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PRESSURE CHANGES IN REINJECTION WELLS AND GRAVITY CHANGES IN OTAKE GEOTHERMAL FIELD, JAPAN

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ABSTRACT

In the Otake geothermal field, gravity changes at reinjection well OR-15 have been monitored together with pressure changes using water level data for wells OR-15, OR-19 and O-16R to clarify the behavior of the reinjected water in the reservoir and its effect on the production zone. Using these data, the correlation between water level changes in the observation wells, changes in flow-rate of reinjected water and the observed gravity changes have been studied.

The water level changes in OR-15 are similar to the water level changes in O-16R. The reinjection area is subdivided into four blocks. Multiple regression analysis shows the pressure changes around these wells are affected not only by the reinjection rate changes in the immediate block but also by the reinjection changes in other blocks and the amount of rainfall (after a 3-month time lag). However, the pressure changes in OR-19 strongly correlate with the reinjection flow-rate in block D, and the presence of an impermeable structure between OR-15 and OR-19 is indicated.

The repeated gravity measurements show the gravity changes at each station have similar tendencies. However , a discrepancy was recognized between the values of the maximum value minus minimum value at each station. The general tendency of gravity changes at OR-15 is similar to the water level changes in OR-15. A quasi-three-dimensional inversion of the gravity changes was therefore applied to delineate the behavior of reinjected water in the reservoir and its effect in the production zone. From the inversion results, the geothermal reservoir in the Otake field is considered to be controlled by a NW-SE trending structure between OR-15 and OR-19. In addition, the reinjected water in the reservoir is considered to be flowing mainly in a northerly direction.

1. INTRODUCTION

Located in central Kyushu, Japan, the Otake Geothermal Power Plant (12.5MW) has been operated in stable condition by Kyushu Electric Power Co. Inc. since 1967. In addition, the Hatchobaru Geothermal Power Plant (110MW) is located about 2km south of the Otake Geothermal Power Plant. This Otake-Hatchobaru Geothermal field is one of the most active Geothermal fields in Japan. The thermal origin of Otake-Hatchobaru Geothermal field is presumed to be related to Late Kujyu volcanism which was active from 200,000 to 100,000 years ago (Manabe et al., 1986). The geothermal structure in the Otake geothermal field has a typical fractured-type structure associated with fault systems. The main NW-SE trending faults are the Sujiyu Fault, the Hizenyu Fault, the Yokoo Fault and the Otake Fault. The geothermal reservoir is located at a depth of 300m-600m (elevation of 700m-400m) and forms the hydrothermal reservoir of the mushroom type (Taguchi et al., 1985). Acid altered zones, which are aquicludes, are distributed in the thickness from 200m to 500m on the geothermal reservoir. It is likely that these acid altered zones function as cap rocks. It is inferred from the homogenization temperatures of fluid inclusions that the reservoir temperature is about 200-230℃ (Matsumoto et al., 1989).

However, little exploration has been done in and around the Otake Power Station recently. Therefore, information about the reservoir in the Otake geothermal field seems to be insufficient compared to the Hatchobaru Geothermal Power Station.

Allis and Hunt (1986), Hunt (1995) and Tagomori et al. (1996) reported attempts to estimate the reservoir behavior from repeated gravity measurements. Following the methods developed in these reports, gravity values and water levels in three wells have been monitored in the reinjection area of the Otake geothermal field in order to understand the behavior of reinjected water.

This paper presents some results concerning the correlation between water level changes in the observation wells, flow-rate changes of reinjected water, observed gravity changes and results concerning the behavior of reinjected water obtained by using quasi-three-dimensional inversion of the gravity changes.

2. GRAVITY AND WATER LEVEL MEASUREMENTS

2.1 Water level meters and observation wells

The field can be divided into 4 blocks in reinjection area : A, B, C, D (Fig. 1). In January 1996, two water level meters were set in two observation wells, OR-15 (Block B) and OR-19 (Block D), to measure the pressure changes in the reinjection area, and the water level changes in O-16R (Block C) were monitored from October 1997. The water level sensors were installed at a depth of 150m in the borehole of OR-15, and at 200m in OR-19 and O-16R. The locations of these three wells are shown in Fig. 1. A type LS-16 (FUJIKAWA KIKAI) seal gauge was used as a water level sensor and a U-LOGGER L810B (UNIPULSE) was used as a data logger. The data were stored on a memory card in the data-logger, and were usually collected once or twice a month by using a computer.

2.2 Gravity meter and gravity observations

The gravity meter used in this study is a SCINTREX CG-3M autogravimeter. Gravity change values at the wellhead of OR-15 have been monitored. The gravity value is measured every three hours, and 120 readings (2 min) are taken for each measurement. The gravity meter calculates the average value and the standard error of the 120 sample data for each measurement. The data are stored in the gravity meter and are collected once or twice a month by using a notebook-type computer and a serial cable.

2.3 Drift correction

Three benchmarks beside Route 210 (No.2553, No.2556 and No.2557) were used as base stations. These benchmarks are located about 10km north of the Otake geothermal field. The gravity values at these stations were measured once or twice a month and the gravity meter drift calculated using the data from at these stations.

3. OBSERVATION RESULTS

3.1 Reinjection rate changes in each block

Fig. 2 shows the reinjection flow-rate changes for each of blocks, A,B,C and D. The solid line shows a smooth curve calculated using the cubic spline method, and the solid circles show the 5-day flow-rate average of the reinjected water.

The reinjection flow-rate in block A is the largest, and that in block C, in which O-16R is located, is the second largest. The reinjection flow-rate in block B, in which OR-15 is located, and that in block D, in which OR-19 is located, are relatively small, compared to those in block A and C. In block A, the reinjection flow-rate changes are significantly greater than in the other blocks, therefore the total reinjection flow-rate changes in the field resemble those in block A.

3.2 Amount of rainfall

Koike et al. (1991), Watanabe et al. (1994) and Fukuda et al. (1995) reported that gravity changes seem to be related to changes in the amount of rainfall, after a time lag. In Otake field, there is a possibility that the water level changes and gravity changes may similarly be affected by the changes in the amount of rainfall. The amount of rainfall from June to August measured at the Otake Power Station is relatively large (Fig. 3). Therefore, if rainfall affects gravity and caused water level changes, these effects should be recognizable during and after August, and they should be disregarded when we examine reservoir behavior on the basis of gravity and/or water level data.

3.3 Water level changes in OR-15, OR-19 and O-16R

The water level changes in OR-15, OR-19 and O-16R are shown in Fig. 4 ; the solid line shows a smooth curve calculated using the cubic spline method and the solid circles show the 5-day average water levels. The water level changes in OR-15 are similar to those in O-16R, but there is little correlation between the changes in OR-15 and OR-19. Moreover, the difference in water level elevation between OR-15 and OR-19 is about 150m, in spite of the fact that the horizontal distance between these two wells is only about 200m.

3.4 Correlation between gravity data and water level data

The gravity changes after earth tide and drift corrections at the OR-15 wellhead are shown in Fig. 5. The solid line shows a smooth curve calculated using the cubic spline method and the solid circles show the 5-day average values of gravity data.
Since the general tendency of gravity changes at OR-15 is similar to the water level changes in OR-15 (Fig. 4), the gravity changes are considered to reflect pressure changes mainly around OR-15 (The correlation coefficient between the gravity changes and water level changes is 0.604). There is a little difference between these two tendencies, therefore, the gravity changes are considered to be affected not only by the pressure changes around OR-15 but also by some other factors.

3.5 Correlation between water level changes and reinjection flow-rate changes

Comparing the water level changes in OR-15 with the reinjection flow-rate changes in block B, a clear correlation is recognized in the period from October to February, but the correlation coefficient for the whole period is only 0.02. This shows that pressure changes in OR-15 are affected not only by the reinjection flow-rate changes in block B but also by some other factors.
Comparing the water level changes in OR-15 with the reinjection flow-rate changes in block C, no such clear correlation is recognized and the correlation coefficient between these sets of data is -0.26. A similar tendency is recognized in the period from January 1997 to September 1997. Moreover, comparing the water level changes in OR-15 with the reinjection flow-rate changes in block A, a similar tendency is recognized also in the period from August 1996 to February 1997. This suggests the pressure changes in OR-15 are affected by the reinjection flow-rate changes in block B, C and D. This point of view will be discussed later in Section 4.

4. FACTORS AFFECTING GRAVITY AND WATER LEVEL CHANGES

4.1 Multiple Regression Analysis

Since the water level changes are likely to be affected not only by the reinjection flow-rate changes in the blocks where the wells are located but also by some other factors, such as impermeable structures around or between the OR-15 and OR-19 wells, the amount of rainfall and so on, the multiple regression analysis method is used to estimate the influence of these factors.
In the multiple regression analysis used for this study, the water level values or gravity values are used as criterion variables (y), while the reinjection flow-rates in block A (X_1), block B (X_2), block C (X_3) and block D (X_4) as well as the amount of rainfall in and around the Otake geothermal field (X_5) are used as explanatory variables. In this case, calculating the regression coefficients such as a_0, a_1, a_2, a_3, a_4 and a_5 in equation (1) by using the least squares method, the degree of each effect can be roughly estimated.

$$y = a_0 + a_1 \cdot X_1 + a_2 \cdot X_2 + a_3 \cdot X_3 + a_4 \cdot X_4 + a_5 \cdot X_5 \cdots\cdots (1)$$

Using the least squares procedure, the regression coefficients (a_0, ・・・, a_5) can be calculated by minimizing the residual sum of square values (Q).

$$Q = \sum_{i=1}^{n} \{y_i - (a_0 + a_1 \cdot X_{1i} + a_2 \cdot X_{2i} + a_3 \cdot X_{3i} + a_4 \cdot X_{4i} + a_5 \cdot X_{5i})\}^2 \cdots\cdots (2)$$

4.2 Correlation between the water level changes in OR-15, OR-19 and O-16R

Following the procedure described in Sub-section 4.1, some multiple regression analysis were carried out in this study. Fig. 4 shows the results of the multiple regression analysis whose criterion variable is the water level in OR-15, OR-19 and O-16R. The equations derived from the multiple regression analysis are as follows :

Water level in OR-15 (Block B) = 840
+ 0.09 x Reinjection flow-rate in block A
+ 0.15 x Reinjection flow-rate in block B
+ 0.13 x Reinjection flow-rate in block C
+ 0.00 x Reinjection flow-rate in block D
+ 0.01 x Amount of rainfall
(90-day time lag)

Water level in OR-19 (Block D) = 737
+ 0.01 x Reinjection flow-rate in block A
+ 0.00 x Reinjection flow-rate in block B
+ 0.02 x Reinjection flow-rate in block C
+ 0.18 x Reinjection flow-rate in block D
+ 0.00 x Amount of rainfall

Water level in O-16R (Block C) = 711
+ 0.09 x Reinjection flow-rate in block A
(15-day time lag)
+ 0.11 x Reinjection flow-rate in block B
+ 0.14 x Reinjection flow-rate in block C
+ 0.00 x Reinjection flow-rate in block D
+ 0.05 x Amount of rainfall
(90-day time lag)

The correlation coefficient between the calculated values and the observed water levels is 0.76 for OR-15, 0.87 for OR-19 and 0.97 for O-16R. According to the regression analysis results, the pressure changes in OR-15 are considered to be controlled mainly by the reinjection flow-rate in block A (with no time lag), block B (with no time lag), block C (with no time lag) and the amount of rainfall (with a 90-day time lag).
The water level changes in OR-19 have a tendency similar to the reinjection flow-rate changes in block D. Since the correlation coefficient between these two values is relatively high, the reinjection flow-rate changes in block D are considered to be a main factor controlling the water level changes in OR-19. From the

multiple regression analysis of the water level changes in OR-19, the reinjection flow-rate changes in block A, in block C and in block D are considered to be factors affecting the water level in OR-19. The amount of rainfall does not seem to have much effect on the water level changes in OR-19.
The pressure changes in O-16R are considered to be controlled mainly by the reinjection flow-rate in block A (with a 15-day time lag), in block B (with no time lag), in block C (with no time lag) and the amount of rainfall (with a 90-day time lag). Comparing the regression analysis results of water level changes in OR-15 with those of water level changes in O-16R, it is considered that the influence of rainfall on the water level changes in O-16R located near to the mountain side is stronger than on the water level changes in OR-15.

4.3 Gravity changes at OR-15 and reinjection flow-rate changes

There is little correlation between the gravity changes at OR-15 and the reinjection flow-rate changes in block B (The correlation coefficient is 0.01). The result of the multiple regression analysis carried out in order to clarify this problem is :

Gravity changes at OR-15 = 120.48
+0.0001 × reinjection flow-rate in block A
+0.0012 × reinjection flow-rate in block B
+0.0002 × reinjection flow-rate in block C
+0.0000 × reinjection flow-rate in block D
+0.0004 × amount of rainfall
(90-day time lag)

This result suggests that the gravity changes in OR-15 are controlled by the reinjection flow-rate in block A (with no time lag) , in block B(with no time lag), in block C (with no time lag) and the amount of rainfall (with a 90-day time lag). The influence of the reinjection flow-rate in block B, where OR-15 is located, is strongest among all the blocks in the Otake geothermal field.

5. ESTIMATE OF THE DISTRIBUTION OF WATER LEVEL CHANGES

5.1 Quasi-three-dimensional density analysis

The results of repeated gravity measurements in the Otake geothermal field, show the patterns of gravity changes at each gravity station are similar to each other. However, a discrepancy was recognized between the values of the maximum value minus minimum value at each measuring station. Besides, the general tendency of gravity changes at OR-15 is similar to the water level changes in OR-15. Since the gravity changes at each gravity station are likely to be affected not only by the density changes in the surrounding area the station but also by the density changes in a relatively broad area, a quasi-three-dimensional inversion of the gravity changes was applied to delineate the behavior of reinjected water in the reservoir and its effect in the production zone.
The vertical component of the gravity can be calculated using the formula for a rectangular parallelepiped block.

$$g = G\rho\int_{z1}^{z2} dz\int_{yo-b}^{yo+b} dy\int_{xo-a}^{xo+a} dx\frac{z}{\left(x^2+y^2+z^2\right)^{3/2}}$$
$$= -G\rho\left[x\ell n(y+R)+y\ell n(x+R)\right]-z\tan^{-1}\frac{XY}{ZR}\Bigg|_{x=xo-a}^{x=xo+a}\Bigg|_{y=yo-b}^{y=yo+b}\Bigg|_{z=z_1}^{z=z_2}$$

where

g = gravity
G = universal gravitational constant
ρ = the density of rectangular parallelepiped block
$R=\sqrt{x^2+y^2+z^2}$

In the quasi-three-dimensional density analysis used in this study, the subsurface density structure was modeled by three dimensional blocks (Fig. 6), and gravity values at each station were estimated by taking the sum of gravity values of each these blocks for the inversion process. In the inversion process, only the density of the blocks, where the water level is actually observed depths from 50m to 150m, can be changed so that the calculated gravity changes may fit the observed gravity changes. After the inversion process, the water level change is estimated by the following formula because these density changes are believed to occur due to the water level change.

$$Water\ level = \frac{\Delta\rho H}{W_\rho\phi}$$

where

$\Delta\rho$ = density changes
H = horizontal size of block
$W\rho$ = water density at the water level
ϕ = porosity

The water density (90℃) of the water level is assumed to be 0.96512g/cm^3, given the measured temperature around the water level, and the porosity is assumed to be 15% based on the measured porosity of core samples.
The flow chart of the quasi-three-dimensional density analysis is shown in Fig. 7.

5.2 Distribution of gravity changes from February 1998 to April 1998

The distribution of the gravity changes between February 1998 and April 1998 is shown in Fig. 8. The values of gravity change range from –20 to 10 μ gal, and the decrease of gravity is relatively large in the northeastern and the southwestern parts of the field. Since the water levels in all the observation wells fell (OR-15 : -6.6m, OR-19 : -1.1m, O-16R : -7.9m) during the period, the decrease of the gravity in the northeastern part, where the reinjection area is located, is considered to be affected by the drop of the water level caused by the decrease of the total reinjection rate (-200t/h) during this period.
On the other hand, a zone trending in a NW-SE direction and which indicates remarkable horizontal changes in gravity is recognized between OR-15 and OR-19. So, we estimate the distribution of the water level changes in this period by using quasi-three-dimensional density analysis.

5.3 Distribution of the water level change for February 1998 to April 1998, calculated by quasi-three-dimensional density Analysis

The distribution of water level changes between February 1998 and April 1998 estimated by quasi-three-dimensional density analysis is shown in Fig. 9. A NW-SE trending lineament between OR-15 and OR-19 is recognized clearly on this map. The geothermal reservoir in the reinjection area of the Otake geothermal field is therefore considered to be controlled by a NW-SE trending structure between OR-15 and OR-19 resulting in the water level changes in the northern portion of the reinjection area being larger than these in the southern portion. A comparison between the observed and the calculated water level changes obtained by the inversion is given in Table 1.

6. CONSIDERATIONS

6.1 Factors that affect gravity changes and pressure changes around OR-15

According to the multiple regression analysis, gravity changes around OR-15 are likely to be controlled by the reinjection flow-rate changes in blocks A, B and C. The reason why the influence degree of pressure changes in OR-15 is larger than that in OR-19, is probably that the area around OR-15 is more strongly affected by the hydraulic conditions controlling the reinjected water flow, but further investigation of this matter will be required. Comparing the water level changes in OR-15 with the gravity changes around OR-15, there seems to be a strong correlation between these two sets of data during some periods. The gravity changes observed in the study area are believed to reflect not only the local reservoir pressure changes around OR-15 but also the general reservoir pressure changes over a relatively broad area.

6.2 Factors affecting water pressure changes in OR-19

The pressure changes in OR-19 strongly correlate with the reinjection flow-rate in block D. The water level changes in OR-19 are therefore considered to be controlled mostly by the reinjection flow-rate changes in the western portion of the reinjection area, while the reinjection flow-rate changes in other portions have little effect on the water level changes in OR-19.
Further evidence of the presence of an impermeable structure between OR-15 and OR-19 is indicated by the large water level difference (150m) between these two wells which are only about 200m.

6.3 Distribution of water level change

Because a good correlation is obtained between the observed water level changes and the changes calculated by quasi-three-dimensional density analysis, it is considered that the general tendency of the water level changes can be estimated from quasi-three-dimensional analysis of gravity changes. According to the inversion results, the geothermal reservoir is considered to be controlled by a structure striking NW-SE between OR-15 and OR-19. Since, the Otake Fault is located close to the NW-SE trending structure, this structure is likely to be associated with the Fault. The reinjected water in the reservoir is considered to flow mainly into the northern portion of the reinjection area because the water level change in the north (derived from the inversion results) is greater than that in the south.

7. CONCLUSIONS

Multiple regression analysis and quasi-three-dimensional density analysis, together with repeated gravity measurement data, repeated water level measurement data, reinjection flow-rate data and rainfall data in the Otake geothermal field indicate :

- The geothermal reservoir in the Otake field is considered to be controlled by a structure striking in a NW-SE direction which seems to be associated with the Otake Fault.
- The pressure changes around OR-15 are considered to be affected not only by the reinjection rate changes around OR-15 but also by the reinjection changes in blocks A and C, and the amount of rainfall.
- The rainfall in and around the Otake field seems to affect reservoir pressure changes around OR-15 and O-16R after a 3-month time lag.
- The gravity changes seem to reflect the density changes in a relatively broad area, but not the local and rapid density changes caused by the reinjected water.
- The general tendency of the water level changes is considered to be reasonably estimated by quasi-three-dimensional density analysis.
- The reinjected water in the reservoir is considered to be flowing mainly to the north.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

Manabe, T. and Ejima, Y. (1986). *Reservoir Structure of the Hatchobaru Geothermal Field and Evaluation*, Chinetsu, Japan Geothermal Energy Ass, Vol. 23(3), pp.197-205.

Taguchi, S., Irie, A., Hayashi, M. and Takagi, H. (1985). *Subsurface Thermal Structure Revealed by Fluid Inclusion Thermometer at the Otake Geothermal Field, Kyushu*, Journal of the Geothermal Research Soc. of Japan, Vol. 7(4), pp.401-413.

Matsumoto, T., Kumagae, I., Harada, S., Fujino, T., Yahara, T. and Takagi, H. (1989). *Operation Record and Management of the Otake and Hatchobaru Geothermal Power Station*, Chinetsu, Japan Geothermal Energy Ass, Vol. 26(4), pp.239-261.

Allis, R.G. and Hunt, T.M. (1986). *Analysis of exploitation-induced gravity changes at Wairakei Geothermal Field*, Geophysics 51, pp.1647-1660.

Hunt, T.M. (1995). *Microgravity measurements at Wairakei Geothermal Field, New Zealand : a review of 30 years data (1961-1991)*, Proc. World Geothermal Congress 1995, pp.863-868

Tagomori, K., Ehara, S., Nagano, H. and Oishi, K. (1996). *Study on Reservoir Behavior based on Gravity Changes in the Hatchobaru Geothermal Field*, Journal of the Geothermal Research Soc. of Japan, Vol. 18(2), pp.91-105

Koike, K., Doi, E. and Ohmi, M. (1991). *Seasonal Fluctuations and Analysis of Ground-Water Level Using Multivariate Regression Model*, Geoinformatics, Vol. 2(3), pp.255-263. (in Japanese with English abstract)

Watanabe, T., Okubo, S. Sakashita, S. (1994). *The effect of rainfall on the gravity field*, Proceedings of the Conference of the Volcanological Society of Japan in 1997, pp.275. (in Japanese)

Fukuda, Y., Yusa, Y. and Takemura, K. (1995). *Application of the Precise Gravity Measurements for the Study of Groundwater Level Changes*, Study Report of NISSAN-KAGAKU SHINKO ZAIDAN, Vol. 18, pp.65-68. (in Japanese with English abstract)

Table 1. Comparison between observed and calculated water level changes (February 1998 to April 1998).

	Observed water level changes	Calculated water level changes
OR-15 well	-6.6m	-6.3m
OR-19 well	-7.9m	-7.3m
O-16R well	-1.1m	-0.7m

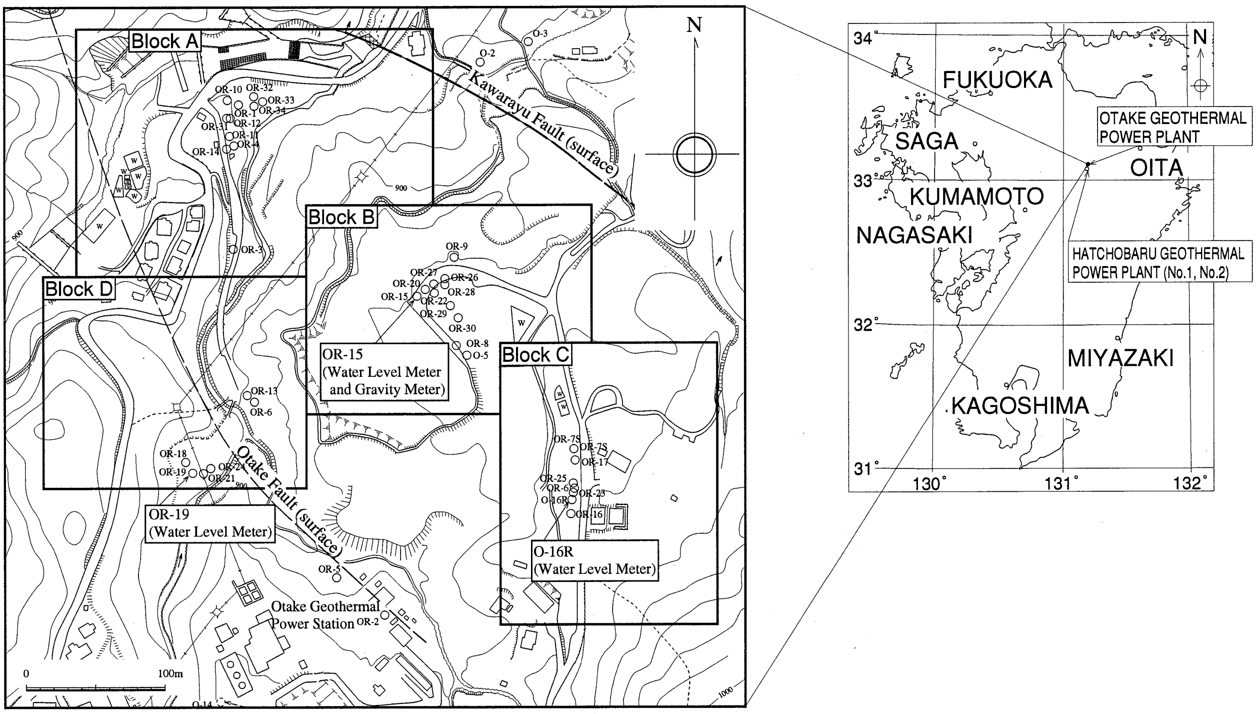

Figure 1. Location map of the four blocks (A, B, C, and D) in Otake field. Contour interval for topography is 10m.

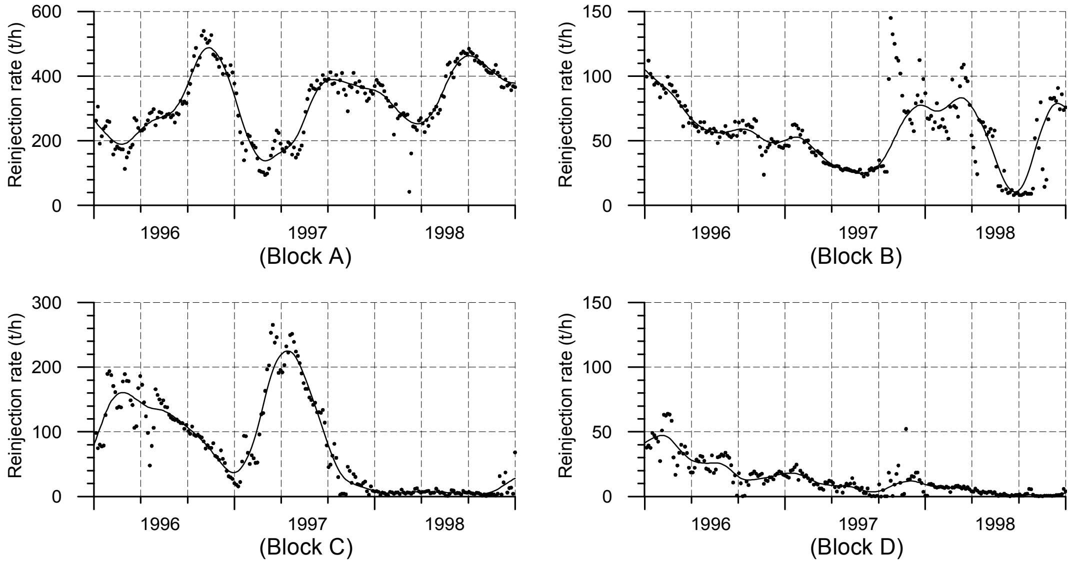

Figure 2. Reinjection rate changes in each block. Note the rates and changes in rate in block A are much lager than in other blocks.

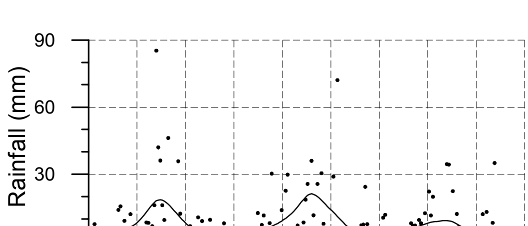

Figure 3. Amount of rainfall in and around the Otake geothermal field

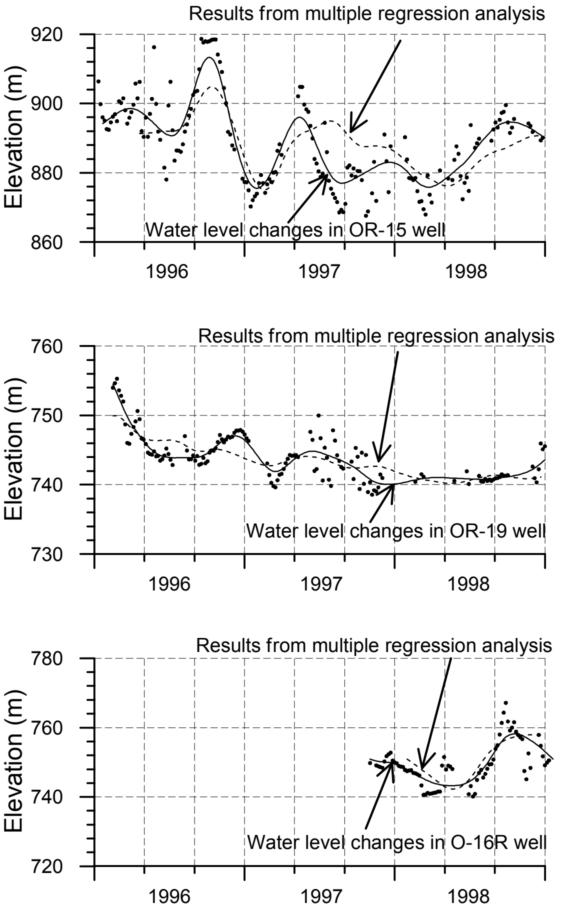

Figure 4. Comparison between observed water level changes and values calculated by multiple regression analysis

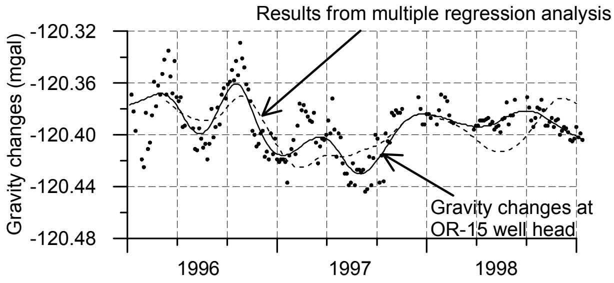

Figure 5. Comparison between observed gravity changes at OR-15 and values calculated by multiple regression analysis

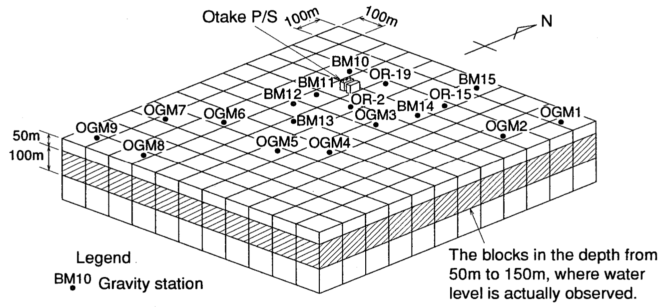

Figure 6. Subsurface density model for quasi-three-dimensional analysis

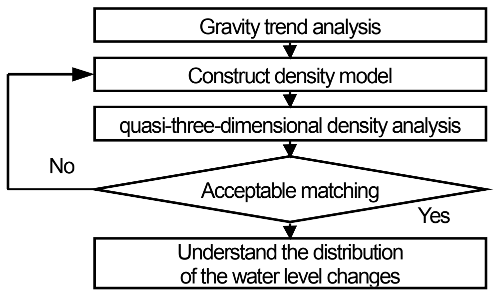

Figure 7. Flow chart of the quasi-three-dimensional density analysis

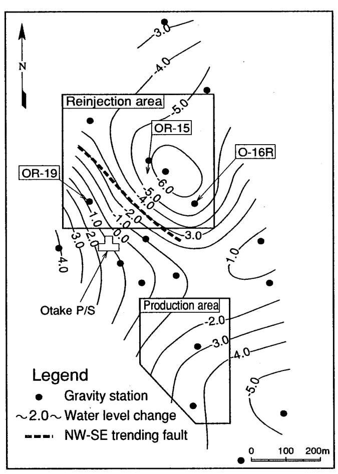

Figure 8. Distribution of gravity changes in Otake geothermal field between February 1998 and April 1998

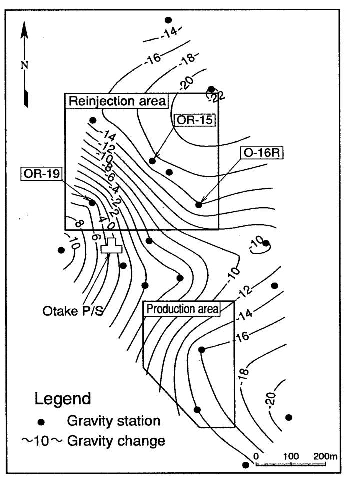

Figure 9. Distribution of water level changes in Otake geothermal field, between February 1998 and April 1998, calculated by quasi-three-dimensional analysis