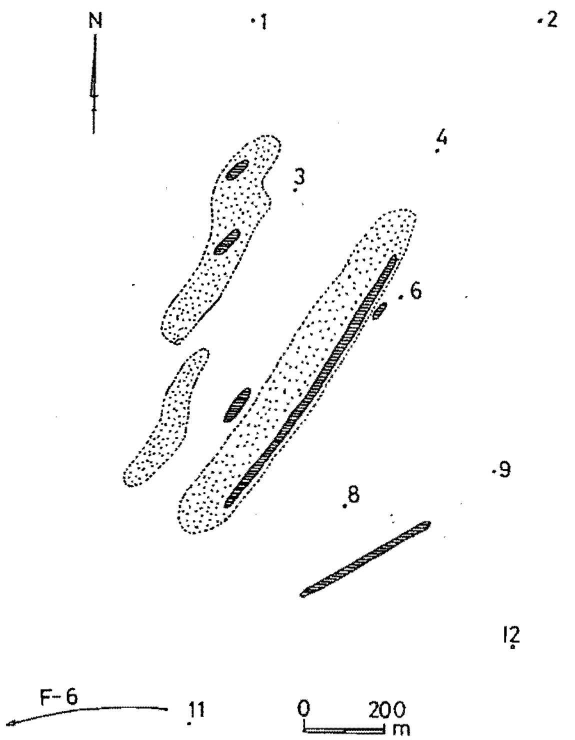

Fig.2 Map showing fracture extension integrated by Tomographic/VSP and reflection method in the Mori geothermal field.

Geophone was set in F-6 well. From 1 to 12 number is shear wave vibrator point.

Solid line means that the difference in S-wave velocity ranges from 0.10 to 0.15 km/s. Dots mean that the difference in S-wave velocity ranges 0.05 - 0.10 km/s.

Fractures are developed in the Pre-Tertiary formation having NW-SE direction.

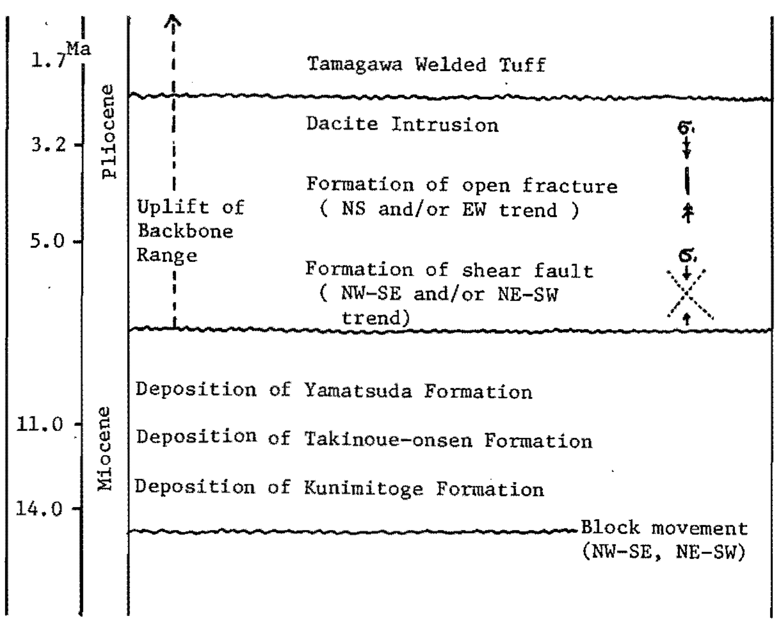

Fig.3 Geological development and history of tectonic movement of the Kakkonda Geothermal Field

INTERPRETATION OF A PRESSURE INTERFERENCE TEST OF THE SUMIKAWA GEOTHERMAL FIELD

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Introduction

In reservoir engineering, pressure interference testing is a fundamental tool for establishing reservoir connectivity and for computing interwell properties. An interference test consists of the discharge (and/or injection) of one or more wells, and the measurement of the resulting pressure disturbance in shutin observation wells. These pressure records reflect the spatially-integrated properties of the reservoir in the region between the discharging well and the observation well(s), and thus provide direct information regarding average reservoir properties on a large scale which are unobtainable by any other technique.

A large-scale reservoir interference test at Sumikawa was performed in the fall of 1986 by Mitsubishi Metal Company under NEDO's program ''Development of Geothermal Reservoir Evaluation Technology'' (Maeda, *et al.*, 1987). Well S-4 (see Figure 1 for well locations) was discharged starting at 11:20 local time on September 2, 1986 and was shutin at 16:30 hours on November 3, 1986; the liquid fraction of the discharge was simultaneously reinjected into Well S-2. Four observation wells (O-5T, S-3, N60-KY-1 and N60-KY-2) were equipped with capillary-tube type pressure gauges. No pressure measurements were made in either the production well (S-4) or the relatively shallow disposal well (S-2), however.

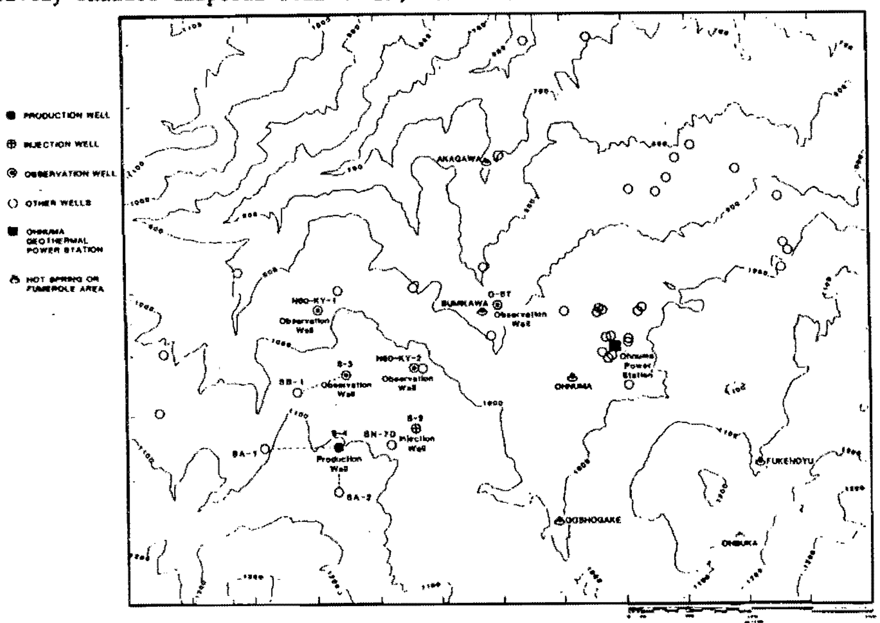

Figure 1. Locations of wells involved in 1986 Sumikawa interference test.

The pressure signals observed in wells O-5T, N60-KY-2 and S-3 cannot be attributed to the discharge of S-4. On the other hand, a clear response was recorded in Well N60-KY-1; the overall amplitude of the pressure deflection in Well N60-KY-1 exceeded three bars. It is likely that if a signal of comparable amplitude (i.e., 3 bars) had been present in the neighborhood of any of the other observation wells, such a signal should have been distinguishable from background interference. Although it is impossible to make definite quantitative statements concerning the coupling between Wells S-4 and S-2 (on the one hand) and Wells O-5T, KY-2 and S-3 (on the other), it seems reasonably clear that any such coupling must be at best fairly weak, at least in comparison with that observed between Well S-4 and Well N60-KY-1. The pressure response of Well N60-KY-1 is further discussed in the following sections.

Pressure History and Discharge Data

Well N60-KY-1 is cased and cemented to 1001 meters depth (-7 mASL); uncemented slotted liner is present from that point to 1604 meters depth (-610 mASL). Only two mud loss zones were encountered in the uncemented part of the hole: at -166 mASL and at -568 mASL. The deeper of these mud loss zones (-568 mASL) corresponds to the major feedpoint for this well. Short term injection test results indicated a relatively low permeability-thickness product

(~0.0035 darcy-meters) in the region immediately surrounding the well. The well, however, responded almost immediately (i.e., within a few hours) to fluid production from Well S-4. During the interference test, the pressures in Well N60-KY-1 were monitored using a capillary-tube type gauge located at -183 mASL. The measured pressure data were corrected for (1) a number of gaps in the pressure record (2) influence of an injection test (August 4-10, 1986) of Well N60-KY-1 and a prior long term (Fall 1985) discharge test of Well S-4, and (3) effect of changing temperatures in the depth interval between the gauge location (-183 mASL) and the major feedpoint for the well at -568 mASL. The final corrected pressure interference signal in Well KY-1 at -568 mASL is shown in Figure 2.

Well S-4 was drilled in 1983 to a total depth of 1552 meters (-445 mASL). The bottom of the 7-inch casing was set at 1071 meters, and an open hole completion was employed below this depth. The major feedpoint for Well S-4 is located at -413 mASL. The stable feedpoint pressure and temperature are ~95 bars and (295-300)°C respectively. Although no downhole pressure measurements in Well S-4 were made during the 1986 discharge test, it seems virtually certain 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 discharge. Well test pressure transient analysis is traditionally based on assumptions of single-phase isothermal flow. As discussed by Garg and Pritchett (1988), linear single-phase analysis techniques may be applied for interference test interpretation so long as the discharge rate history used in the analysis is suitably modified to reflect the influence of the two-phase zone in the vicinity of the production well. The effective discharge rate history for Well S-4 used in interference pressure analysis is given in the following table.

Time Interval	Effective Discharge Rate
prior 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

For the sake of simplicity, we will ignore the slight difference in elevation between the feedpoints of Well S-4 (-413 mASL) and Well N60-KY-1 (-566 mASL), and will treat Well KY-1 as if it were located directly north of Well S-4. Assuming that the coordinates of the S-4 feedpoint coincide with the origin ($x=y=z=0$), the coordinates of the feedpoint of Well KY-1 are ($x=0$, $y=1120$ meters, $z=0$).

Pressure-Interference Data Interpretation

Most traditional well-test interpretation techniques are based on the radial flow model. Assume that the aquifer tapped by Wells S-4 and KY-1 is of constant thickness H, and is characterized by the east-west permeability (k_x) and the north-south permeability (k_y). The vertical permeability k_z is infinite, or at least large enough that vertical variations in pressure disturbance are unimportant. The best fit to the pressure history at KY-1 feedpoint (see Figure 2) was obtained for the following values of the permeabilities:

k_y = 11 millidarcies

$H\,(k_x k_y)^{0.5}$ = 2.4 darcy-meters.

The deep andesite formation which contains the feedpoints of Wells S-4 and KY-1 is probably at least 500 meters thick, and may be thicker. If so, then the east-west permeability (k_x) is around an order of magnitude smaller than that in the north-south direction.

The overall fit of the radial flow model to data is reasonably good (Figure 2). At least two disturbing features are present, however. First, we note that the buildup portion of the response is not well reproduced, particularly for late buildup times. Second, we observe that the initial pressure decline upon initiation of S-4 discharge appears to occur later in the computed history than in the measured data set (see Figure 3). Because of these deficiencies of the radial flow model, a variety of other flow models (an unbounded point-source model; a point source model with a lower horizontal impermeable boundary; a point source model with an impermeable lower boundary and a constant pressure upper boundary; a point source model with impermeable upper and lower boundaries; an unbounded north-south channel model; a channel model with a southern boundary; and a channel model with northern and southern boundaries) were considered in hopes of finding a more appropriate representation. We shall herein describe only the final model (channel model with northern and southern boundaries).

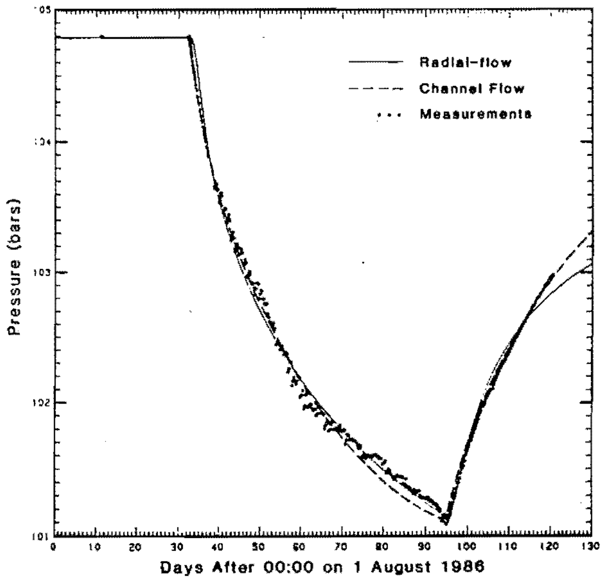

Figure 2. Comparison of computed interference pressure signal at Well KY-1 with measurements.

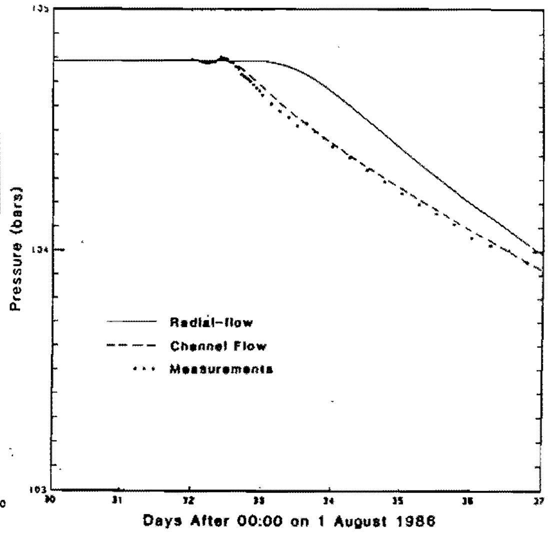

Figure 3. Early portion of KY-1 response computed by radial-flow and channel flow models compared with measurements.

The ''channel model'' considers a north-south (y) oriented horizontal permeable channel of constant cross-section. Within the cylindrical channel, rock properties are treated as homogeneous. The permeabilities in the cross-section plane (k_x, k_z) are large enough that the problem may be treated as one-dimensional. This model is characterized by four free parameters; the north-south permeability k_y, the cross-section A, the location of the southern constant-pressure boundary Δy_s and the location of the northern impermeable boundary Δy_n. The optimum fit was obtained with the following parameter values:

k_y = 195 millidarcies, A = 0.51 km^2
Δy_s = 9.86 km, Δy_n = 2.56 km.

The channel model correctly reproduces both the prompt early response to S-4 discharge, and the late time buildup portion of the pressure history (Figures 2 and 3).

Structural Interpretation

The feedpoints of both Wells S-4 and 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 is to be found. If the crystalline layer is assumed to be essentially impermeable, then the thickness of the permeable (andesite) layer, sandwiched between the marine/volcanic complex and the crystalline granitic basement, is about 0.5 to 0.6 kilometers. Since the cross-section area of the channel is ~0.51 km^2, it follows that the width (east-west) of the channel is about 1 km. It is noteworthy that, about 2 km farther to the east, a similar north-south permeable channel of ~1 km width (permeable zone 3 in Figure 4) was identified associated with the Ohnuma Geothermal Field based on stable shutin pressure evidence.

The granitic basement appears to dip abruptly ~0.7 km west of Well S-4; this geological discontinuity is an obvious candidate for the western boundary of the deep flow channel (permeable zone 1 in Figure 4). If this geometric interpretation is valid, the implication is that another north-south vertical barrier is present ~0.2 to 0.3 km east of Well S-4. Such a flow barrier would lie between Wells S-4, S-3, N60-KY-1 and 50-HM-3 (to the west) and Wells S-2, S-1, N60-KY-2 and Y-2T (to the east). The exact physical character of this north-south barrier is at present uncertain. It may be that the flow barrier is in fact a relatively narrow impermeable zone between two high permeability zones - one to the west and one to the east.

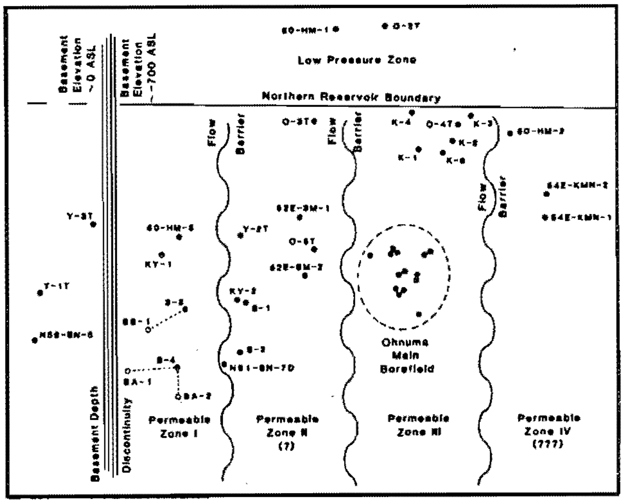

Figure 4. Estimated locations of deep permeable channels in Sumikawa/Ohnuma area.

An east-west reservoir boundary located north of wells O-3T and O-4T was identified based on static pressure evidence. The presence of this northern boundary is confirmed by the above interpretation of the signal observed in Well KY-1 from the S-4 discharge test. The exact numerical result was 1440 meters north of Well KY-1, but great precision is not claimed for this determination.

The channel flow model also suggests the presence of a constant-pressure boundary located some 9.86 km south of Well S-4. It seems implausible that the flow channel could extend so far south. The explanation for this peculiar result is intrinsic in the linear character of the flow model. In particular, it was assumed that the flow channel contains single-phase liquid. It is likely that two-phase conditions prevail in the flow channel a short distance (less than 1 km) south of Well S-4. This suggests that the actual position of the southern boundary is probably much closer to Well S-4 than the 9.86 km indicated by the single-phase treatment.

<u>References</u>

Garg, S. K. and J. W. Pritchett, ''Pressure Interference Data Analysis for Two-Phase (Water/Steam) Geothermal Reservoirs,'' *Water Resources Research, Vol. 24, pp. 843-852*, 1988.

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