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HYDROLOGY OF THE SUMIKAWA GEOTHERMAL PROSPECT, JAPAN

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INTRODUCTION

The Sumikawa geothermal field is located in the Hachimantai volcanic area in northern Honshu, Japan. Various investigations have been carried out in the area in recent years to assess the suitability of the field for electrical power production. This paper summarizes the principal characteristics of the natural fluid circulation system at Sumikawa and relates them to local geological structure. These features are deduced primarily from static (shut-in) pressure determinations in wells in the field and from a limited amount of pressure-transient testing. It is concluded that extensive natural two-phase flow prevails at intermediate depths at Sumikawa, and that a very high permeability zone is present below ~ 1 km depth containing fluids with temperatures exceeding 300°C. This zone is a suitable target for further study and possible future development.

GEOLOGICAL SETTING

Figure 1 shows the region of particular interest. The area depicted is about 28 square kilometers; the Sumikawa geothermal field lies in the western part of the area. To the east, the Ohnuma geothermal power station has been producing about 10 MW of electrical power for several years using a small borefield immediately surrounding the power station. The terrain is extremely irregular; Mt. Yake lies just to the southwest of the illustrated area and Mt. Hachimantai is just to the southeast. To the north of these volcanic peaks, the terrain drops away rapidly. Between the Sumikawa prospect (which may be regarded as centered in the neighborhood of the S-series wells: S-1, S-2, S-3 and S-4) and the Ohnuma borefield is a north-south region of relatively low ground surface elevation where natural hot-springs and fumaroles are found.

As discussed at length by Kubota (1985), the Sumikawa/Ohnuma area lies within a north-south oriented regional graben structure which extends many kilometers both north and south of the area shown in Figure 1. Indeed, the Sumikawa field itself appears to be located along the western edge of the graben. Figure 2 shows an east-west cross-section corresponding to line A-A′ in Figure 1. Figure 3 shows a similar north-south section (B-B′). These structural interpretations are based almost exclusively upon drilling experience – the only available seismic survey was far too regional in scope to be useful for local structural interpretation, and the results of a gravity survey are difficult to interpret owing to a lack of density contrast among the various deep formations in the area.

Extensive faulting has rendered the detailed geological structure at Sumikawa somewhat obscure, but the abundance of drilling logs from the various wells in the area has revealed an underlying geological sequence which applies to most of the area illustrated in Figure 1. In order of increasing depth, these are:

"ST" Formation:	Surficial andesitic tuffs, lavas and pyroclastics of Recent origin (from Mt. Yake).
"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 which are apparently extensively fractured.
"BA" Formation:	Crystalline intrusive rocks (mainly granodiorite and diorite).

As pointed out by Kubota (1988), the "BA" formation is the deepest so far encountered by drilling (well SN-7D bottomed in this formation at 2486 meters depth), but the pre-Tertiary basement which presumably underlies the above sequence has not yet been reached. Little

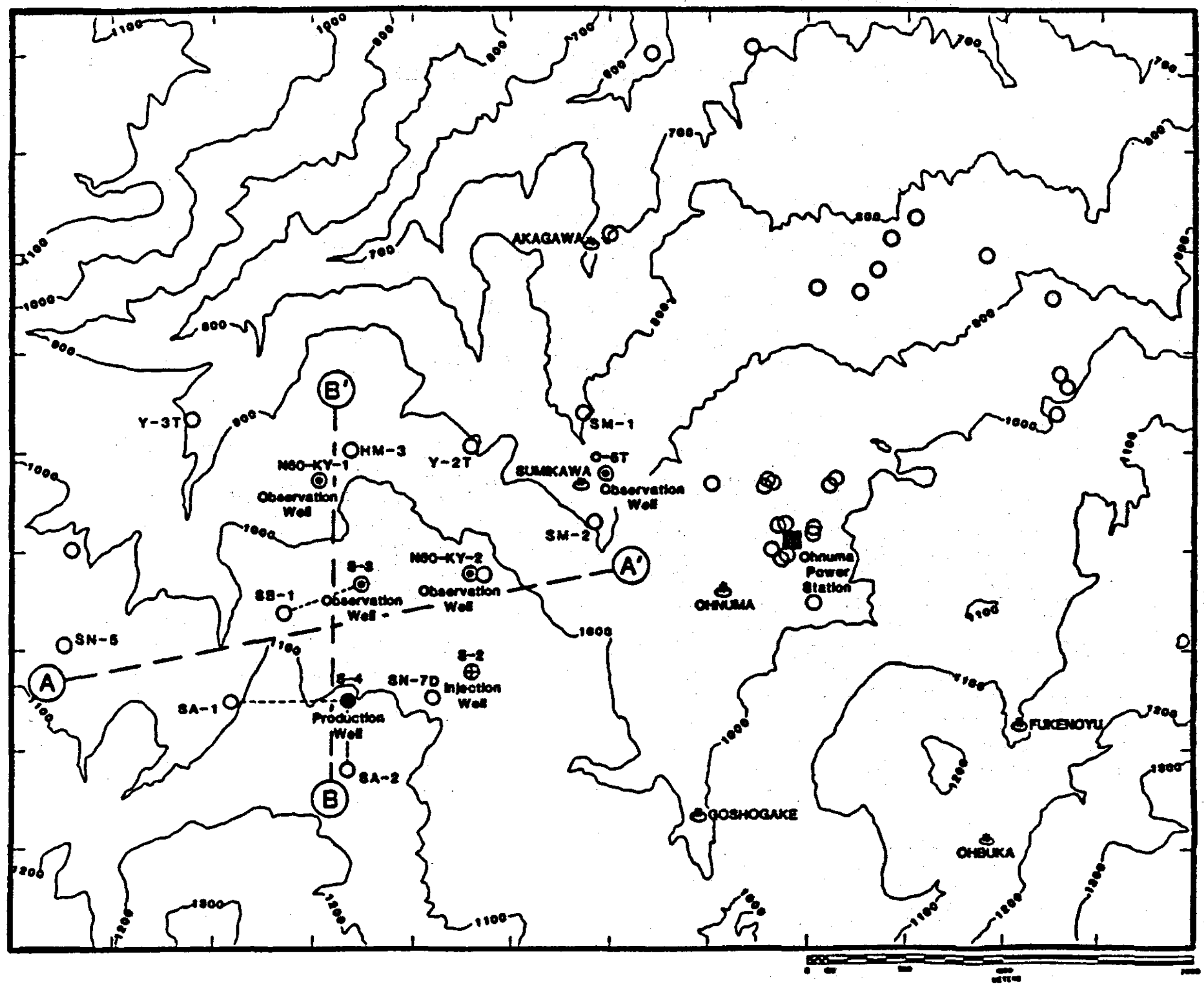

Figure 1. The Sumikawa/Ohnuma area, showing locations of wells, the Ohnuma power station, and cross-sections A-A′ and B-B′.

evidence exists for significant permeability deep within the "BA" formation, however, so that it may be permissible to regard this layer as the "basement" from a hydrological standpoint. Further investigation is clearly needed to reveal the structure of the deepest parts of the field.

UNDERGROUND TEMPERATURES

At Sumikawa, underground temperatures are highest to the south and decline to the north and northwest. Figure 4 shows the estimated temperatures at sea level (~ 700 - 1100 m depth) in the area, based mainly on temperature surveys in shut-in wells. The area depicted in Figure 4 is the same as in Figure 1. The highest temperature so far measured in the field is at the bottom of well SA-2 (317°C at 840 meters below sea level); this is also the southernmost deep well at Sumikawa.

Temperatures are significantly higher at Sumikawa (near the S-series wells) than at the nearby operating Ohnuma borefield. On the whole, temperatures appear to increase monotonically with depth; large-scale temperature inversions are not observed. Ishido, *et al.* (1987) report the results of a self-potential survey in the area which shows a major positive anomaly in the neighborhood of the S-series wells, which is indicative of the presence of upwelling deep hot water in this vicinity. On the other hand, the relatively low temperatures encountered to the north and west of the Sumikawa field are consistent with interpretations by Kubota (1988) and by Maki, *et al.* (1988a) that these are areas in which cold water is flowing downward into the reservoir. Observed surface manifestations of hot-water upflow (hot springs) are generally located along a north-south axis lying between Sumikawa and Ohnuma – additional hot spring areas are located farther north of the area illustrated in Figure 4 along the same axis.

STATIC PRESSURE DISTRIBUTION

Maki, *et al.* (1988b) have examined the various downhole feedpoint pressure determinations available from wells in the Sumikawa/Ohnuma area in detail. Evidence from a series of 32 shallow (80 meters) heat-flow holes drilled throughout the area (but not shown in Figure 1)

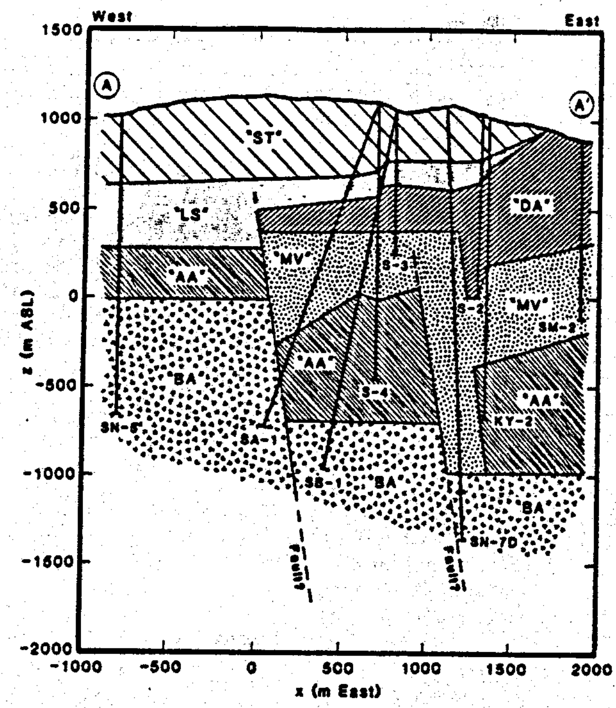

Figure 2. East-west A-A′ geological cross-section through the Sumikawa area.

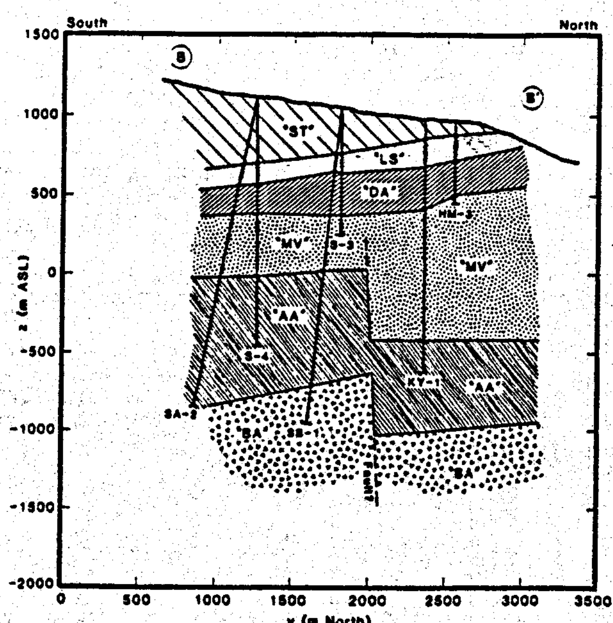

Figure 3. North-south B-B′ geological cross-section through the Sumikawa area.

indicates that near-surface pressures are cold-water hydrostatic relative to a water table depth which follows the local surface very closely; the water table is approximately 45 (± 21) meters below ground. At great depth, however, pressures are surprisingly uniform throughout the area; apart from a small region immediately adjacent to the Ohnuma power station, deep shut-in pressures may be correlated by:

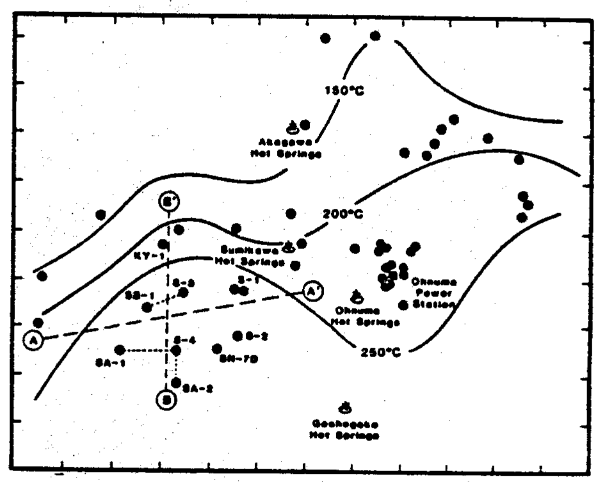

Figure 4. Temperatures at sea-level elevation in the Sumikawa/Ohnuma area (adapted from Kubota, 1988).

$$P \text{ (bars)} = 62 - 0.0776\ Z$$

where Z is elevation, measured in meters with respect to sea level (meters ASL). The standard deviation of this correlation from the measurements is only 1.4 bars (comparable to the reliability of the pressure determinations themselves). This pressure correlation was developed for wells in the southern part of the area (south of the 800 m ASL ground surface elevation contour).

This expression yields one atmosphere pressure at Z = + 786 meters ASL; it follows that in regions with lower ground surface elevation underground pressures must be lower than the above. Indeed, measured pressures in wells in the extreme northern part of the area are less than the above correlation, by an amount comparable to the difference in hydrostatic head between the local ground surface and + 786 m ASL. The clear implication is that a deep reservoir boundary must be present, oriented roughly east-west, at about the location of the 800 m ASL ground surface elevation contour (that is, passing approximately through the Akagawa hot spring area).

In graphical form, underground shut-in pressures at Sumikawa appear to be distributed with elevation as indicated in Figure 5, which is based exclusively on measured pressures in the area. So long as the ground surface elevation is above 800 m ASL, pressures below ~ 350 m ASL all lie on the same line. In areas of high ground surface elevation, however, a transition region characterized by pressures in the 25 to 30 bar range and pressure gradients which are significantly subhydrostatic is present, above which a shallow cold-water hydrostatic zone extends upwards to the ground surface. This transition zone corresponds spatially to the location of the "LS" formation (~ 600 m ASL), which appears to serve as a caprock. The

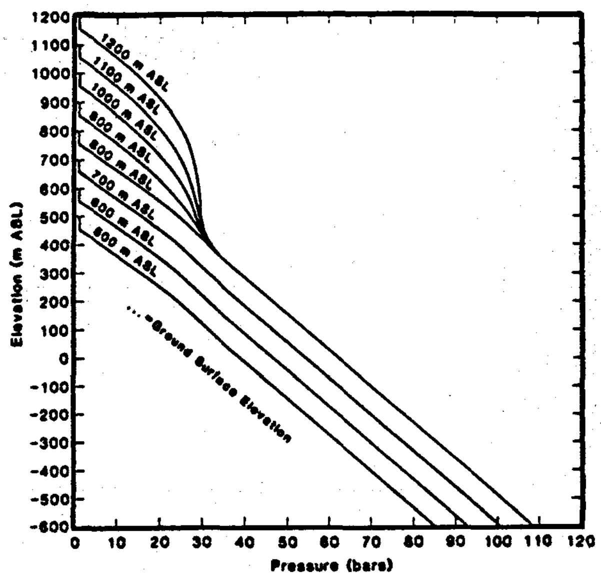

Figure 5. Static underground pressures in Sumikawa/Ohnuma area; influence of elevation and topography.

underlying subhydrostatic region is clearly associated with two-phase flow.

Below the "LS" caprock in the southern part of the system the two-phase (water-steam) flow zone extends at least as deep as + 350 m ASL. Note that the two-phase region could extend much deeper than this, since the presence of a hydrostatic gradient does not preclude two-phase behavior, but only indicates that liquid water is the dominant mobile phase. Closer to the caprock, however, the sub-hydrostatic gradient is indicative of high steam saturations. Confirmation is provided by drilling experience: well S-1 struck a permeable zone during drilling at ~ 450 meters depth (below the "LS" formation) which discharged dry steam. Since temperatures increase to the south toward Mt. Yake, it is likely that the depth reached by the two-phase zone increases to the south. North of the S-series wells, however, the two-phase zone apparently disappears, as evidenced by lower temperatures. It is noteworthy that the "LS" caprock formation peters out to the north and east of the S-series wells.

The substantial horizontal pressure gradients found in the "ST" formation above the lake sediments imply that the average permeability of these shallow volcanic rocks is relatively low. Furthermore, the permeability of the lake sediment ("LS") formation itself which separates the cold groundwater above from the hot two-phase zone below must be exceedingly low; a simple calculation shows that the vertical permeability of this layer must be a great deal less than 0.05 millidarcy. On the other hand, the remarkable homogeneity of the deep pressure distribution is indicative of substantial horizontal communication at depth in the area south of the 800 m ASL ground surface elevation contour. Laboratory tests have been carried out on cores from all the major formations; these indicate that the small-scale matrix permeabilities of these formations are all essentially zero, so that any large-scale permeability must be due to the presence of fractures.

PRESSURE-TRANSIENT RESULTS

In 1986, a large-scale pressure-interference experiment was carried out at Sumikawa. Deep well S-4 was discharged starting on September 2 and subsequently was shut in on 16:30 on November 3; the liquid fraction of the discharge was simultaneously reinjected into nearby shallow well S-2. Four shut-in observation wells (O-5T, S-3, KY-1 and KY-2) were equipped with downhole pressure gauges of the capillary-tube type (the flowing wells were not instrumented, however). No signals attributable to the S-4 discharge were recorded in O-5T, KY-2 or S-3, but a clear and immediate response was observed in deep well KY-1, located 1.1 km north of S-4. The principal feedpoints for wells KY-1 and S-4 both lie within the deep "AA" (altered andesite) formation, below the "black shale" marine/volcanic complex and above the granodiorite "BA" formation (see Figure 3).

Maki, *et al.* (1988c) have analyzed the pressure response of well KY-1 to the S-4 discharge. These studies all involved using the linear pressure-diffusivity equation; fluid properties assumed were those of water at 250°C, and measured rock porosities and compressibilities were employed. Figure 6 shows the measured response in KY-1 to the discharge/shutin of S-4. The first step in the analysis was to try to match the measured signal using the classical line-source technique. Optimizing the line-source ("radial flow") solution yielded, for the free parameters in the analysis:

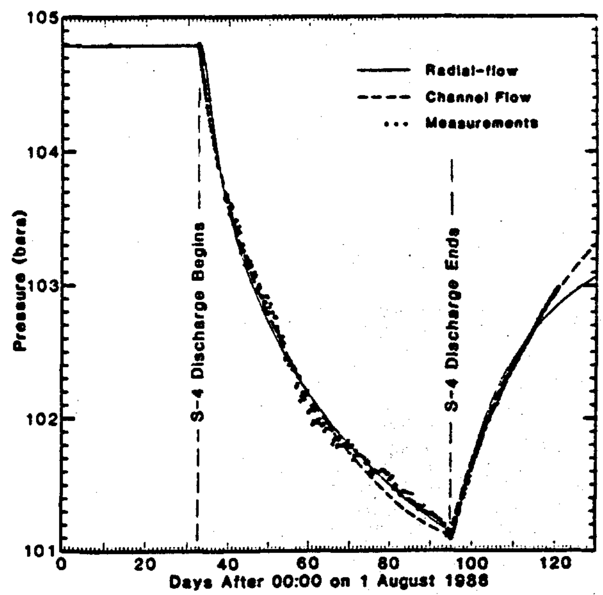

Figure 6. Pressure interference in well KY-1 due to discharge test of well S-4.

H (formation thickness)	= 220 meters
kH (permeability-thickness)	= 2.4 darcy-meters

providing a formation permeability of 11 millidarcies (presumably of the "AA" formation). The match of this solution to the measured response was superficially good (solid line in Figure 6), but it should be noted that the computed buildup response is in relatively poor agreement. An even more serious problem is illustrated in Figure 7 which shows only the first few days of the drawdown portion of the response on an expanded scale: clearly, the line-source radial-flow solution fails to explain the extremely rapid response to S-4 discharge observed in well KY-1.

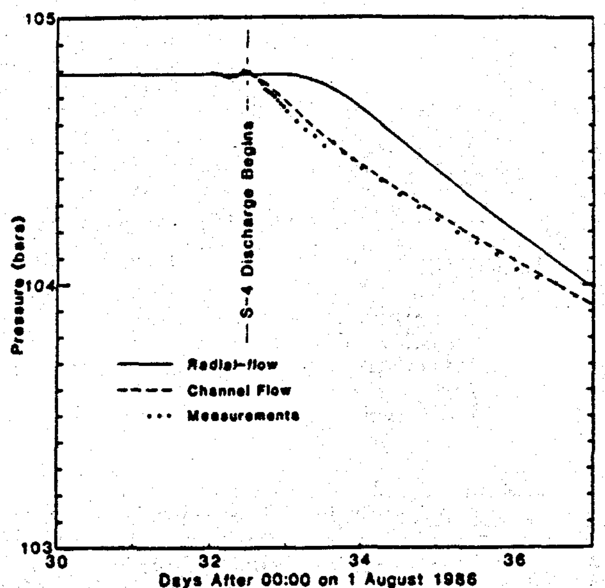

Figure 7. Early portion of response to S-4 discharge as measured in well KY-1.

Several other flow models were then employed in search of a better match with measurements – see Maki, *et al.* (1988c) for details. Finally, the following "channel-flow" representation was found. It was assumed that a permeable horizontal "channel" of constant cross-section area and constant permeability is present, oriented north-south, which contains the feedpoints of both wells (S-4 and KY-1). The east, west, upper and lower boundaries of the channel are impermeable. To the north, the channel terminates at an impermeable northern barrier; to the south, it ends at a constant-pressure boundary (representing the influence of a two-phase region). The free parameters in the model are (1) the channel cross-section area, (2) the channel permeability, (3) the distance to the northern (impermeable) boundary, and (4) the distance to the southern (constant-pressure) boundary. Minimization of the deviations between measurements and computed pressures yielded:

Cross-section	= 0.51 square kilometers
Permeability	= 195 millidarcies
Impermeable boundary position:	1.44 km north of well KY-1
Constant-pressure boundary position:	9.86 km south of S-4

Results from this model are shown in Figures 6 and 7 as the broken lines. The fit is essentially exact, in view of the noise level in the measured signal. The above parameter values, moreover, are supported by independently-obtained information. In particular, the above model suggests the presence of a reservoir boundary about 1.4 km north of well KY-1. This essentially corresponds to the location of the 800 m ASL ground elevation contour which appears to represent a reservoir boundary based on static pressure evidence (see above). Figure 3 shows a longitudinal (north-south) section through the channel, which presumably consists of the altered andesite ("AA") formation. Evidently, the "MV" black-shale layer above and the "BA" granodiorites below serve as aquitards. In the neighborhood of well S-4, the channel appears to have a vertical thickness of about 0.7 – 0.8 km, but thins somewhat to the north.

Figure 2 also shows the lateral channel boundaries. To the west, the channel is bounded by "BA" granodiorite owing to the presence of a fault (downthrown to the east) associated with the graben boundary. To the east, the boundary consists of "MV" black shale, as evidenced by drilling logs from well SN-7D. Indeed, the cross-section area of the "AA" body containing well S-4 appears to be approximately 0.5 square kilometers, in good agreement with the value obtained from the model. The only troubling implication of the model is that the southern constant-pressure boundary is located almost 10 km south of well S-4. It is very unlikely that the channel extends this far. Recall, however, that the analysis employed assumed linear single-phase fluid behavior in the channel. In reality, as noted above, it is likely that a two-phase mixture is present at depth to the south of well S-4. The resulting increase in compressibility would slow the transmission of pressure signals to the south. Approximate calculations indicate that, under these circumstances, the probable true position of the southern constant-pressure boundary (corresponding to a channel full of two-phase fluid) is only a few hundred meters south of well S-4.

The very high north-south permeability inferred for the "AA" formation (200 millidarcies) would tend to explain the apparent uniformity of pressures at depth in the Sumikawa area, and also accounts for the extremely rapid response of well KY-1 to the S-4 discharge. One proposed hypothesis is that the permeable zone really consists of a single north-south fracture which is intersected by both wells. This is unlikely, however, for two reasons. First, it is difficult to understand how the large fluid storage capacity implied by an effective channel cross section of 0.5 km^2 could be provided by a single fracture.

Furthermore, both wells were subjected to short-term cold-water injection testing after drilling. While these tests implied good permeability for well S-4, the apparent permeability for KY-1 is very low. If KY-1 intersects a large fracture (responsible for the observed pressure response), the cold-water injectivity should be good.

We believe that a different interpretation is more likely. The observed high regional permeability is probably due to a series of large parallel north-south fractures in the "AA" formation. Superimposed upon this major fracture network is a second fracture network consisting of a very large number of relatively low-permeability minor fractures which are oriented in a more or less isotropic fashion. The major fractures serve to transmit pressure signals over long distances, but the minor fractures provide pressure communication among the major fractures and between the major fractures and the wells. Evidently, while well S-4 is well-connected to the major fracture network, the coupling with KY-1 is poor – sufficient to transmit pressure signals quickly from a nearby major fracture, but insufficient to permit high fluid injection rates. Kubota (1988) notes that numerous regions of lost-circulation were encountered while drilling the southern (S-series) wells, but that farther north (where temperatures are lower) the fractures frequently appear to be sealed with vein materials. Such self-sealing would presumably act mainly to inhibit flow in the minor fracture network, and may be responsible for the poor injectivity of well KY-1.

CONCLUSIONS

The Sumikawa field is a very promising prospect for future development for electrical power generation. Consideration is now being given to the construction of a power station of ~ 50 MW capacity. In view of the large deep volume within the "AA" formation characterized by both high permeabilities and high temperatures, such a development would appear to be well within the capacity of the reservoir. Additional exploration and testing is currently being carried out at Sumikawa to further delineate the characteristics and capacity of the reservoir.

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