL); uncemented slotted liner is present from that point to 1604 meters depth (−613 m ASL). Only two mud loss zones were encountered in the uncemented part of the hole; at −169 m ASL and at −571 m ASL. The deeper of these mud loss zones (−571 m ASL) is in the "altered andesite" formation; the shallow mud loss zone (at −169 m ASL) is contained in the "marine/volcanic complex" formation.

Well S-4 was drilled vertically to a total depth of 1552 m ASL (−445 m ASL); the bottom of the 7-inch casing was set at 1071 meters (36 m ASL), and an open hole completion was used below this depth. The major feedpoint for well S-4 is located at −413 m ASL in the "altered andesite" formation. The horizontal distance between S-4 and KY-1 is about 1176 meters. It is highly likely that S-4 and KY-1 communicate with each other through the "altered andesites".

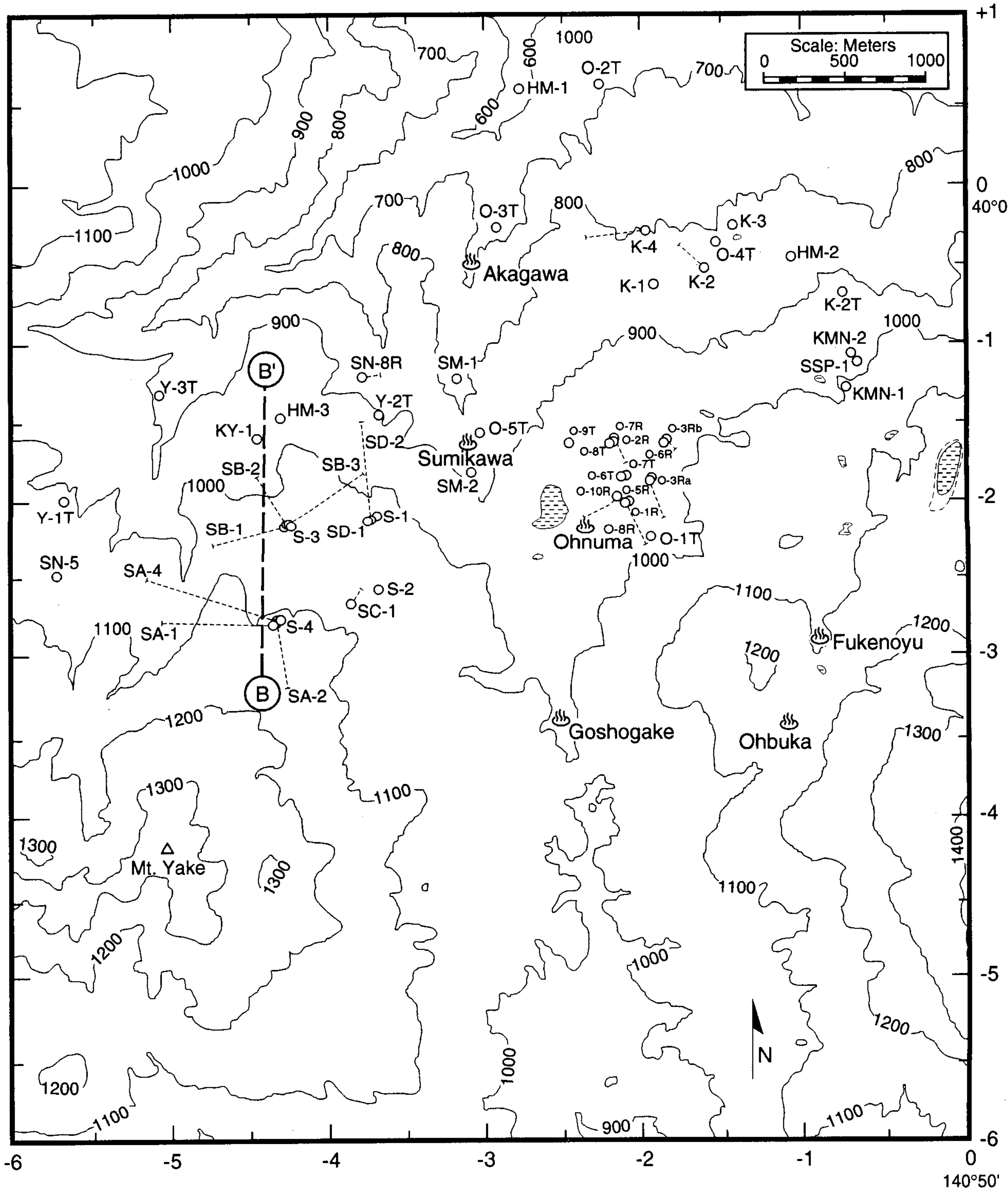

Figure 1. The Sumikawa/Ohnuma area, showing locations of boreholes and cross-section B–B′. The origin of the local co-ordinate system is 40°N latitude and 140°50′E longitude.

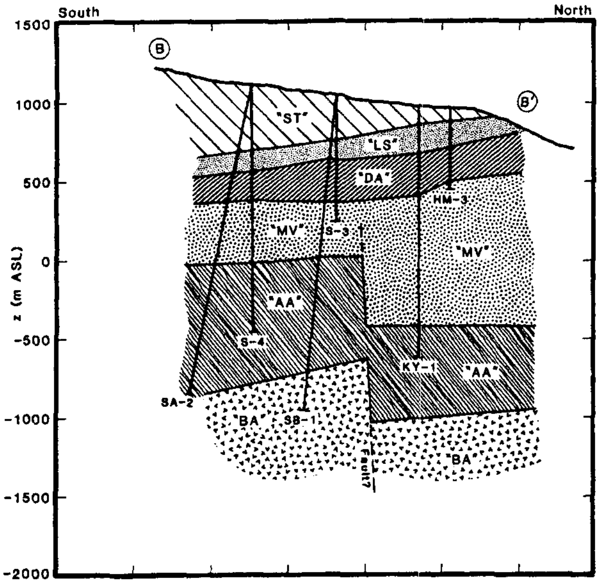

Figure 2. North-south B–B′ (total length = 3.5 km) geological cross-section through the Sumikawa area.

In the fall of 1986, well S-4 was discharged for approximately three months (September 2, 1986 to November 29, 1986); separated water from the S-4 discharge was injected into nearby relatively shallow slim hole S-2 (feedzone depth = 131 m ASL). Four observation boreholes (O-5T, S-3, KY-1 and SD-1) were equipped with capillary-tube pressure gauges. Pressure measurements were, however, not made in either the production (S-4) or the injection (S-2) boreholes. No pressure signal attributable to the discharge (or injection) of well S-4 (slim hole S-2) was seen in boreholes O-5T, S-3 and SD-1. On the other hand, a clear response associated with the discharge of S-4 was recorded in KY-1; the pressure in KY-1 started to decline within a couple of hours after the initiation of discharge from well S-4. Because of the low vertical permeability of the black shales, it is unlikely that injection into S-2 is in any way responsible for the observed pressure signal in KY-1.

Starting at 19:00 hours on May 16, 1989, cold river water was intermittently injected into well S-4 until 14:00 hours on May 19, 1989. Borehole KY-1 was equipped with a capillary-tube type pressure gauge during the latter injection test. KY-1 responded quickly (within a couple of hours) to each change in injection rate.

Pritchett, *et al.* (1989) analyzed the pressure response recorded in KY-1 due to the 1986 discharge of well S-4. These authors postulated the presence of a north-south oriented permeable horizontal "channel" of constant cross-section area and uniform permeability; the feedpoints of S-4 and KY-1 were assumed to lie within the permeable channel. The east, west, north, upper and lower boundaries of the channel are impermeable. To the south, the channel ends in a constant pressure boundary (presumably representing the influence of a two-phase region in the reservoir). Minimization of the deviations between measurements and computed pressures was used to infer the following parameter values:

- Channel cross-section area: 0.51 km^2
- North-south permeability: 195 millidarcies
- Distance to northern (impermeable) boundary: 1.44 km north of KY-1
- Distance to southern (constant pressure) boundary: 9.86 km south of S-4

Since the "altered andesite" layer is about 500 meters in thickness, the channel width (*i.e.*, east-west extent) is around 1 km.

The "channel model" outlined above, however, does a poor job of reproducing the high frequency pressure response recorded in KY-1 during the 1989 injection test of well S-4. Garg, *et al.* (1991) and Ishido, *et al.* (1992) discuss alternative models for the 1986 and 1989 tests. The pressure responses computed by the "anisotropic line-source model" (Garg, *et al.*, 1991) and by the "double porosity channel model" (Ishido, *et al.*, 1992) for both the 1986 and 1989 tests appear to agree reasonably well with the pressure measurements. Both Garg, *et al.* (1991) and Ishido, *et al.* (1992) used an "effective discharge rate" history for S-4 (1986 test) originally derived by Pritchett, *et al.* (1989). It is significant that the "effective discharge rate" history for S-4 (1986 test) does not strictly speaking, represent measured values; Pritchett, *et al.* (1989) invoked a variety of assumptions to derive this "effective discharge rate" history. In the following, an alternate interpretation of the 1986 discharge rates for S-4 is used to arrive at a new reservoir model.

DISCHARGE RATE HISTORY (1986) FOR WELL S-4

Well S-4 discharge was initiated at 11:20 hours LT on September 2, 1986, and ended at 16:30 hours LT on November 3, 1986. The flow rate measurements performed during the S-4 discharge are summarized in Table 1. Apparently, no measurements of water discharge rate were made between September 27, 1986 and November 2, 1986.

It is likely that two-phase (water/steam) boiling flow was induced locally in the reservoir adjacent to the S-4 feedpoint by the pressure reduction associated with the discharge. The stable feedzone pressure and temperature for well S-4 are estimated to be 93 (±1) bars and

Table 1. Measured discharge rates (1986) from well S-4.

Date	Steam Discharge	Water Discharge	Total Discharge
02 Sept 1986	32 kg/s	18 kg/s	50 kg/s
03 Sept 1986	28 kg/s	14 kg/s	42 kg/s
05 Sept 1986	27 kg/s	15 kg/s	42 kg/s
08 Sept 1986	26 kg/s	16 kg/s	42 kg/s
13 Sept 1986	26 kg/s	18 kg/s	44 kg/s
20 Sept 1986	26 kg/s	20 kg/s	46 kg/s
26 Sept 1986	27 kg/s	20 kg/s	47 kg/s
30 Sept 1986	26 kg/s	?	?
09 Oct 1986	26 kg/s	?	?
18 Oct 1986	26 kg/s	?	?
27 Oct 1986	26 kg/s	?	?
03 Nov 1986	26 kg/s	24 kg/s	50 kg/s

Note: Well S-4 discharge began 02 Sept at 11:20, and ended 03 Nov at 16:30

(295–300)°C, respectively. The saturation pressure at which water will boil at (295–300)°C is (80–86) bars. Thus, a pressure reduction of (7–13) bars at the feedzone will result in *in situ* boiling. The productivity/injectivity index for S-4 is of the order of 1 kg/s-bar (Garg, *et al.*, 1994); therefore, the pressure drop for a discharge rate of 50 kg/s is ~ 50 bars. It is thus likely that *in situ* boiling occurred more or less simultaneously with the initiation of discharge from S-4 on September 2, 1986. Pritchett, *et al.* (1989) assumed that *in situ* boiling did not start until September 7, 1986 (*i.e.*, five days after the start of S-4 discharge test). The argument advanced by Pritchett, *et al.*, (a decrease in the pressure decline rate in KY-1 around September 7) in support of a delayed *in situ* boiling is rather tenuous.

The two-phase region created during the S-4 discharge test was very likely of limited extent. The average temperature in the region between S-4 and KY-1 is about ~ 250°C. To boil water at 250°C would require a pressure reduction exceeding 50 bars, and only 3 bars reduction was observed at KY-1. Therefore, it is likely that the flow between S-4 and KY-1 was single-phase during the discharge test except for a two-phase region immediately surrounding the S-4 feedpoint. Garg and Pritchett (1988) discuss methods for analyzing pressure interference data from a hot water geothermal reservoir which evolves into a two-phase system as a result of fluid production, and in which the observation well remains in the single-phase (liquid) part of the reservoir. According to Garg and Pritchett (1988), single-phase solutions may be applied for interference test interpretation provided that the discharge rate history used in the analysis is suitably modified to reflect the influence of the two-phase zone. The "effective discharge rate" for use in analysis is only a fraction of the actual (or measured) discharge rate.

Pritchett, *et al.* (1989) used the following procedure to estimate the "effective discharge rate" history for well S-4 after September 7, 1986 (*i.e.*, after the presumed start of *in situ* boiling). Shortly after the start of discharge of S-4, the pressures in KY-1 started declining at a rate of ~ 80 bars/year. After the S-4 discharge was stopped on November 3, 1986, the pressures (in KY-1) began to recover initially at a rate of ~ 40 bars/year (Figure 3). Linear superposition theory implies that the change in slope of the pressure history (–80 bars/year) at the onset of discharge should bear the same relation to the causative change in discharge rate (0 to 50 kg/s) that the change in slope at shutin (from –8 bars/year to +40 bars/year = 48 bars/year) bears to the relevant change in discharge rate, *i.e.*,

$$\frac{\dot{M}^{*}-\dot{M}^{**}}{\dot{M}_o}=\frac{48}{80}=0.6 \quad , \qquad (1)$$

where

$\dot{M}_o$ = "effective discharge rate" at the start of discharge test,

$\dot{M}^{*}$ = "effective discharge rate" prior to shutin,

$\dot{M}^{**}$ = after flow rate.

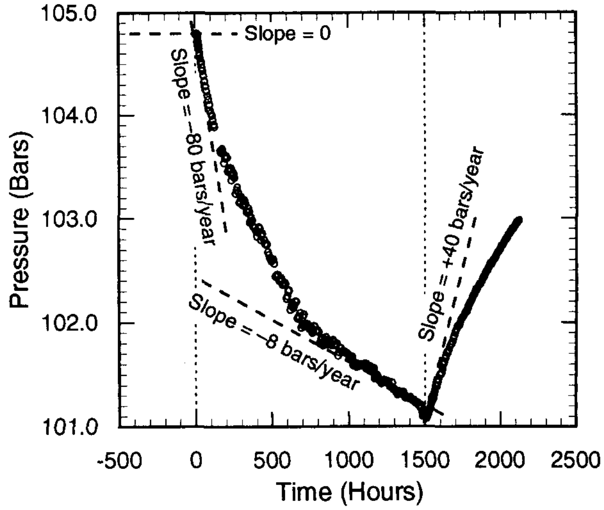

Figure 3. Measured pressure interference signal in well KY-1 (1986). Pressures have been adjusted for gaps/offsets in measurements. All times are in hours since 00:00 hours LT on September 2, 1986.

The afterflow $\dot{M}^{**}$ will usually be a small fraction of the discharge rate. It may, however, persist for a long period of time, until the entire steam zone has condensed away. Assuming that $\dot{M}_o$ and $\dot{M}^{**}$ equal 50 kg/s and 4 kg/s respectively (Pritchett, *et al.*, 1989), $\dot{M}^*$ was estimated to be ~ 34 kg/s. The "effective discharge rate" for well S-4 utilized by Pritchett, *et al.* (1989) in their analysis of pressure interference response is given in Table 2.

Table 2. "Effective discharge rate" history for well S-4 used by Pritchett, *et al.* (1989).

Time Interval			$\dot{M}_{eff}$
08/04	20:00 to 09/02	11:20	0 kg/s
09/02	11:20 to 09/03	12:00	50 kg/s
09/03	12:00 to 09/07	00:00	42 kg/s
09/07	00:00 to 11/03	16:30	34 kg/s
11/03	16:30 to 11/29	09:00	4 kg/s

In so far as boiling started immediately after the initiation of discharge from S-4, it is likely that $\dot{M}_o$ is substantially smaller than 50 kg/s. A possible approach to the determination of $\dot{M}_o$ is described in the next section.

DETERMINATION OF INITIAL "EFFECTIVE DISCHARGE RATE" $\dot{M}_o$ FOR WELL S-4 (1986 TEST)

In May 1989, cold water was injected intermittently into well S-4; the injection rate history is given in Table 3. Injection rates are quoted in cubic meters per second; for present purposes it is suffices to assume that 1 m^3/s equals 1,000 kg/s. The measured pressure response in KY-1 is shown in Figure 4. Each change in S-4 flow rate produces a distinct pressure response in KY-1; the lag time between flow rate and discernible pressure changes is between 1 and 2 hours. From 1843 to 1850 hours, the injection rate into S-4 was about 114 kg/s. The pressure in KY-1 did not start increasing until some time after 1844 hours. Between 1844 and 1851 hours (*i.e.*, 8 hours after the start of injection), the pressure change (Δp) was 0.31 bars.

Garg and Pritchett (1990) present an approximate analytic solution for cold water injection into a single-phase hot water reservoir. Beyond the cold front surrounding the injection well, the pressure response is determined by the kinematic viscosity of the *in situ* fluid. This means that the pressure response of slim hole KY-1 to injection into S-4 should be computed using *in situ* fluid properties. The latter result together with linear superposition theory implies that the pressure change in KY-1 should bear the same relation to injection rate (1989 test) and to "effective discharge rate" (1986 test). Given the amplitudes of pressure changes over comparable time periods (8 hours after the start of discharge/injection) during the 1986 discharge (0.086 bars) and 1989 injection (0.310 bars) tests, and the injection rate (114 kg/s) for the 1989 test, the "effective discharge rate" $\dot{M}_o$ for the early part of the 1986 test can be computed as follows:

Table 3. Flow rate history for cold water injection into well S-4 (May 1989). All times are in hours since 00:00 hours LT on March 1, 1989.

Time Interval (Hours)			$\dot{M}_{inj}$ (m^3/s)
1843.0	–	1850.0	0.1139
1850.0	–	1865.933	0.
1865.933	–	1876.0	0.1230
1876.0	–	1889.167	0.
1889.167	–	1900.0	0.1214
1900.0	–	1904.0	0.0191
1904.0	–	1906.0	0.0339
1906.0	–	1908.0	0.0689
1908.0	–	1912.0	0.0970
1912.0	–		0.

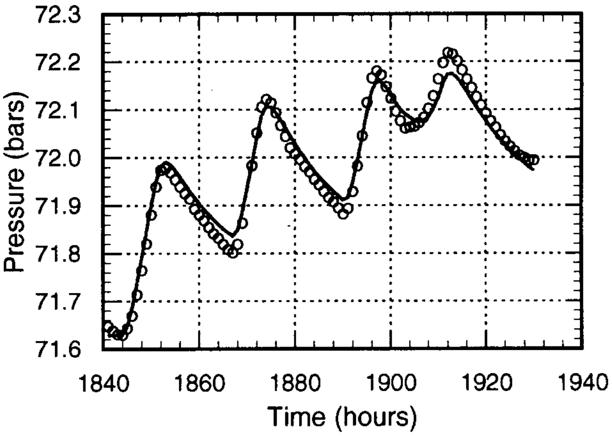

Figure 4. Comparison between measured (o) and computed (–) pressures in N60-KY-1 during the 1989 test. All times are in hours since 00:00 hours LT on March 1, 1989.

$$\dot{M}_o = \frac{114 \times 0.086}{0.310} \approx 30 \text{ kg/s}.$$

The initial "effective discharge rate" $\dot{M}_o$ is thus 60 percent of the measured total discharge rate (50 kg/s) on September 2, 1986.

Since the total discharge rate during the 1986 test varied considerably, it is likely that the "effective discharge rate" also underwent changes. Equation (1) implies that the change in "effective discharge rate" at shutin on November 3, 1986 was about 0.6 $\tilde{M}_0$ (~ 18 kg/s). Variations in the "effective discharge rate" prior to shutin (or the afterflow rate after shutin) cannot, however, be determined from the available data. Stated somewhat differently, the "effective discharge rate" history for S-4 (1986 test) is not well characterized.

ANALYSIS OF 1989 INTERFERENCE TEST

S-Cubed's well test program DIAGNS (Alexander, *et al.*, 1992) was used to analyze the pressure response recorded in KY-1 as a result of cold water injection into well S-4. DIAGNS is a workstation-based system for examination, processing, analysis, interpretation and inversion of well test data. The program performs non-linear least squares estimation of reservoir model parameters for a variety of mathematical models. Confidence bounds, correlation and covariance matrices are also estimated to provide guidance in evaluating the confidence in and suitability of model parameters.

The pressure interference response recorded in KY-1 during the 1989 test was modeled using the line-source model. Both S-4 and KY-1 are assumed to fully penetrate an infinite reservoir. The 1989 test data can be fitted adequately without invoking the existence of any boundaries. The average reservoir temperature in the region occupied by S-4 and KY-1 is about 250°C. Dynamic viscosity and density for liquid water at a temperature of 250°C are approximately 10^{-4} Pa-s and 800 kg/m^3, respectively. The initial pressure p_i was kept fixed at 71.629 bars. The only unknown parameters in the model are permeability-thickness kh and storage ϕch. Two different analyses were performed using pressure/flow rate data for (1) first injection/fall-off cycle (t = 1843–1866 hours), and (2) complete 1989 injection test (t = 1843–1930 hours). The unknown parameters kh and ϕch were varied to obtain the best possible match between the measured and computed pressures (Figures 4 and 5). The final model parameters are:

(i) First injection/fall-off cycle

kh = 16.3 darcy-m
ϕch = 8.45×10^{-9} m/Pa

(ii) Complete injection test

kh = 14.8 darcy-m
ϕch = 7.89×10^{-9} m/Pa

An examination of the sensitivity of the mathematical fits to variations in model parameters (kh, ϕch) showed that the two sets of parameter values are compatible with each other. Thus, the best estimates for formation kh and ϕch from the1989 data are 15.6 (±0.8) darcy-m and 8.2 (±0.3) 10^{-9} m/Pa, respectively. To evaluate the appropriateness of the line-source model, additional analyses of 1989 pressure data were performed using several other mathematical models (*e.g.*, Warren-Root and MINC/gradient flow double porosity models). No significant improvement (over the line-source model) in fit to pressure data was obtained. Therefore, the line-source model provides the proper framework for analyzing the 1989 pressure interference test between S-4 and KY-1.

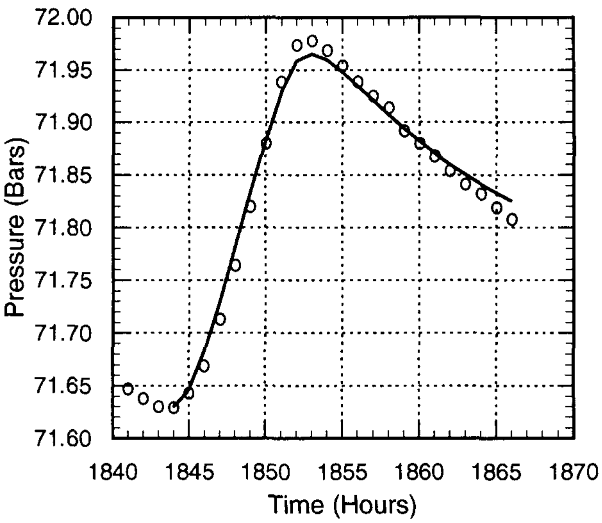

Figure 5. Comparison between measured (o) and computed (–) pressures in KY-1 for the first injection/fall-off cycle. All times are in hours since 00:00 hours LT on March 1, 1989.

1986 PRESSURE INTERFERENCE TEST: EARLY RESPONSE

In this section, the pressure response recorded in KY-1 during the first 24 hours of the 1986 discharge test is considered. The choice of the time interval (*i.e.*, the time interval between the start of discharge test at 11:20 hours on September 2 to 12:00 hours on September 3) is dictated by the following considerations. The duration of the first injection/fall-off cycle during the 1989 injection test was approximately 24 hours. To meaningfully compare the formation parameters inferred from the1986 and 1989 tests, it is essential to consider similar time periods for the two tests. Analysis of 1989 pressure interference data for the first injection/fall-off cycle did not indicate the presence of any boundaries; it is, therefore, likely that the early portion of 1986 test data is most diagnostic of formation properties. Finally, it should be noted that except for the early part of the flow test, the "effective discharge rate" history for the 1986 test is poorly known.

Like the 1989 test, the pressure interference response observed in KY-1 during the 1986 test was modeled using the line-source solution. As before, both S-4 and KY-1 are assumed to fully penetrate an infinite aquifer. The initial pressure p_i was kept fixed at 104.796 bars. (The pressure gauge was set at different depths in the 1986 and the 1989 tests.) The "effective discharge rate" for S-4 was assumed to remain constant (=30 kg/s) for the first 24 hours of the discharge test. Minimization of the deviations between the measured and computed pressures gave the following values for the unknown model parameters (kh, φch):

$$kh = 12.9 \text{ darcy-m}$$
$$\varphi ch = 7.32 \times 10^{-9} \text{ m/Pa}$$

The measured and computed pressures (Figure 6) are in excellent agreement. The φch value obtained from the 1986 test is slightly lower than that implied by the 1989 test. The "effective discharge rate" for the 1986 test (30 kg/s) is not very precise; variations of the order of 10 to 20 percent in the "effective discharge rate" cannot be ruled out. A second calculation was accordingly run using an "effective discharge rate" of 33 kg/s (*i.e.*, increasing the "effective discharge rate" by 10 percent); this analysis resulted in a 10% increase in the inferred values for kh (14.2 darcy-m) and φch (8.05×10^{-9} m/Pa). The latter result implies that for the 1986 test, both kh and φch scale linearly with the "effective discharge rate". Considering the range of uncertainty for the 1986 "effective discharge rate", it is reasonable to conclude that the model parameters (kh, φch) obtained from the 1986 and 1989 tests are consistent.

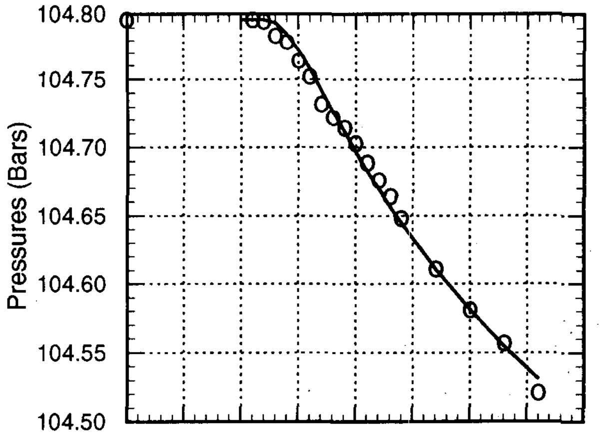

Figure 6. Comparison between measured (o) and computed (–) pressures in KY-1 during the early part (*i.e.*, first 24 hours) of the 1986 test. All times are in hours since 00:00 hours LT on September 2, 1986.

1986 PRESSURE INTERFERENCE TEST: LATE TIME RESPONSE

The uncertainties associated with the S-4 "effective discharge rate" make it impossible to obtain a unique interpretation of the observed pressure interference signal in KY-1. In this section, the effect of uncertainties in the "effective discharge rate" on the inferred formation parameters will be examined. To provide a comparison with the previous work of Pritchett, *et al.* (1989), the "effective discharge rate" for the base case (case 1) was assumed to be 60 percent of that used (Table 2) by Pritchett, *et al.* (1989). The line-source solution was used to fit the pressure response in KY-1. The best fit was obtained by assuming that the aquifer penetrated by S-4 and KY-1 is bound by impermeable boundaries to the east, the west and the north; to the south, a constant pressure boundary (presumably reflecting the presence of a two-phase zone) terminates the aquifer. The formation parameters inferred for case 1 are given in Table 4. The computed pressure history for KY-1 is in good agreement with the measurements (Figure 7). The east-west width (w) of the permeable aquifer is about 3.8 km; thus, kA ($= khw$) is estimated to be ~ 51 mdarcy-km^2. The latter value for kA is approximately 50 percent of that (~ 99 mdarcy-km^2) obtained by Pritchett, *et al.* (1989). Pritchett, *et al.* assumed the formation porosity φ and compressibility c to be 0.05 and 1.7×10^{-9} Pa^{-1}, respectively; with A equal to 0.51 km^2, the areal storage (φcA) calculated by Pritchett, *et al.* is ~ 4.3×10^{-5} m^{2}Pa^{-1}. The areal storage φcA ($= \phi chw$) obtained from the present interpretation (~ 3.1×10^{-5} m^{2}Pa^{-1}) is about 70 percent of that given by Pritchett, *et al.* Recalling that the "effective discharge rates" used for the present interpretation are only 60 percent of those employed by Pritchett, *et al.* (1989), it is concluded that the formation parameters (*i.e.*, kA, φcA) obtained from the two interpretations are similar.

To assess the impact of uncertainties in the "effective discharge rate" history for S-4 on the inferred formation parameters, four additional "effective discharge rate" histories (cases 2 through 5, Table 5) were considered. In all cases, the initial "effective discharge rate" was kept at 30 kg/s; furthermore, the jump in discharge rate at the moment of shutin (1504.5 hours, Table 5) was taken to be 18 kg/s. The discharge rate history for case 2 is the simplest; both the discharge rate and the afterflow rate were assumed to be simple constants. Apart from a gradual reduction in the afterflow rate, the discharge rate history for case 3 is identical with that for case 2. In case 4, the discharge rates prior to shutin were varied in direct proportion to the measured discharge rates. It is possible (perhaps even likely) that the ratio between the measured and "effective discharge rates" did not remain constant during the 1986 test; for case 5; the "effective discharge rate" (as a fraction of the measured discharge rate) was assumed to decline with time.

Table 4. Formation parameters inferred using different "effective discharge rate" histories for well S-4 (1986 test).

	Case 1	Case 2	Case 3	Case 4	Case 5
Permeability-thickness *kh* (darcy-m)	13.5	13.5	13.5	9.7	13.8
$\varphi c h$ storage (m/Pa)	8.1×10^{-9}	8.7×10^{-9}	8.5×10^{-9}	8.2×10^{-9}	8.0×10^{-9}
Distance to western impermeable boundary (km west of KY-1)	1.77	2.08	4.31	10.0	1.88
Distance to eastern impermeable boundary (km east of KY-1)	2.00	2.32	1.87	1.61	2.06
Distance to northern impermeable boundary (km north of KY-1)	1.19	1.55	0.95	1.07	1.61
Distance to southern constant pressure boundary (km south of KY-1)	9.43	6.87	10.1	No boundary	10.5

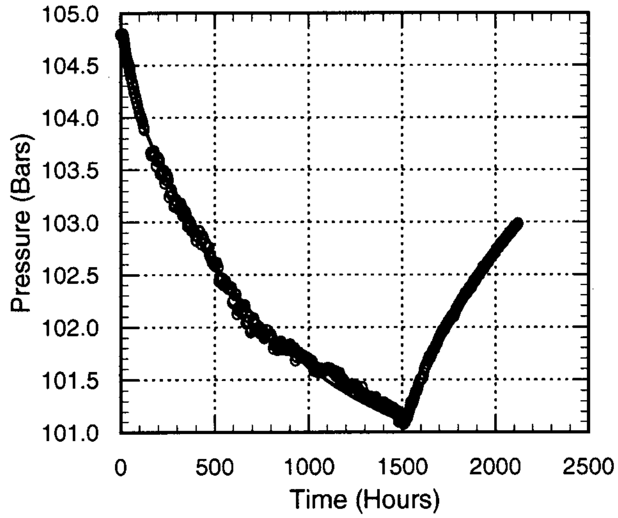

Figure 7. Comparison between measured (o) and computed (–) pressures in KY-1 during the 1986 test (case 1). "Effective discharge rate" history for S-4 is assumed to be identical (apart from a multiplicative factor of 0.6) to that used by Pritchett, *et al.* (1989). All times are in hours since 00:00 hours LT on September 2, 1986.

The formation parameters inferred for cases 2 through 5 are given in Table 4. With the exception of case 2, the computed pressures are in good agreement with measurements (see *e.g.*, Figure 8). The formation permeability-thickness and storage parameters do not differ significantly (an exception is *kh* value for case 4) from case-to-case. Unfortunately, the inferred distances to different boundaries vary significantly between the different cases. It is thus clear that the available data do not permit a unique interpretation of the measured pressure interference signal in KY-1. While the formation permeability thickness and storage are well constrained from both the 1986 and 1989 tests, the distances to the various boundaries (or even the presence of boundaries) are much less certain.

STRUCTURAL INTERPRETATION

The feedpoints of both S-4 and N60-KY-1 are located within a deep "altered andesite" layer. Above this layer lies a thick formation consisting of alternating marine sediments (black shales) and dacite volcanic flows; because of the presence of shales, it is likely that the average vertical permeability is rather low. Below the andesite layer, a crystalline granitic layer ("granodiorite" formation) is to be found. Sumikawa well SA-1 produces from the "granodiorite" layer. Since no

Table 5. Assumed "effetive discharge rate" history for well S-4 (1986 test) for cases 2, 3, 4, and 5. All times are in hours since 00:00 hours LT on September 2, 1986.

	Time Interval (Hours)	$\dot{M}_{eff}$ (kg/s)
Case 2	0.00 - 11.33	0.0
	11.333 - 1504.5	30.0
	1504.5 -	12.0
Case 3	0.00 - 11.333	0.0
	11.333 - 1504.5	30.0
	1504.5 - 1600.0	12.0
	1600.0 - 1700.0	6.0
	1700.0 - 1800.0	3.0
	1800.0 -	1.5
Case 4	0.00 - 11.333	0.0
	11.333 - 36.0	30.0
	36.0 - 276.0	25.2
	276.0 - 444.0	26.4
	444.0 - 588.0	27.6
	588.0 - 684.0	28.2
	684.0 - 1504.5	30.0
	1504.5 - 1600.0	12.0
	1600.0 - 1700.0	6.0
	1700.0 - 1800.0	3.0
	1800.0 -	1.5
Case 5	0.0 - 11.333	0.0
	11.333 - 36.0	30.0
	36.0 - 500.0	25.0
	500.0 - 1504.5	20.0
	1504.5 - 1600.0	2.0
	1600.0 - 1800.0	1.0
	1800.0 -	0.0

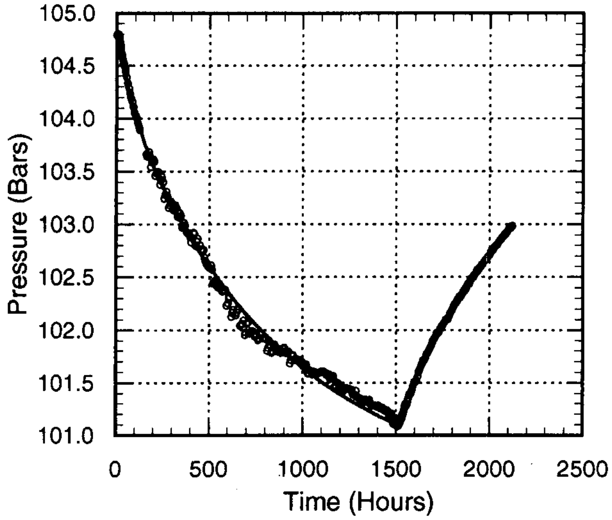

Figure 8. Comparison between measured (o) and computed (–) pressures in KY-1 during the 1986 test (case 3). "Effective discharge rate" history for S-4 (case 3) is given in Table 5. All times are in hours since 00:00 hours LT on September 2, 1986.

pressure interference has been observed between wells S-4, SA-1 and SC-1, it is likely that the "granodiorite" formation has poor vertical permeability.

The thickness of the andesite layer sandwiched between the "marine/volcanic complex" and the "granodiorite" formations is about 500 meters. Assuming that the andesite layer is permeable over its entire thickness, Pritchett, *et al.* (1989) estimated the east-west width of the permeable channel (in the "altered andesite" layer) to be about 1 km (see Figure 9). The "granodiorite" formation appears to rise abruptly ~ 0.7 km west of well S-4; this geologic discontinuity was assumed to constitute the western boundary of the permeable channel (Pritchett, *et al.*, 1989). Pritchett, *et al.* postulated that another north-south vertical barrier is present ~ 0.2 to 0.3 km east of well S-4 (Figure 9). Based on the results presented in this paper, it is suggested that the east-west extent of the permeable channel is considerably larger than 1 km and that no barrier separates Zones I and II in Figure 9. In the latter connection, we note that a tracer was injected into well SD-1 on June 17, 1991; within a couple of days, the tracer was recovered in well S-4. The latter result implies a permeable connection between wells S-4 and SD-1. The non-response of SD-1 during the 1986 test of S-4 must thus be ascribed to causes other than the lack of a permeable connection between the two wells. Perhaps the internal flow in SD-1 masked the pressure interference associated with the discharge of S-4.

The feedzones for wells SA-2, SA-4 and SB-1 (feedzone depth = 1600 m TVD) presumably lie in the permeable layer intercepted by KY-1 and S-4. In an effort to improve the productivity and injectivity of wells, MMC injected cold river water into wells S-4, SA-2, SA-4 and SB-1 in April and May 1989. As already noted, injection into well S-4 produced a pressure interference signal in KY-1. Injection into SB-1 also resulted in a pressure disturbance in KY-1. Unlike wells S-4 and SB-1, injection into wells SA-2 and SA-4 did not result in any discernible pressure response in KY-1. Two possibilities exist. It may be that the feedzones for SA-2 and SA-4 are somehow disconnected from the permeable channel intersected by S-4, SB-1, and KY-1. The more likely possibility is that two-phase conditions are prevalent at the feedzones for SA-2 and SA-4; injection into a two-phase zone will not produce a pressure disturbance in a distant borehole such as KY-1.

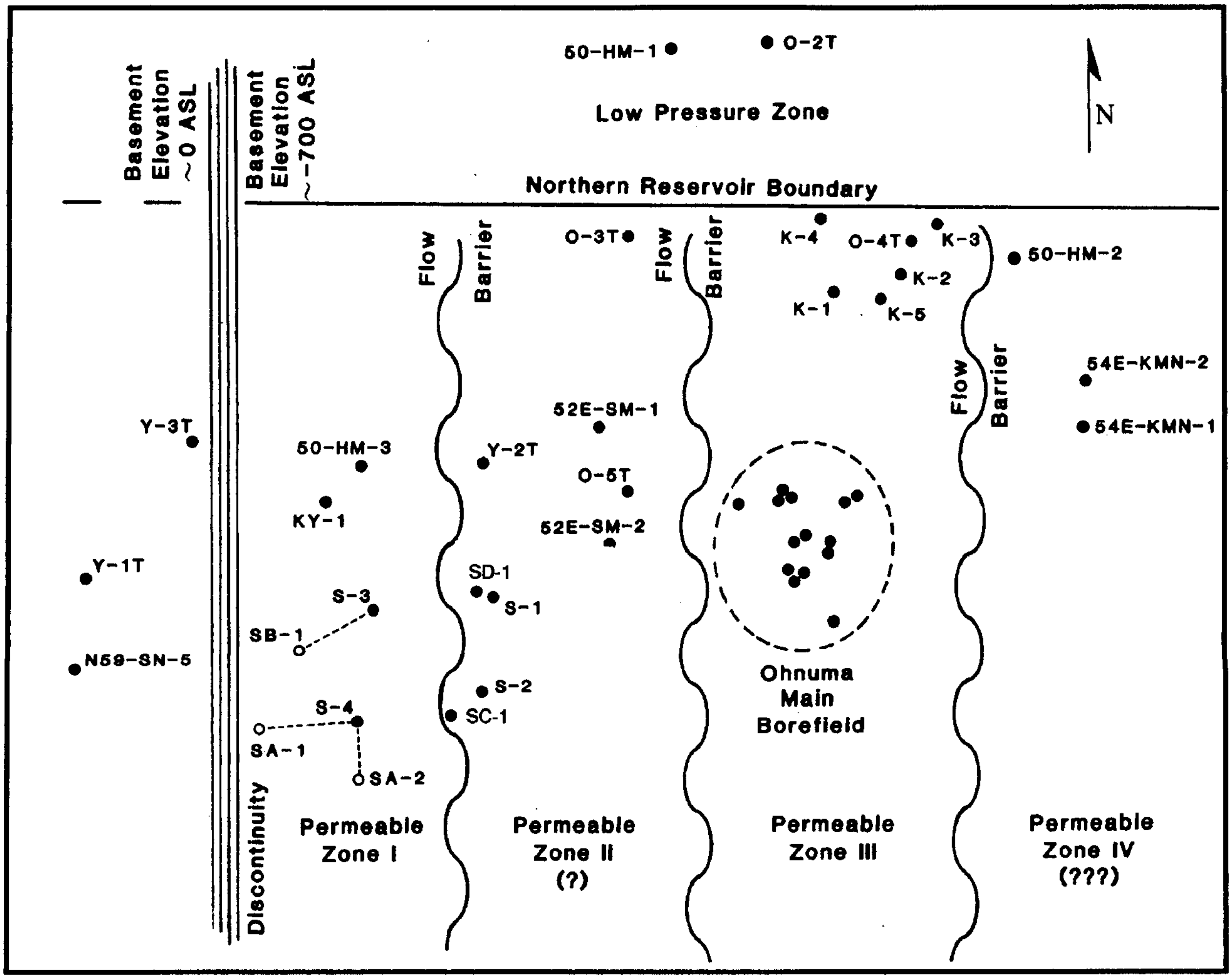

Figure 9. Estimated locations according to Pritchett, *et al.* (1989) of deep permeable channels in Sumikawa/Ohnuma area. Interpretations presented in this report suggest that there is no barrier between permeable zones I and II.

The presence of an impermeable boundary to the north of KY-1 is implied by the analyses shown in Table 4; this result is in accord with the earlier interpretation by Pritchett, *et al.* (1989). The distance to this northern boundary is of the order of 1 km north of slim hole KY-1. The northern boundary is probably associated with the dacitic dike along the Kumazawa river.

Analyses of 1986 test data (Table 4; Pritchett *et al.*, 1989), suggest the presence of a constant-pressure boundary to the south of well S-4. It is, however, unlikely that this boundary is located as far south (*i.e.*, 6 to 10 km south of well S-4) as that implied by the results given in Table 4. The explanation for this peculiar result is intrinsic in the linear character of the flow model. More specifically, it was assumed that the reservoir contains single-phase liquid. In reality, two-phase conditions prevail under undisturbed conditions a short distance (~ 1 km) south of well S-4. This suggests that the actual location of the constant pressure southern boundary is quite close to well S-4. Unfortunately, uncertainties in the "effective discharge rate" history for well S-4 (1986 test) preclude a precise determination of the distances to the various reservoir boundaries.

The high north-south permeability (*kh* > 10 darcy-m) inferred for the "altered andesite" formation would tend to explain the apparent uniformity of pressures at depth in the Sumikawa area, and also accounts for the extremely rapid response of KY-1 to the S-4 discharge/injection. Both S-4 and KY-1 were injection tested shortly after drilling and well completion. While these tests implied good injectivity for S-4, the apparent injectivity for KY-1 is very small (Garg *et al.*, 1994). If

KY-1 intersects a high permeability reservoir, then the cold water injectivity should be good. The slim hole (KY-1) was tested shortly after completion; it is possible that fractures were laden with drilling mud and cuttings at the time of the injection test. Drilling mud/cuttings reduce only the near well permeability (and hence borehole injectivity); far field permeability is not affected.

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