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PRESSURE INTERFERENCE TESTS AT THE OGUNI GEOTHERMAL FIELD, NORTHERN KYUSHU, JAPAN

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ABSTRACT

The subsurface stratigraphy in the Oguni geothermal field (northwestern Hohi geothermal region) consists of a sequence of indurated sediments and volcanics overlying a granitic basement. The Hohi formation and the upper part of the Shishimuta formation constitute the principal geothermal aquifers. The feedzone pressures indicate that the northwestern Hohi region consists of two pressure zones, *i.e.*, a high-pressure zone in the southern part of the Oguni geothermal field, and a low-pressure zone in the central and northern parts of the northwestern Hohi area.. To delineate the permeability structure for the Oguni Geothermal Field, Electric Power Development Co., Ltd. performed numerous pressure transient tests. Analyses of pressure interference data indicate that the low-pressure zone has a transmissivity of 100–250 darcy-meters. In contrast to the high transmissivity of the low-pressure zone, the high-pressure zone has only a modest transmissivity. The pressure interference data are consistent with the presence of one or more no-flux boundaries between the low- and high-pressure zones.

1. INTRODUCTION

The Oguni and the Sugawara Geothermal Fields together comprise the northwestern Hohi geothermal region, Kumamoto and Oita Prefectures, Kyushu, Japan (see Figure 1). An area of numerous hot springs, it is approximately 40 km southwest of the coastal resort of Beppu, and some 20 km north of Mt. Aso, an active caldera. The New Energy and Industrial Technology Development Organization (NEDO) carried out a regional (200 km^2 area) exploration program in the Hohi area during the years 1979–1985. The Electric Power Development Co., Ltd. (EPDC) initiated a geothermal exploration program in the Oguni area in 1983. The Oguni field, delineated by the "GH" series boreholes, is located at the northeast end of Kumamoto Prefecture. The topography of the Oguni field is dominated by Mt. Waita (Figure 1), which rises to an elevation of about 1500 m ASL (meters above sea level) to the southeast of the field. Many of the boreholes are located on the flanks of Mt. Waita. Striking WNW–ESE is the valley containing the hot spring areas (and towns) of Takenoyu and Hagenoyu. To the north of the valley is the Sugawara plateau (in Oita Prefecture) where NEDO has drilled a number of boreholes (BS series, Figure 1) for a binary power plant. Although the northern Hohi area has been subdivided into two separate geothermal fields (Oguni, Sugawara), the area constitutes a single hydrological unit.

The subsurface stratigraphy in the northwestern Hohi area consists of a sequence of indurated sediments and volcanics overlying a granitic basement (Figure 2). The stratigraphic sequence above the basement consists of the Pliocene Taio formation, the late Pliocene/early Pleistocene Shishimuta formation (pre-Kusu group), the lower to middle Pleistocene Hohi and Kusu formations, and the upper Pleistocene Kuju formation. The Nogami mudstones (part of the Kusu group) and the Kuju volcanics appear to function as a caprock for the geothermal system. Based upon feedpoint locations, it appears that the Hohi formation and the upper part of the Shishimuta formation constitute the principal geothermal aquifers. The Hohi formation consists of lavas and pyroxene andesitic rocks while the Shishimuta formation is primarily dacitic pyroclastics.

The feedzone pressures (Garg, *et al.* 1993) imply that the northern Hohi region consists of two pressure zones (a high-pressure zone in the area of boreholes GH-15, GH-19, GH-6, HH-2, N2-KW-3 and DY-2 in the southern part of the Oguni field; a low-pressure zone in the central and northern parts of the area shown in Figure 1). The feedzone pressures for the "low-pressure zone" boreholes can be fit by the straight line shown in Figure 3. However, the pressures for "high-pressure zone" boreholes (GH-6, GH-15, GH-19, HH-2, DY-2, N2-KW-3), lie considerably above the straight line in Figure 3, as do those from the shallow boreholes (MW-5, DB-9, DB-10) which do not penetrate the deep reservoir.

The average reservoir temperature at Oguni is about 225°C. The maximum stable preproduction subsurface temperature of 240°C was measured at total vertical depths of 1027 and 1576 m, in the GH-10 and GH-20 wells, respectively. Temperatures decline rapidly to the east and west of the 1 km wide subsurface zone defined by the Oguni boreholes GH-4, GH-10, GH-11, and GH-12 [*Garg et al.*, 1993]. The Oguni reservoir fluid is a relatively homogenous sodium-chloride brine of moderate salinity with an average chloride concentration of about 1100 mg/L. The reservoir fluid is a single-phase liquid. None of the geothermal boreholes provide any direct evidence of a two-phase zone at depths greater than 300 m in the Oguni geothermal field. However, the presence of boiling at depths less than 300 m is suggested by the occurrence of warm and boiling steam-heated sulfate and bicarbonate spring waters in the area.

To delineate the permeability structure for the Oguni Geothermal Field, EPDC performed numerous pressure transient tests. The available data set includes (1) cold fluid injection tests in single boreholes, (2) pressure drawdown and buildup tests in single boreholes, and (3) pressure interference tests involving multiple boreholes. This paper is restricted to analyses of the Oguni pressure interference test data from both slim holes and large-diameter wells.

2. PRESSURE INTERFERENCE TESTS

In March 1991, EPDC installed downhole gauges of the capillary tube type in slim holes GH-3, GH-4, GH-5, N2-KW-1, N2-KW-2, and N2-KW-3. These six (6) slim holes were used as shutin observation boreholes during four separate production/injection tests carried out by EPDC from April 15, 1991 to April 27, 1992. With the exception of slim hole N2-KW-3, all the other observation boreholes lie in the low-pressure zone. During test 1, low-pressure well GH-20 was discharged for 12 days from April 15, 1991 to April 27, 1991. The separated liquid water was injected into low-pressure well IH-1 and high-pressure well GH-15. Interference test 2 (June 5 to July 20, 1991) employed GH-11 as the production well and IH-1 and GH-15 as the injectors. For interference test 3 (September 5 to October 20, 1991), low-pressure wells GH-12 (producer) and IH-2 (injector) were used as the active boreholes. Interference test 4 (December 13, 1991 to April 27, 1992) involved simultaneous discharge from boreholes GH-10, GH-11, GH-12 and GH-20, and injection into boreholes GH-17, IH-1, IH-2, GH-15 and GH-19. The feedpoint locations and the feedpoint formations of all the production, injection and observation boreholes involved in these pressure interference tests are given in Table 1.

Because of the relatively simple borehole configuration (Figure 4) employed during the first three interference tests, pressure data from these tests are especially useful for defining the reservoir permeability structure. As can be seen from Figure 4, observation slim holes N2-KW-2 and GH-3 are much closer to injection well IH-1 than production well GH-20. The measured pressure response in slim holes N2-KW-2 and GH-3 shows that these slim holes do not respond to injection into IH-1. Apparently, the recompleted well IH-1 (feedzone depth: 313m) injects fluid into a shallow aquifer, and injection into well IH-1 plays no role in the pressure response recorded in the various observation boreholes.

The active production and injection wells involved in the first three 1991 tests are as follows:

(i) Tests 1 and 2

(a) Low-Pressure Zone

Production Wells: GH-20 (April 15 to April 27), and GH-11 (June 5 to July 20)

Injection Well: IH-1*

*Shallow Feedzone

(b) High-Pressure Zone

Production Well: None

Injection Well: GH-15 (April 15 to April 27 and June 5 to July 20)

(ii) Test 3

(a) Low-Pressure Zone

Production Well: GH-12 (September 5 to October 20)

Injection Well: IH-2 (September 5 to October 20)

(b) High-Pressure Zone

No activity.

Flow histories for all the active production and injection wells with the exception of IH-1 are illustrated in Figure 5. For analysis purposes, it is convenient to consider tests 1 and 2 together. Analyses of selected pressure responses monitored in several observation boreholes are given in Sections 2.1-2.4.

2.1. Observation Slim Holes GH-3 and N2-KW-2

Slim holes GH-3 and N2-KW-2 were drilled from the same pad. Both the vertical and horizontal distances between the feedpoints of these slim holes are relatively small. Not surprisingly, slim holes GH-3 and N2-KW-2 exhibit similar pressure responses. To analyze the observed pressure response during tests 1 and 2, the line source solution (see *e.g.*, Streltsova, 1988) was used. It is assumed that boreholes GH-20, GH-11, GH-3, and N2-KW-2 fully penetrate an areally infinite reservoir. The *in situ* density, viscosity and temperature of water are assumed to be 840 kg/m^2, 1.2×10^{-4} Pa-s, and 220°C, respectively. In the process of modeling the pressure interference response, it was found that the introduction of a no flux boundary led to much better agreement between the measured and computed pressures. For the sake of simplicity, it was somewhat arbitrarily assumed that the no flux boundary is located south of the observation boreholes (The relative locations of the high- and low-pressure zones indicates that the no flux boundary is probably oriented in a NW-SE direction). The unknown parameters in the model were varied to obtain the best possible match between the computed and measured pressures (see *e.g.*, Figure 6). The final model parameters are:

GH-3:

$$kh = 260 \text{ darcy-m}$$
$$\varphi ch = 7.0 \times 10^{-7} \text{ m/Pa}$$
$$Y = 1310 \text{ m south of GH-3}$$

N2-KW-2:

$$kh = 220 \text{ darcy-m}$$
$$\varphi ch = 7.4 \times 10^{-7} \text{ m/Pa}$$
$$Y = 1560 \text{ m south of N2-KW-2}$$

The formation parameters (kh, φch, Y) inferred from separate fits to pressure data from slim holes GH-3 and N2-KW-2 are quite similar. The inferred value for the storage parameter φch ($\sim 7 \times 10^{-7}$ m/Pa) is fairly high. Since the permeable zone at Oguni is, at most, a few hundred meters in thickness and the formation porosity does not exceed 0.1, the latter result implies that the reservoir rocks are very compressible. This is a reasonable conclusion since the feedzones for both GH-3 and N2-KW-2 are in the Shishimuta formation, which is primarily dacitic pyroclasitics. As already indicated above, the boundary orientation (*i.e.*, an east-west direction south of the observation boreholes) was fixed arbitrarily. A different choice for boundary orientation will yield a different value for distance to the boundary. The essential point is that the pressure-interference data from GH-3 and N2-KW-2 imply the presence of a linear barrier.

2.2. Slim Hole GH-4

Pressure response of GH-4 (Figure 7) to discharge from wells GH-20 and GH-11 (tests 1 and 2) was fitted in a manner similar to that for slim holes GH-3 and N2-KW-2. The computed model parameters are:

$$\text{kh} = 150 \text{ darcy-m}$$
$$\varphi\text{ch} = 1.9 \times 10^{-6} \text{ m/Pa}$$
$$\text{Y} = 880 \text{ m south of GH-4}$$

The permeability-thickness value derived form the pressure response of GH-4 is considerably less than those obtained from pressure data for slim holes GH-3 and N2-KW-2. This indicates some permeability heterogeneity in the Oguni geothermal field. The large value for the storage parameter φch implies that the reservoir rocks are very compressible.

2.3. Slim Hole N2-KW-1

Among the observation boreholes, slim hole N2-KW-1 is the farthest removed (1400 ± 300 meters) from production wells GH-20 and GH-11 (see Figure 4). It appears that the pressure in N2-KW-1 was declining prior to discharge test of well GH-20. Attempts to model the pressure response in N2-KW-1 due to production from GH-20 and GH-11 using the line-source model were largely unsuccessful. It was next decided to model the pressure response associated with production from GH-20 and from GH-11 separately. Again, the comparison between the measured and computed pressure response due to discharge from GH-20 was poor. This may be due to the secular drift in N2-KW-1 pressure, and the relatively small pressure change associated with discharge from GH-20. The pressure response corresponding to GH-11 discharge can be adequately fitted (Figure 8) using the line-source model with the following parameter values:

$$\text{kh} = 100 \text{ darcy-m}$$
$$\varphi\text{ch} = 9.4 \times 10^{-6} \text{ m/Pa}$$

2.4. Slim Hole N2-KW-3

The high-pressure zone slim hole N2-KW-3 responds to injection into wells GH-15 (tests 1/2 and 4) and GH-19 (test 4). The fall-off record for the field-wide test consists of two distinct parts corresponding to shutin of GH-15 (April 21, 1992) and GH-19 (April 27, 1992). The fall-off data show that a flow rate change in either GH-15 or GH-19 produces an almost instantaneous pressure response in N2-KW-3. The line-source solution was used to match the fall-off pressure response for test 4. The best fit was obtained using a single no-flux boundary. The boundary orientation was arbitrarily assumed to be to the east of slim hole N2-KW-3. The model parameters obtained by minimizing the deviations between the measured and computed pressures (see Figure 9) are:

$$\text{kh} = 14.4 \text{ darcy-meters}$$
$$\varphi\text{ch} = 4.1 \times 10^{-8} \text{Pa}^{-1}$$
$$\text{Y} = 860 \text{ m}$$

The inference of a linear no-flux boundary is in keeping with the notion of hydraulic separation between the low- and high-pressure reservoirs.

3. CONCLUSIONS

The pressure interference tests have been invaluable for characterizing the detailed permeability structure of the Oguni Geothermal Field. The “low-pressure zone” in the northern Hohi reservoir (Oguni and Sugawara geothermal fields) has a transmissivity of 100–250 darcy-meters. The east-west transmissivity, as determined from the pressure response of slim holes GH-3 and N2-KW-2 to discharge from wells GH-20 and GH-11, is around 250 darcy-meters. The north-south transmissivity obtained from the pressure response observed in N2-KW-1 is about 100 darcy-meters. In contrast to the high transmissivity of the “low-pressure zone”, the “high-pressure zone” has only a modest transmissivity. The pressure interference test data are consistent with the presence of one or more no-flux boundaries between the low- and high-pressure zones.

4. REFERENCES

Garg, S.K., J.W. Pritchett, T.G. Barker, L.A. Owusu, J. Haizlip, and A.H. Truesdell. Resevoir Engineering Studies of the Oguni Geothermal Field (Phase 3), *Report SSS-FR-92-13899*, S-Cubed, La Jolla, California, March, 1993.

Streltsova, T.D., *Well Testing in Heterogeneous Formations,* John Wiley and Sons, New York, 1988.

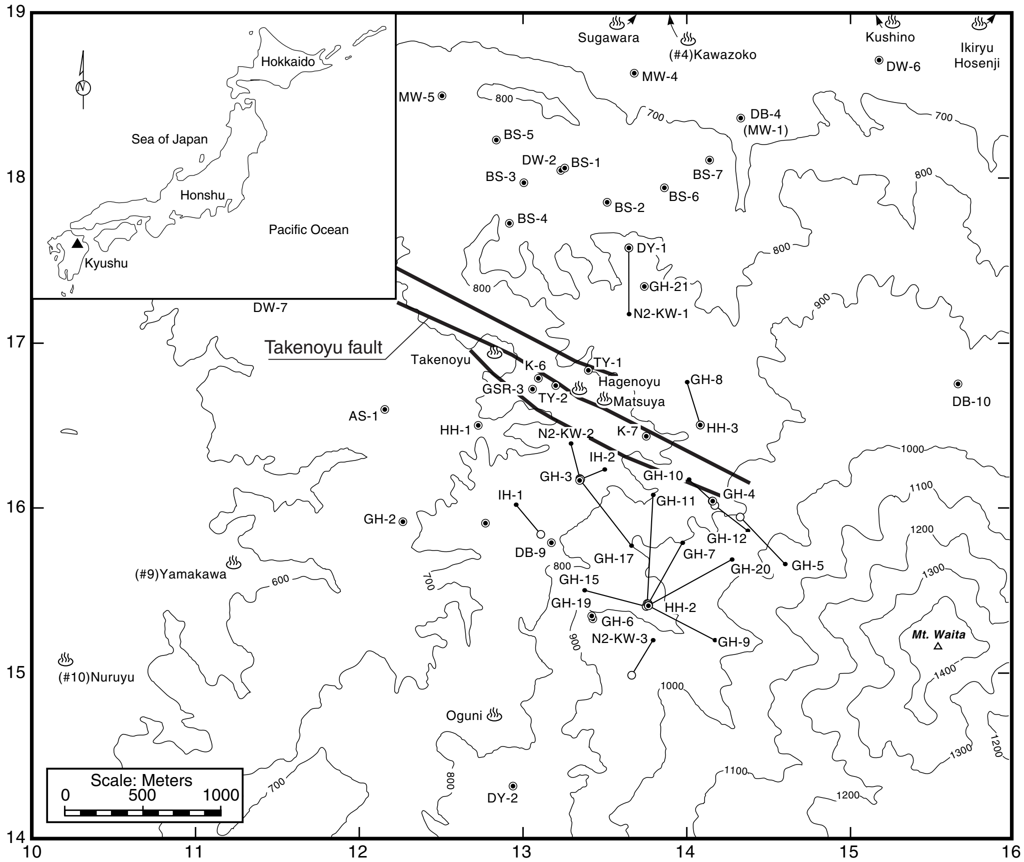

Figure 1. The Oguni and Sugawara geothermal fields, northwestern Hohi area, Kyushu, Japan. The Oguni Geothermal Field is delineated by the "GH" series boreholes; the "BS" series boreholes are drilled in the Sugawara Geothermal Field. The WNW–ESE faults are indicated by heavy solid lines. The inset map of Japan shows the location of the Hohi area (solid triangle). All horizontal distances are with respect to the Central Kyushu Co-ordinate System (CKCS). The origin of CKCS is located at 33°0' north latitude and 131°0' east longitude.

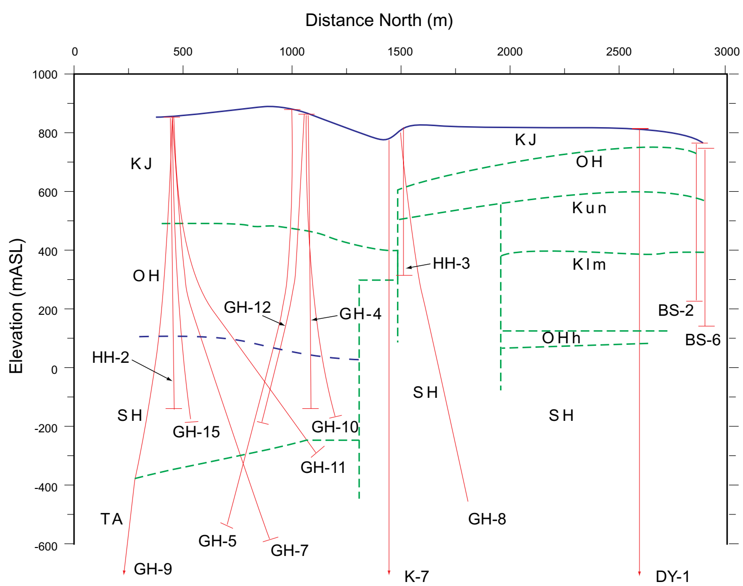

Figure 2. A schematic south-north stratigraphic cross section striking north along east-west CKCS co-ordinate 14. The ordinate is meters north from north-south CKCS co-ordinate 15. The following abbreviations are used for formation names: KJ (Kusu); Kun (Kusu/Nogami mudstone); Klm (Kusu/Machida lava); OH (Hohi); OHh (Hohi/Hatchobaru lava); SH (Shishimuta); TA (Taio).

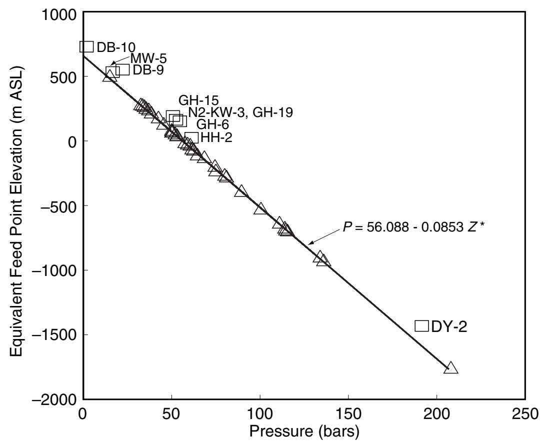

Figure 3. Correlation of pressure with equivalent feedpoint elevation of low-pressure zone boreholes (Δ). Also shown as □ are boreholes (DB-10, MW-5, DB-9, GH-15, N2-KW-3, GH-19, GH-6, HH-2, DY-2) not included in the pressure correlation.

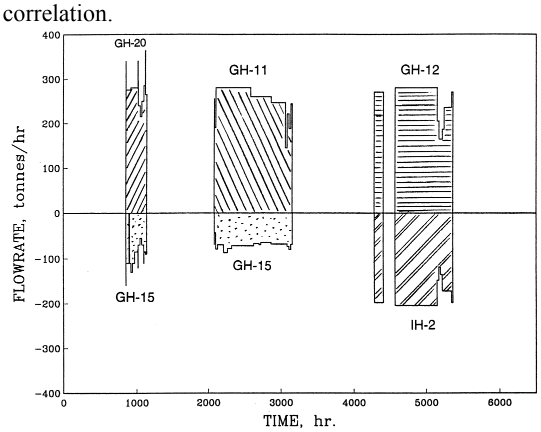

Figure 5. Flow histories of "active" production and injection wells involved in pressure interference tests 1–3.

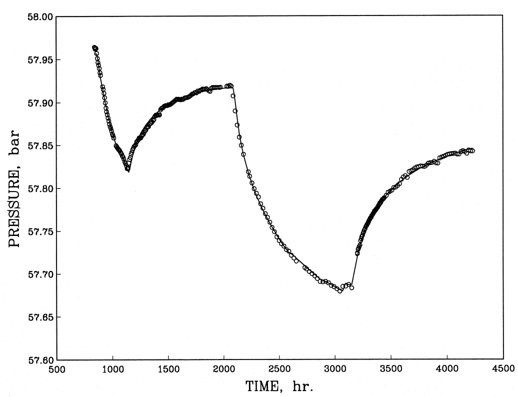

Figure 7. Comparison of measured pressures (o) in slim hole GH-4 with computed response (—) due to production from wells GH-20 and GH-11 (interference tests 1 and 2).

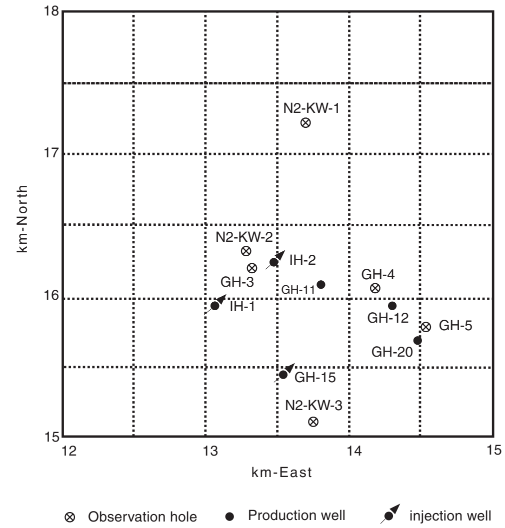

Figure 4. Horizontal feedzone locations of the various production, injection, and observation boreholes involved in Oguni pressure interference tests 1–3.

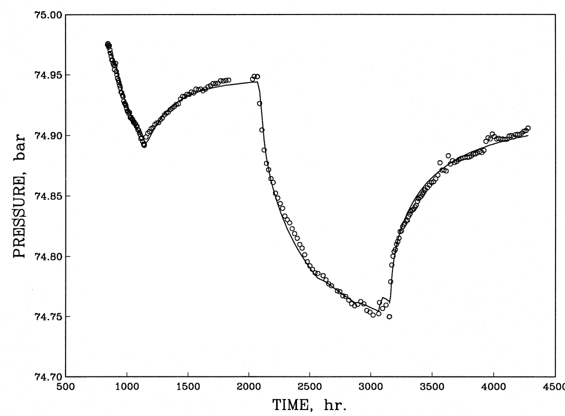

Figure 6. Comparison of measured pressures (o) in slim hole GH-3 with computed response (—) due to production from wells GH-20 and GH-11.

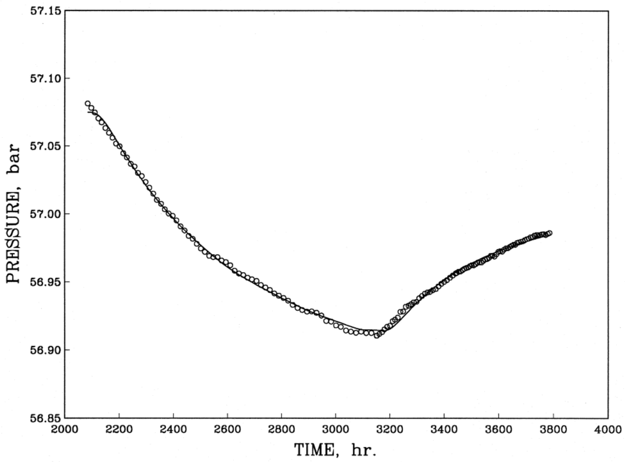

Figure 8. Comparison between measured pressures (o) in slim hole N2-KW-1 with computed response due to production from well GH-11.

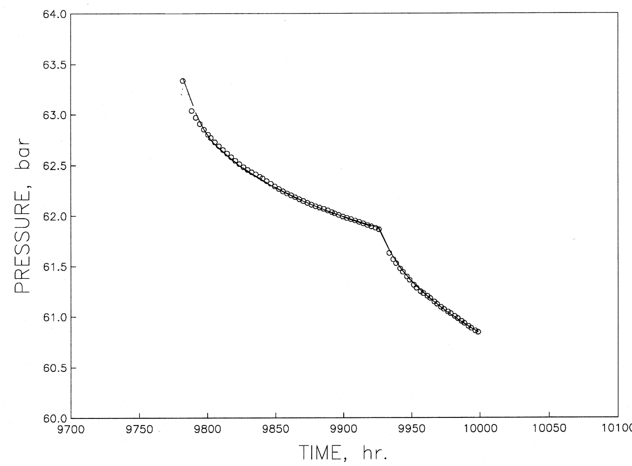

Figure 9. Comparison between measured (o) and computed (—) response in slim hole N2-KW-3 (pressure interference test 4) following shutin of injection wells GH-15 (April 21, 1992) and GH-19 (April 27, 1992).

Table 1. Principal feedzone locations for all the production, injection and observation boreholes involved in the Oguni pressure interference tests along with the feedpoint formation. All the horizontal distances (m North and m East) are with respect to the Central Kyushu Co-ordinate System.

Well	Feedpoint Depth (m ASL)	Feedpoint Coordinates		Feedpoint Formation
		m (North)	m (East)	
N2-KW-1	–39	17225	13684	Shishimuta
N2-KW-2	–80	16323	13270	Shishimuta
N2-KW-3	158	15129	13734	Hohi
GH-3	–249	16201	13312	Shishimuta*
GH-4	–40.	16066	14181	Shishimuta
GH-5	–210.5	15794	14525	Shishimuta
GH-10	–146	16175	14029	Shishimuta
GH-11	–282	16090	13790	Taio
GH-12	114	15947	14294	Hohi**
GH-15	178	15474	13529	Hohi
GH-17	25	16051	13432	Shishimuta
GH-19	154	15325	13424	Hohi
GH-20	–702	15701	14467	Taio
IH-1	442	15866	13111	Hohi
IH-2	235	16248	13463	Hohi

* Extrapolated from N2-KW-2
** From electric logging