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USE OF SLIM HOLES FOR GEOTHERMAL EXPLORATION AND RESERVOIR ASSESSMENT: A PRELIMINARY REPORT ON JAPANESE EXPERIENCE

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ABSTRACT

The publicly available Japanese data on the use of slim holes in geothermal exploration and reservoir assessment are reviewed in this report. Slim holes have been used for (1) obtaining core for geological studies, (2) delineating the stratigraphic structure, (3) characterizing reservoir fluid state (pressure, temperature, *etc.*), and (4) defining the permeability structure for reservoir assessment. Examples of these uses of slim hole data are presented from the Hohi Geothermal Area and the Sumikawa Geothermal Field. Discharge data from slim holes and production wells from the Oguni Geothermal Field indicate that it may be possible to infer the discharge rate of production wells based on slim hole measurements.

1. INTRODUCTION

The principal cost associated with the identification, assessment, and development of geothermal reservoirs for electrical power production is the high cost of drilling the exploration, production, and injection wells. A major impediment to the exploration of new geothermal areas is the high cost of conventional rotary drilling. A conventional 1200 to 1800 m deep rotary-drilled well can cost millions of dollars. Compared to conventional large-diameter wells, the drilling costs for small-diameter (less than 10 cm) slim holes are relatively low. Because of this cost differential, it would be desirable to use slim holes for geothermal exploration and reservoir assessment. At present, there exists little experience in the U. S. geothermal industry in the use of slim holes for exploration and reservoir assessment purposes. Combs and Dunn (1992) have argued the need for a U. S. Department of Energy (DOE)-industry coupled slim hole research and development program.

In contrast to the situation in the United States (*i.e.*, lack of sufficient experience with slim holes in geothermal exploration), the Japanese routinely employ small-diameter core holes in geothermal exploration and reservoir assessment. Besides obtaining core for geological studies, slim holes have been used for characterizing reservoir fluid state and reservoir permeability structure. Most of the Japanese data pertaining to slim holes are proprietary. Sufficient published data are, however, available to produce a preliminary report on Japanese experience, and to provide some tentative conclusions about using slim holes to predict production capability of large-diameter wells.

The publicly-available Japanese data on the use of slim holes in geothermal exploration and reservoir assessment are reviewed in Section 2. It is often difficult to induce deep small-diameter holes (depths >> 300 m) to discharge. A parallel theoretical study discussing the effect of well-diameter on the production behavior of geothermal boreholes is presented elsewhere (Pritchett, 1992); important conclusions of that study are summarized in Section 3. Prediction of the production characteristics of large-diameter wells on the basis of tests performed in small-diameter core holes is also discussed in Section 3.

2. REVIEW OF PUBLISHED JAPANESE SLIM HOLE DATA

The first commerical scale geothermal power station in Japan (Matsukawa Geothermal Power Plant) was commissioned in 1966. As of March 1991, the total installed capacity stood at ~ 270 MW. Additional geothermal power plants are under development at several sites in the Tohoku and Kyushu districts (see Figure 1).

Since the first oil crisis in 1974, the Japanese government (primarily through the Geological Survey of Japan, Agency of Industrial Science and Technology, New Energy and Industrial Technology Development Organization (NEDO)) has actively promoted the exploration and development of geothermal resources (see JGEA, 1992). As discussed by Maki and Kawano (1988), NEDO has been carrying out government subsidized geothermal surveys throughout Japan since 1980. Under its "Geothermal Development Promotion Survey" program, NEDO drilled 189 wells. The report by Maki and Kawano (1988) presents a statistical analysis of penetration rates for 47 HQ (98 to 101 mm) and NQ (76 to 78 mm) core holes drilled during Japanese fiscal years 1984–1986. Most of the boreholes drilled by NEDO have been injection tested; in addition, a small number (5 to 10 percent) of boreholes have been discharged (Kawano, personal communication, 1992).

In addition to core holes drilled by NEDO and other governmental agencies, a large number of core holes have been drilled by private developers. Unfortunately, because

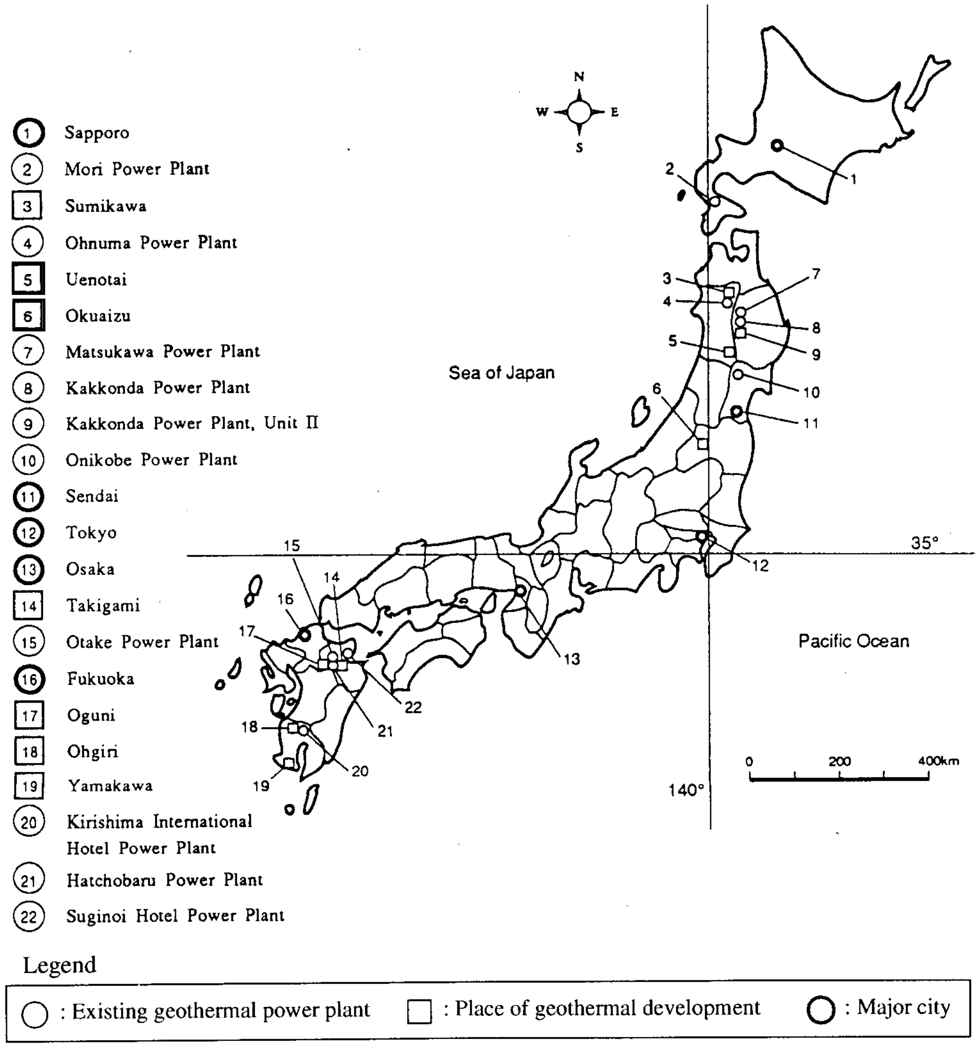

Figure 1. Geothermal power plants and places of geothermal development in Japan (from JGEA, 1992).

of proprietary and other (*e.g.*, language) reasons, most of the data obtained from these core holes are not easily accessible. In the following paragraphs, we briefly describe the publicly available reports on the use of core holes for reservoir assessment purposes.

2.1 HOHI GEOTHERMAL AREA

During the years 1978–1985, the Ministry of International Trade and Industry conducted a regional exploration survey in the Hohi area, Kyushu, Japan (NEDO, 1987). The main area of the survey encompassed 200 km^2 centered on Mt. Waita. As part of this exploration program, both small-diameter core holes ("DB" and "DW" series) and large-diameter production-size wells ("DY" series) were drilled. All of the "DB", "DW", and "DY" series boreholes were injection tested. Since no downhole pressure measurements were made during these injection tests, the injection test data are not useful for inferring formation properties for reservoir assessment purposes. None of the small-diameter "DB" and "DW" series slim holes were discharged; of the "DY" series wells, only two wells (DY-1 and DY-5) could sustain discharge. Murakami, *et al.* (1986) discuss the discharge characteristics of well DY-1. The well was continuously discharged for a six-month period in 1982 at discharge rates between 16 kg/s and 60 kg/s.

Pritchett, *et al.* (1985) present a preliminary reservoir engineering study of the western portion of the Hohi area (see Figure 2). Although the southeastern part of the study area contains the Hatchobaru and Ohtake geothermal fields, no data from these fields were made available for Pritchett, *et al.'s* (1985) study. Available downhole data consisted of (1) drilling data (circulation loss data, well completion information, and geologic data), and (2) repeat temperature and water level surveys. No downhole pressure measurements were taken; feedpoint pressures were estimated from temperature and water level data. Production data (mainly water and steam flow rates, and wellhead pressure) were available from only one well (*i.e.*, DY-1). Core-hole data were invaluable for defining (1) the stratigraphic sequence, and (2) reservoir temperature and pressure

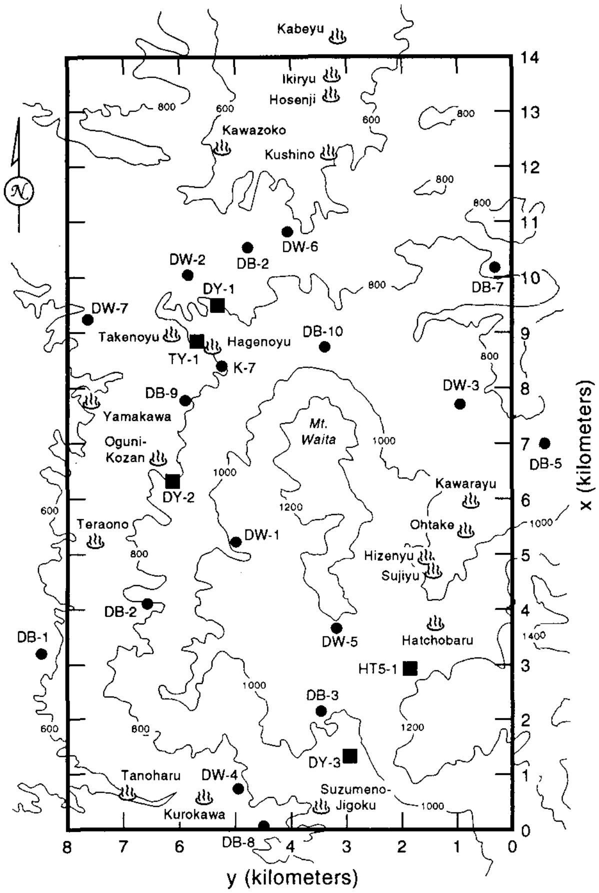

Figure 2. Outline of western Hohi study area showing boreholes, hot springs and surface elevation contours (m ASL) (from Pritchett, *et al.*, 1985). Slim holes are indicated by ● and production wells are represented by ■.

distribution (see Figures 3–5). It can be seen from Figures 3 and 4 that a very large volume of hot reservoir rock is present in the northwestern part of the study area. The feedzone pressures for seven boreholes (five slim holes DB-4, DW-2, K-7, DW-6, and DW-7; and two large-diameter production wells TY-1 and DY-1) in the northwestern area all lie on a straight line (Figure 5); this straight line comprises a lower bound on all the data. Apparently, the northern reservoir forms a separate hydrological entity. The circulation loss data from the northern wells indicated that most of the permeability in the northern reservoir is associated with a horizontal fracture zone in the upper part of pre-Kusu formation near sea-level elevation. Using the reservoir pressure distribution derived essentially from the slim-hole data and the hot spring flow data, Pritchett, *et al.* (1985) estimated a permeability-thickness product of 40 darcy-meters for the northern reservoir.

Since the completion of the above mentioned regional survey of the Hohi area, EPDC and NEDO have carried out additional drilling and well testing programs in the northern Hohi area (Oguni and Sugawara geothermal fields). These new data from production wells have in the main confirmed

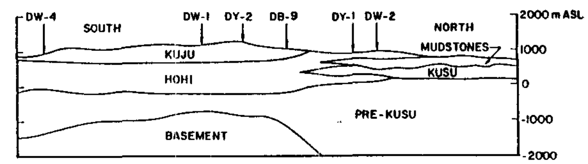

Figure 3. Stratigraphic sequence at Hohi (from Pritchett, *et al.*, 1985).

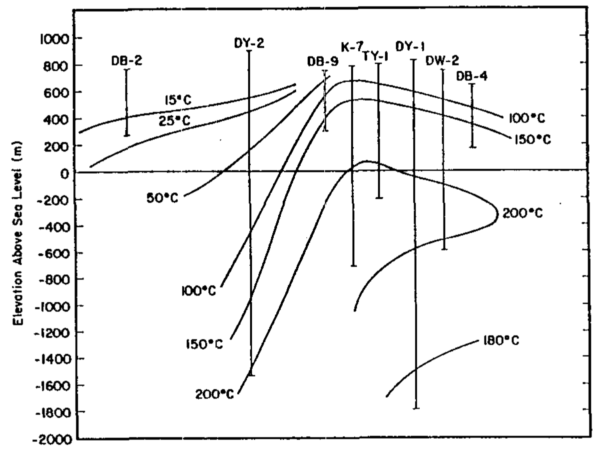

Figure 4. Vertical temperature distribution at Hohi along a line extending from borehole DB-2 to borehole DB-4 (from Pritchett, *et al.*, 1985).

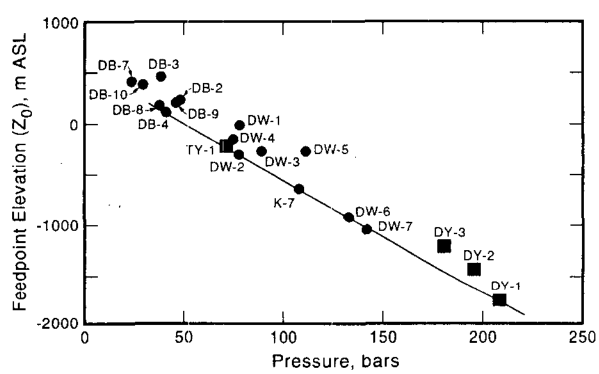

Figure 5. Pressure as a function of elevation for all boreholes in the western Hohi area (from Pritchett, *et al.*, 1985). Slim holes are indicated by ● and production wells are represented by ■.

the conceptual model of Pritchett, *et al.* (1985) for the northwestern Hohi area (surface area ~ 40 km^2; Figure 2) based primarily on the data obtained from slim holes.

It is worthwhile to recall here that Pritchett, *et al.*'s model for the northern Hohi area was based almost entirely on data from (1) seven boreholes (DB-4, TY-1, DW-2, K-7, DW-6, DW-7 and DY-1) of which five were slim holes and (2) surface geological and geophysical surveys (including hot spring discharge rates and temperatures). Of the seven boreholes, five (DB-4, DW-2, DW-6, DW-7 and DY-1) were drilled under the NEDO program; the remaining two wells (TY-1 and K-7) were drilled by local authorities. As already mentioned, production data were available for only one well (DY-1). The modeling experience for the northern Hohi area indicates that a minimum amount of borehole data (water level and temperature data, stratigraphy and circulation loss data from drilling surveys, discharge data from 1 hole) along with surface surveys (*i.e.*, hot spring data, gravity survey) can be used to derive a preliminary estimate of the power potential of a geothermal area. It should be stressed here that while the amount and type of data required for reservoir assessment will vary from case to case, small-diameter core holes can be used to obtain many of the data (*e.g.*, reservoir pressure and temperature estimates, stratigraphy, *etc.*) needed in reservoir engineering studies.

2.2 SUMIKAWA GEOTHERMAL FIELD

Because of their limited capacity, small-diameter core holes are often unsuitable as production or injection wells in a pressure interference test. The amplitude of the pressure signal generated by production from or injection into a core hole is often too weak to be monitored in neighboring wells. On the other hand, small-diameter core holes can be used as monitoring wells. Garg, *et al.* (1991) present a discussion of the pressure-interference testing of the Sumikawa geothermal wells.

The Sumikawa Geothermal Field is located in the Hachimantai volcanic area in northern Honshu, Japan. The region of particular interest is shown in Figure 6. The Sumikawa Geothermal Field lies in the western part (area around boreholes S-1, S-2, S-3 and S-4) of the region depicted in Figure 6. To the east, the Ohnuma power station has been producing about 10 MW of electrical power for several years. The subsurface stratigraphic structure in the Sumikawa area is shown in Figure 7. This is based almost exclusively on drilling experience. The major formations in order of increasing depth are (1) surficial andesite tuffs, lavas and pyroclastics (ST formation), (2) lake sediments (LS

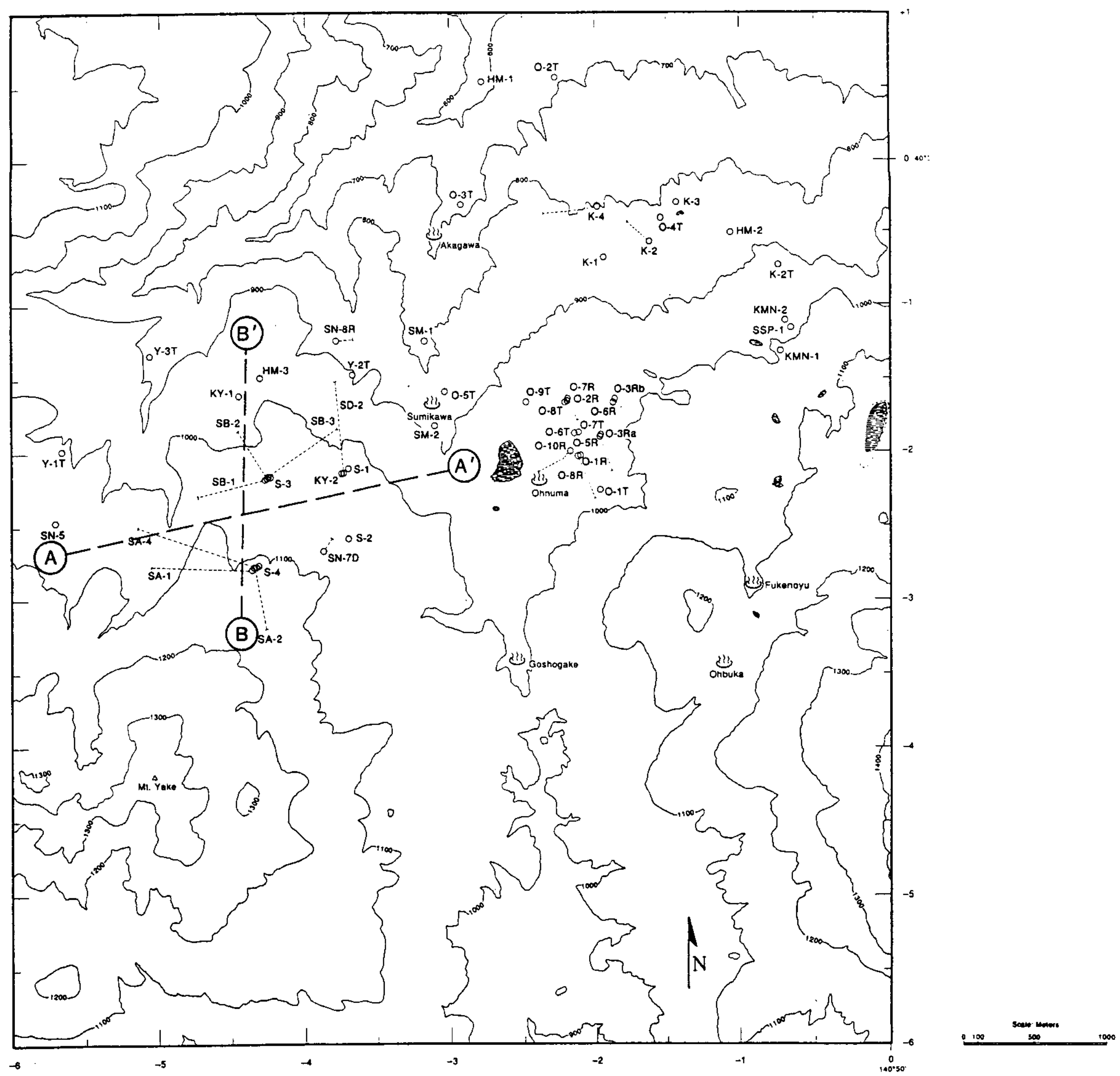

Figure 6. The Sumikawa/Ohnuma area, showing locations of boreholes and cross-sections A–A′ and B–B′ (from Garg, *et al.*, 1991).

formation), (3) Pliocene dacites and tuffs (DA formation), (4) interbedded Miocene dacitic volcanic rocks and black shale (MV or marine/volcanic complex), (5) altered and fractured andesites (AA formation) and (6) crystalline intrusive rocks (GR formation).

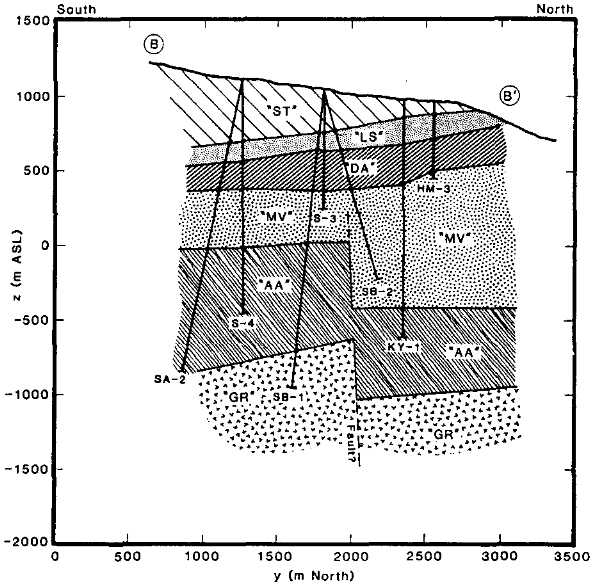

Figure 7. North-south geological cross-section B–B′ through the Sumikawa area (from Garg, *et al.*, 1991).

In April and May 1989, cold water was injected into several wells (SA-1, SA-2, SA-4, S-4, SB-1, SB-2 and SB-3). Slim hole KY-1 responded to injection into wells S-4, SB-1 and SB-2 (see *e.g.*, Figure 8). Apparently, wells S-4 and SB-1 communicate with slim hole KY-1 through the altered andesite layer (AA formation); well SB-2 is connected to slim hole KY-1 through an interbedded dacite layer in the marine/volcanic complex formation.

Pressure response of slim hole KY-1 to production (injection) from well S-4 was interpreted by Garg, *et al.* (1991) to indicate the presence of a very high permeability channel in the altered andesite layer (main production zone at Sumikawa). Pressure interference between slim hole KY-1 and well SB-2 was used to confirm the presence of a moderately high transmissivity layer in the "marine-volcanic complex" formation (main injection zone at Sumikawa). The experience at Sumikawa (as well as several other fields in Japan) has clearly shown that the small diameters of core holes pose no limitations on their use as pressure monitoring wells.

2.3 OGUNI GEOTHERMAL FIELD

In at least some cases, small-diameter core holes have been discharged (1) to collect fluid samples, and (2) to obtain first indications of the productivity of a geothermal formation. Abe, *et al.* (1992) gives tabular values for water and steam flow rates from both the small-diameter core holes and large-diameter production wells in the Oguni Geothermal Field

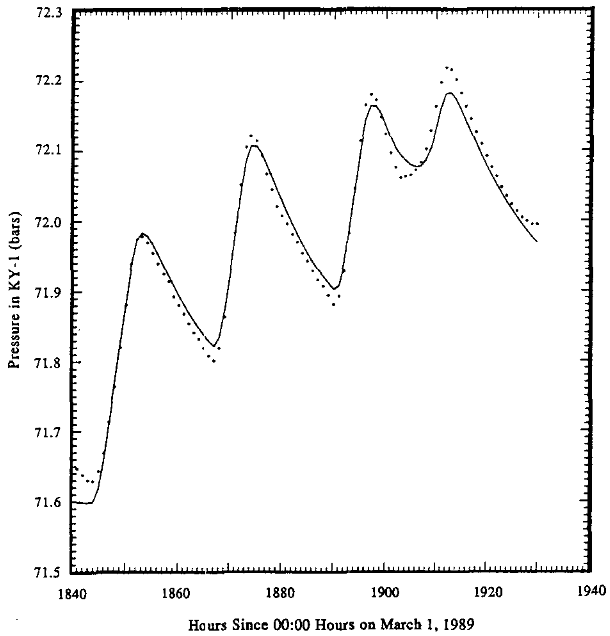

Figure 8. Comparison of computed pressure response of small-diameter core hole KY-1 at Sumikawa with measurements due to cold water injection into well S-4 (—computed, • measurements) (from Garg, *et al.*, 1991).

(the Oguni Geothermal Field forms a part of the northern Hohi area). According to Abe *et al.* (1992), several HQ and NQ size core holes have been successfully discharged (see Table 1). Of course, the production rate of the small-diameter core holes is a small fraction of the large-diameter production-size wells. Ideally, one would like to predict the productivity of large-diameter production wells based on results of injection into or production from small-diameter core holes. The question of the scale-up of production/injection data from core holes to forecast the production behavior of large-diameter wells is considered in Section 3.

3. EFFECT OF BOREHOLE DIAMETER ON PRODUCTION CHARACTERISTICS

Production characteristics of a geothermal borehole are in the main determined by (1) pipe friction and heat losses in the wellbore, and by (2) pressure losses associated with flow in the reservoir rocks. Ignoring pressure transient effects, the flow resistance (or pressure losses) of the reservoir rocks can be represented by the productivity (or injectivity) index. The productivity indices of slim holes and production wells are discussed in Section 3.2.

Pritchett (1992) has carried out a theoretical study of the discharge characteristics of slim holes compared to production wells. To compare the fluid carrying capacity of a borehole as a function of diameter (d), it is convenient to define the "area-scaled well discharge rate" M^* as follows:

$$M^* = M \times \left(\frac{d}{d_o} \right)^2 \qquad (1)$$

Table 1. Diameter, depth, maximum temperature, and production rate for small-diameter core holes and large-diameter production wells in the Oguni area (from Abe, *et al.*, 1992).

Well Name	Final Stage Well Dia. mm	Drilling depth m	Max temp. °C	Steam flow rate t/hr	Hot water flow rate t/hr	Completion year	Note
HH-1	76	700	206	-	-	1984	
HH-2	76	1,000	231	3	2	1984	
HH-3	76	500	210	-	-	1984	
GH-1	76	1,950	175	-	-	1983	
GH-2	76	1,800	155	-	-	1984	
GH-3	76	1,500	223	5	15	1985	
GH-4	76	1,000	239	6	18	1985	
GH-5	76	1,500	235	2	17	1985	directional
GH-6	76	1,000	222	8	28	1985	
GH-7	98	1,544	230	6	20	1985	directional
GH-8	78	1,300	223	7	28	1986	directional
GH-9	81	1,600	243	-	-	1986	directional
GH-10	159	1,063	239	49	119	1986	directional
GH-11	216	1,381	235	45	166	1987	directional
GH-12	216	1,100	230	45	152	1988	directional
GH-13	159	900	181	—	—	1987	directional
GH-14	216	650	225	65	238	1989	directional
GH-15	216	1,190	232	9	28	1990	directional
GH-20	216	1,790	248	82	287	1990	directional

where M is the actual borehole discharge and d_o is the internal borehole diameter (cm). Assuming that (1) the boreholes feed from an all liquid-zone, and (2) the feedzone pressure and temperature are independent of borehole diameter, calculations were carried out for a variety of borehole diameters varying between 5 cm and 35 cm; the results of these calculations are displayed in Figure 9. The wellhead pressure/flowrate relationships for the various borehole diameters do not collapse to a single curve (Figure 9), even when flow rates are adjusted to account for differences in cross-sectional area. Clearly, the area-scaled maximum discharge rate declines with a decrease in borehole diameter. As discussed by Pritchett (1992), both frictional pressure gradient and heat loss effects are more significant for the smaller-diameter slim holes than for the larger-diameter wells. The difference in heat loss effects is probably responsible, at least in some cases, for the difficulty encountered in inducing deep slim holes (depths >> 300 m) to discharge. Theoretical results suggest that to induce deep slim holes to discharge, it may be necessary to employ unusual techniques such as preheating the borehole prior to startup.

For the conditions (feedzone depth = 1500 m, flowing feedzone pressure = 80 bars, feedzone temperature = 250°C, uniform diameter wellbore) considered by Pritchett (1992), the maximum discharge rate (*i.e.*, flow rate at 1 bar wellhead pressure) scales with borehole diameter according to the following relation:

$$M_{\max} = M_o \left(d/d_o\right)^{2.56} \qquad (2)$$

where M_o denotes the maximum discharge rate for a borehole of diameter d_o. Equation (2) implies that the "area scaled" maximum attainable flow rate increases approximately with the square root of borehole diameter.

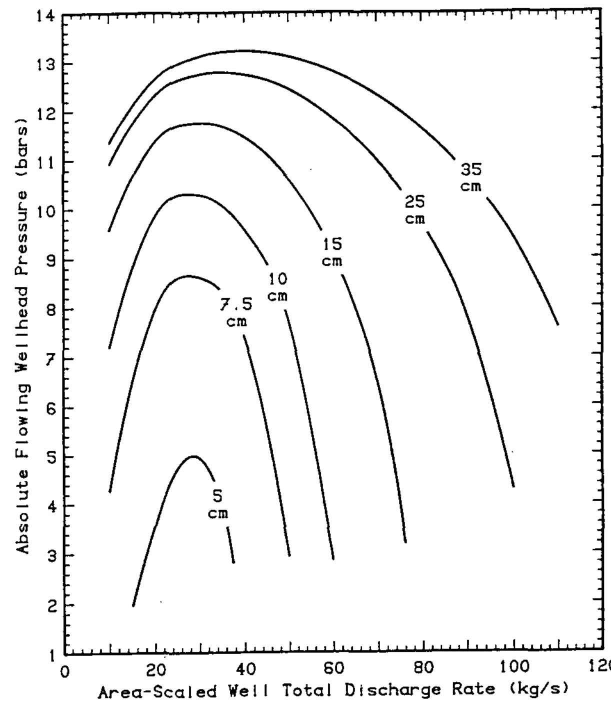

Figure 9. Influence of diameter on borehole performance characteristics (from Pritchett, 1992).

3.1 PREDICTION OF DISCHARGE RATE OF PRODUCTION WELLS FROM SLIM HOLE DATA AT OGUNI GEOTHERMAL FIELD

Abe, *et al.* (1992) do not make it clear if the indicated flow rates for Oguni boreholes in Table 1 are the maximum attainable flow rates for these boreholes. There also exists little reason to expect that the Oguni boreholes conform to the conditions assumed by Pritchett (1992) for his theoretical study. Despite these uncertainties about the Oguni data set, it was decided to investigate the possibility of predicting the discharge rate of the Oguni production wells (GH-11, GH-12, GH-14, GH-15, GH-20) from the slim hole data. Scaled discharge rates for production wells using (1) simple area scaling (Equation 1) and (2) a scaling rule for maximum flow (Equation 2) are given in Table 2. The measured discharges for wells GH-11 (211 t/h), GH-12 (197 t/h), and GH-14 (303 t/h) are bracketed by the average area-scaled discharge rate (176 t/h) and by the average scaled maximum discharge rate (311 t/h) obtained from the measured slim hole discharge data. While the measured discharge rate for well GH-15 (37 t/h) is anomalously low, the measured discharge rate for well GH-20 (369 t/h) is about 20 percent higher than the average scaled maximum discharge rate. The Oguni data are consistent with the premise that it should be possible to infer the discharge rate of large-diameter wells based on production data from small-diameter core holes. It should, however, be stressed that the latter conclusion needs to be tested with data from a statistically significant collection of geothermal fields.

Table 2. Predicted discharge rates for the production-size wells at Oguni (wells GH-11, GH-12, GH-14, GH-15, GH-20) derived from scaling measured discharge rates of slim holes at Oguni Geothermal Field.

Well Name	Final Stage Well Diameter (mm)	Measured Discharge Rate (t/hr)(a)	Area-Scaled Discharge Rate (t/hr)(b)	Scaled Maximum Discharge Rate (t/hr)(c)
HH-2	76	5	40	72
GH-3	76	20	162	290
GH-4	76	24	194	348
GH-5	76	19	153	275
GH-6	76	36	291	522
GH-7	98	26	126	197
GH-8	78	35	268	475
		Average	176	311

(a) Data from Abe, *et al.* (1992)
(b) Equation (1), $d = 216$ mm
(c) Equation (2), $d = 216$ mm

3.2 INJECTIVITY AND PRODUCTIVITY INDICES OF SLIM HOLES AND PRODUCTION WELLS

Theoretical considerations (Pritchett, 1992) imply that apart from any systematic differences resulting from skin effects, the productivity index should exhibit only a weak dependence on borehole diameter. At present, published data comparing the productivity indices (and skin factors) for small-diameter slim holes and production-sized wells are simply unavailable. There is also a need to establish a relationship between injectivity index obtained from cold water injection tests and productivity index obtained from discharge tests. Classical analyses which assume porous-medium flow (see *e.g.*, Garg and Pritchett, 1990) suggest that the injectivity index should be a strong function of the sandface injection temperature. (Note that the dynamic viscosity of water varies greatly with temperature and according to Darcy's law, pressure drop or increase is directly proportional to fluid viscosity.)

Grant, *et al.* (1982) have, however, argued that the conclusions derived on the basis of porous medium flow do not apply to geothermal systems. Most geothermal systems are associated with fractured igneous and metamorphic rocks. The following quotation from Grant, *et al.* (1982) is pertinent:

> "The productivity of a well is found to be less than injectivity. It was argued above (Section 5.6 and A1.4) that transmissivity measured with injection tests is that of the hot reservoir fluid. That is, transmissivity or injectivity measured in injection tests is equal to transmissivity or productivity in discharge. Often this is so. When it is not so, it is usually the case that injectivity is greater than productivity, despite the lower viscosity of hot water."

We do not know what data were used by Grant, *et al.* (1982) in reaching their conclusions. At present, sufficient published data are unavailable which would enable one to state with a high level of confidence that the productivity and injectivity indices are essentially equal for geothermal boreholes.

4. ACKNOWLEDGMENT

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5. REFERENCES

Abe, M., S. Kurishima, and Y. Mezaki (1992) "Drilling of Geothermal Well in the Onikobe Geothermal Field and Developing Oguni Geothermal Field," *Chinetsu, Vol. 29 (1)*, pp. 1–32.

Combs, J. and J. C. Dunn (1992), "Geothermal Exploration and Reservoir Assessment: The Need for a U. S. Department of Energy Slim-Hole Drilling R & D Program in the 1990s", *Geothermal Resources Council Bulletin, Vol. 21., No. 10*, in press.

Garg, S. K. and J. W. Pritchett (1990), "Cold Water Injection Into Single- and Two-Phase Geothermal Reservoirs," *Water Resources Research, Vol. 26*, pp. 331–338.

Garg, S. K., J. W. Pritchett, K. Ariki, and Y. Kawano (1991), "Pressure-Interference Testing of the Sumikawa Geothermal Field," *Proceedings Sixteenth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, January 23–25, pp. 221–229.

Grant, M. A., I. G. Donaldson, and P. F. Bixley (1982), *Geothermal Reservoir Engineering*, Academic Press, New York, p. 310.

Japan Geothermal Energy Association (JGEA) (1992), "Annual Report on Geothermal Energy Development in Japan: 1992", Tokyo, Japan, 12 pp.

Maki, H. and Y. Kawano (1988), "Statistical Analysis of Penetration Rate and Lost Circulation in Geothermal Wells," *Proceedings International Symposium on Geothermal Energy: Exploration and Development of Geothermal Resources*, Kumamoto and Beppu, Japan, November 10–14, pp. 388–391.

Murakami, K., T. Ishido, T. Yoshimura, S. Nakanishi, M. Fukushima, J. W. Pritchett, and S. K. Garg (1986), "Discharge Performance Analysis of Well DY-1 in the Hohi Geothermal Area," *Journal of the Geothermal Research Society of Japan, Vol. 8*, pp. 15–36.

New Energy Development Organization (NEDO) (1987), "Survey of Large-Scale Deep Geothermal Development With Regard to Environmental Conservation: Integrated Evaluation (Hohi Area)," report submitted to Ministry of International Trade and Industry (MITI), Tokyo, Japan, March, 116 pp.

Pritchett, J. W. (1992), "Preliminary Study of Discharge Characeristics of Slim Holes Compared to Production Wells in Liquid-Dominated Geothermal Reservoirs," Report No. SSS-TR-92-13133, S-Cubed, La Jolla, California, July, 48 pp.

Pritchett, J. W., S. K. Garg, W. E. Farrell, T. Ishido, T. Yoshimura, K. Murakami and S. Nakanishi (1985), "The Hohi Geothermal Area, Kyushu, Japan," *Proceedings Tenth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, January 22–24, pp. 79–87.