Short-Term Microgravity Changes Due to Shut-In of Production and Reinjection Wells, the Ogiri Geothermal Field, Japan

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Keywords

Gravity monitoring, shut-in, Ogiri geothermal field, numerical simulation, reservoir model

ABSTRACT

We have carried out the so called hybrid gravity measurements at the Ogiri geothermal field in March – April 2003, during which field wide shut-in of production/reinjection wells took place, and detected small changes less than five microGal. The distribution of measurement stations showing gravity increase and decrease during the shut-in are consistent with the locations of main production and reinjection zones respectively and reproduced by numerical simulation based on a reservoir model which is constructed from various reservoir engineering data.

Introduction

Typically, the data base upon which numerical reservoir models are constructed consists of (1) geophysical and geochemical surveys of various types, usually performed prior to development, (2) geological interpretations of underground structure, (3) downhole pressure and temperature surveys in shut-in wells, (4) flowing downhole surveys in wells, and (5) pressure-transient test results. Once exploitation begins in earnest, additional data become available, such as temporal trends in downhole flowing pressure and wellhead enthalpies, which are used in "history-matching" studies. Observed gravity changes may also play an important role in history-matching process; comparison between observed and calculated changes will provide additional constraints on the mathematical reservoir model and thus improve its quality and reliability (e.g. Ishido et al., 1995).

We have carried out annual microgravity survey six times since 2000 at the Ogiri geothermal field. In April 2003, NKG (Nittetsu Kagoshima Geothermal Co.) carried out shut-in of production and reinjection wells associated with a maintenance of the power station (Horikoshi et al., 2005). We planed and carried out additional repeat measurements using an absolute gravimeter as a reference to detect changes in microgravity corresponding to this shut-in, which was the first field wide one since the startup of the power station in 1996.

Generally, microgravity monitoring involves the measurement of small changes in gravity over time, across a network of stations, with respect to a fixed base. Regional gravity variations can cause errors in the determination of the gravity "datum" against which any measured changes are referred. A combination of absolute and relative gravimetry, which is named "Hybrid Gravity Measurement" (HGM) by Okubo et al. (2002), provides a solution to this problem. It is useful to

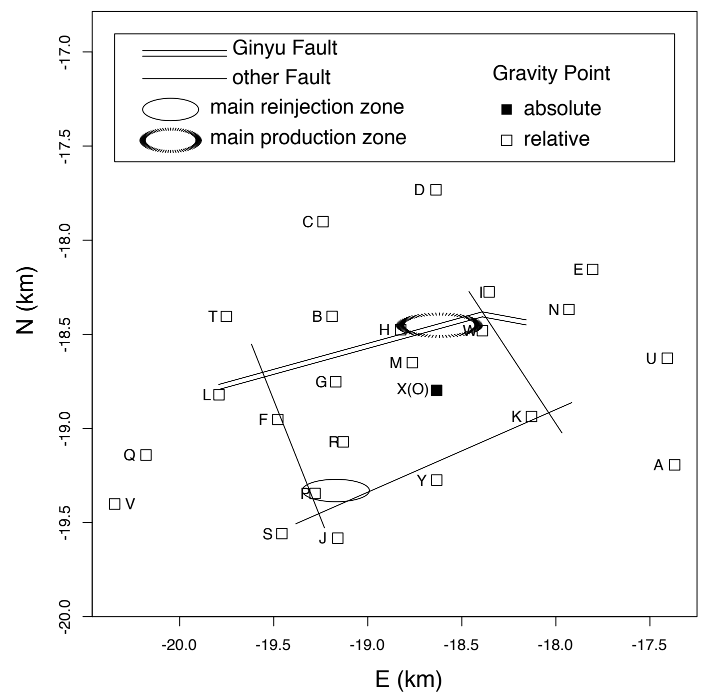

Figure 1. Locations of gravity station in the Ogiri geothermal field. The FG5/217 absolute gravimeter was set at point "X". The base station "O" was set neighbor to point "X" for relative measurements.

connect the array of observation stations with absolute gravity stations, to reduce any uncertainties caused by regional gravity variations.

Based upon the results of preliminary study of "HGM" using "Micro-g FG5L" at the Ogiri field in January 2001 (Sugihara, 2001), we have upgraded it to the standard absolute meter "FG5" (S/N 217) and used it for the survey in March – April 2003. In the present paper, the results of this survey and preliminary history-matching study using a combination of the "STAR" geothermal reservoir simulator (Pritchett, 1995) and the "GEOSYS" database software (Stevens et al., 2000) will be presented.

Repeated Hybrid Microgravity Survey During Field Wide Shut-In at the Ogiri Field

Ogiri Geothermal Field

The 30 MW Ogiri geothermal power plant started its operation in early 1996 on the western slope of Kirishima volcano in Kyushu island, Japan (Goko, 2000). Figure 1 shows the location map of the area as well as the major faults that control the geothermal system in the Ogiri area. Fractured-type geothermal reservoir was found below about 900 m depth along the Ginyu fault. Ten production and nine reinjection wells were drilled to 1000-1500 m depth and to 800-1300 m depth respectively. All waste water is reinjected into a wellfield located about 800 m west of the production area. At first, about 30 % of the fluid was injected using wells that penetrate fractures connected to the production zone. However, the distribution of flow rate among the individual reinjection wells has been adjusted to reduce temperature decline in the production zone on the basis of reservoir pressure and temperature monitoring, periodic geochemical analysis and tracer tests (Yokoi et al., 2001). Main reinjection zone at present is shown in Figure 1.

Relative Gravity Measurements

A "Scintrex CG3M" gravimeter (S/N 367) was used to make relative gravity measurements at 24 points out of the annual-survey network for the present survey in March-April 2003. These points covered a 2 km x 3 km area as shown in Figure 1. Allis et al. (2000) recommended the optimum use of the CG3M gravimeters for geothermal reservoir monitoring. The occupation of each benchmark is typically 15 – 20 minutes, giving at least 30 gravity values, and each benchmark should be revisited at least once during the day and at least one base station should be occupied three times during the day. Such a procedure can cover between 8 and 12 new benchmarks in a day. This method, however, is not suitable for the present measurements, since it is too time consuming to accomplish one survey of 24 benchmarks within as short as possible duration for ensuring simultaneity.

We chose another method for the present surveys: all the benchmarks are visited in a day and base station "O", which is set neighboring to the absolute point "X", is occupied four times at least during the day (see Figure 2, upper panel). The read time of 48 seconds is selected considering the balance between times short enough to give many readings and long

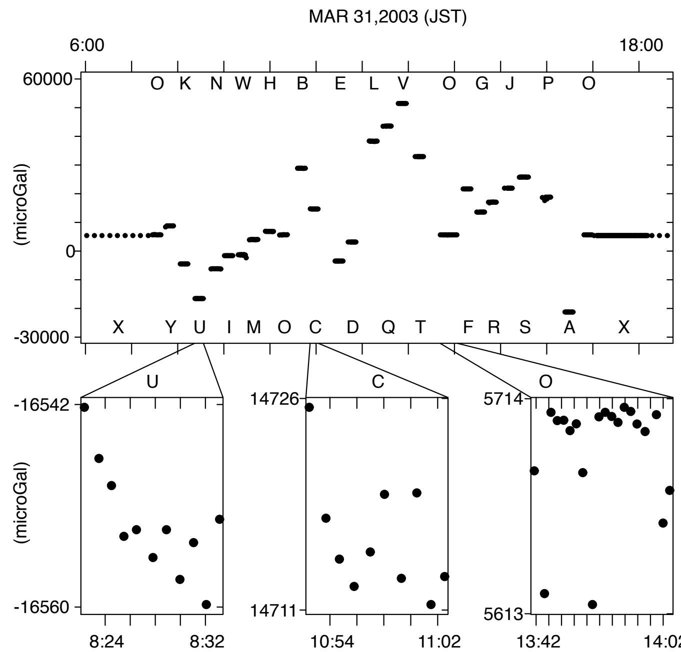

Figure 2. Typical result of one day relative gravity measurements at the Ogiri field. Each cluster of points shown in the upper panel comprises 48-second-instrument-integrated values, some of which are shown in the lower panels. Each station was visited once in each day, and the base station "O" was visited four times during the day. The relative gravimeter "CG3M" was operated in cycling mode at night alongside the "FG5" absolute gravimeter.

enough to give stable mean value. The occupation of each benchmark is typically 10 minutes, giving at least 10 gravity values and showing a short-term drift trend due to the handling history of the meter immediately prior to the set-up at that benchmark (Figure 2, lower panels). Gravity value at each occupation can be estimated with an error of about 5 microGal (1 microGal=10^{-8} m/s^2) in most cases.

The resulting gravity value was then corrected for tides and vertical gradient. The Earth tide correction computed by the "Scintrex" software is based on an algorithm developed by Longman (1959). However, the model used in this software was not accurate enough for microgravity studies. Thus a new correction was computed using the program "BAYTAP-G" (Tamura et al., 1991). For each wave group, the amplitude and phase coefficients of this model were determined on the basis of the analysis of the tide observed at the site.

Absolute Gravity Measurements

An absolute gravimeter observes the acceleration of gravity directly, by observing the free-fall of a reflective corner cube in a vacuum. The "FG5" absolute gravimeters have an estimated instrumental accuracy of 1-2 microGal (Sakagawa et al., 1995). The default settings are to start a series of measurements for 24 hours (called as "project") and collect one set of 100 drops (with 10 seconds drop interval) every 30 minutes. Figure 3 shows the relation among the "drop", "set", "project" and "survey"; e.g. the second "survey", which was made in April 2003, consists of six "projects" and the 3rd project of the second survey consists of 48 "sets". The 47th set of the 3rd project

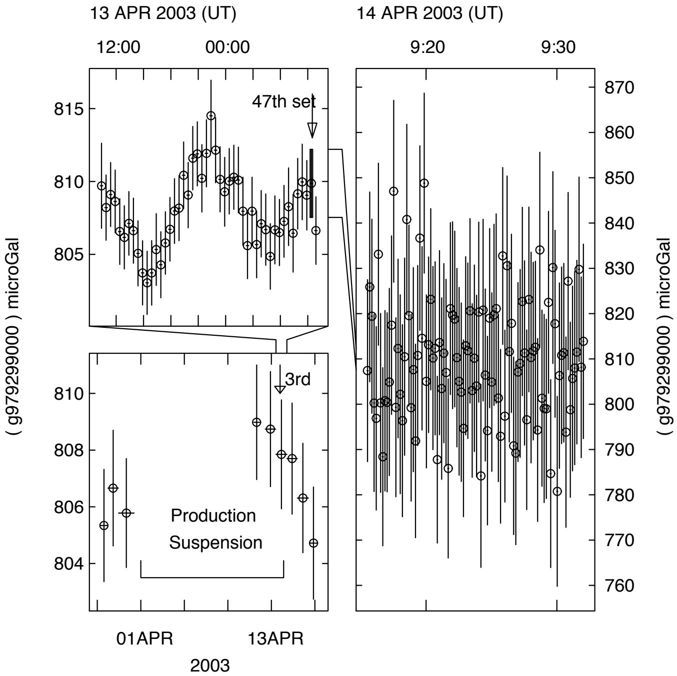

Figure 3. Absolute gravity measurements with the "FG5/217" at the Ogiri field. Two "surveys" were made; the first and second survey consists of three and six "projects" respectively as shown in the lower left panel. For example, the 3rd project of the 2nd survey consists of 48 "sets" as shown in the upper left panel and the 47th set of the 3rd project consists of 100 "drops" as shown in the right panel.

consists of 100 "drops". During each drop 750 samples were fit to a parabolic trajectory and an absolute value of gravitational acceleration was determined. The resulting acceleration was then corrected for Earth tides, ocean loading, polar motion, barometric pressure, and vertical gradient, with a software called as "g".

Figure 3 (upper left panel) shows a typical result at the Ogiri field. Diurnal and semidiurnal gravity changes of 5 to 10 microGals were observed in the "set" values. In the present surveys, the first and second "surveys" were carried out for 3 days (before the field wide shut-in) and for 7 days (from the middle of the shut-in period), respectively. In each survey, the gravimeter was carefully set-up again at the start of each day ("project"), following the procedure shown by Williams et al. (2001). The standard deviations of the half-hourly means ("set" values) are shown for each "project" in lower left panel of Figure 3.

Observed Change

As shown in Figure 3 (lower left panel), the absolute gravity "project" values of the first survey were normal, that is, no change exceeding the standard deviations was present. However, the project values of the second survey showed an increase of more than 2 microGal compared to those of the first survey at the beginning and an obvious decreasing trend afterwards.

Concerning the data obtained by the relative measurements, we made several improvements on the data reduction method considering the characteristics of the data (e.g. cubic regression curve was fitted to the data to estimate daily trend). The dataset contains fewer constraints on the looping process than the usual annual data acquisition since revisiting to the same benchmark was at most four times a day. All the data were processed simultaneously assuming that the gravity value at each benchmark was constant during the period from the first survey to the second survey. Temporal gravity change at each point, therefore, was inferred from the variation in the residuals; the variations of some points are shown in Figure 4.

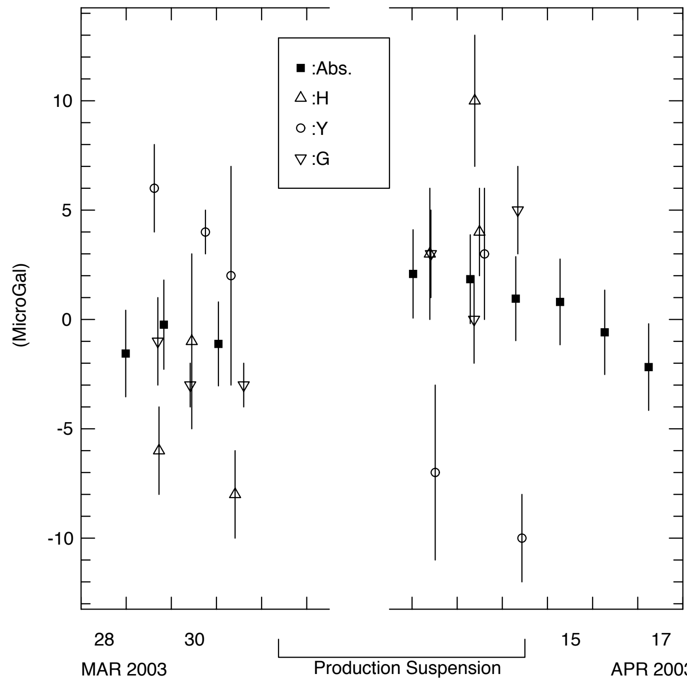

Figure 4. Temporal changes of observed absolute gravity (solid square) and processed residuals of relative measurement for three stations.

Figure 5 shows the difference in the mean residual at each point between the two surveys, the first one during 28-31 March (before the shut-in) and the second one during 12-14 April (latter half of the shut-in period). Positive and negative changes are observed near the main production and reinjection zones, respectively. Considering the estimation errors (shown in Figure 5), the result should be discussed carefully. However, the distribution of observed changes is qualitatively consistent with the expected changes for the shut-in period. It should be noted that temporal change in the observed absolute gravity, shown in Figures 3 and 4, was referred in the data reduction process. Without the absolute data the contrast between the positive and the negative changes is calculated to be about 1-2 microGal smaller than that shown in Figure 5, overleaf.

Calculation of Gravity Change Based upon a Reservoir Model

Reservoir Simulation

A reservoir model of the Ogiri field developed by Nittetsu Kagoshima Geothermal Co. and others reproduces fairly well the production histories such as pressure changes in observa-

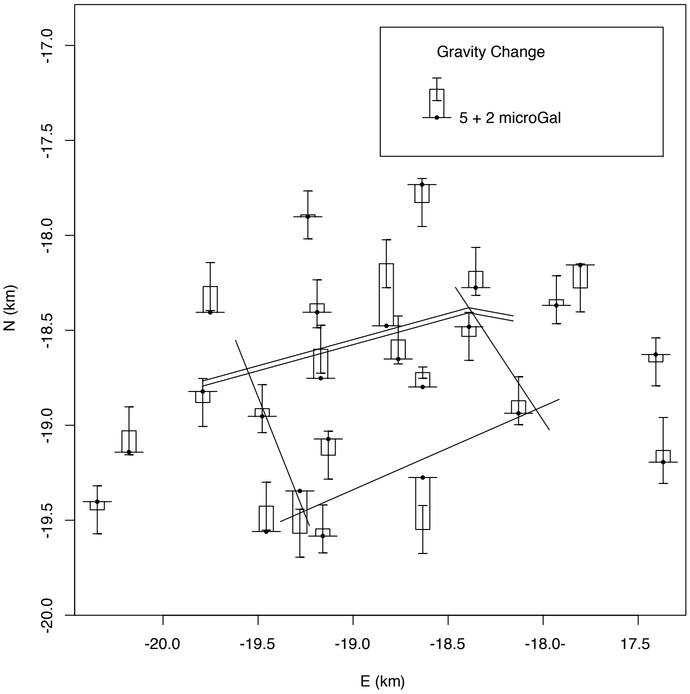

Figure 5. Gravity changes observed between the first survey on 28-31 March (before the shut-in) and the second survey on 12-14 April (latter half of the shut-in period). Positive and negative changes are observed near the main production and reinjection zones, respectively.

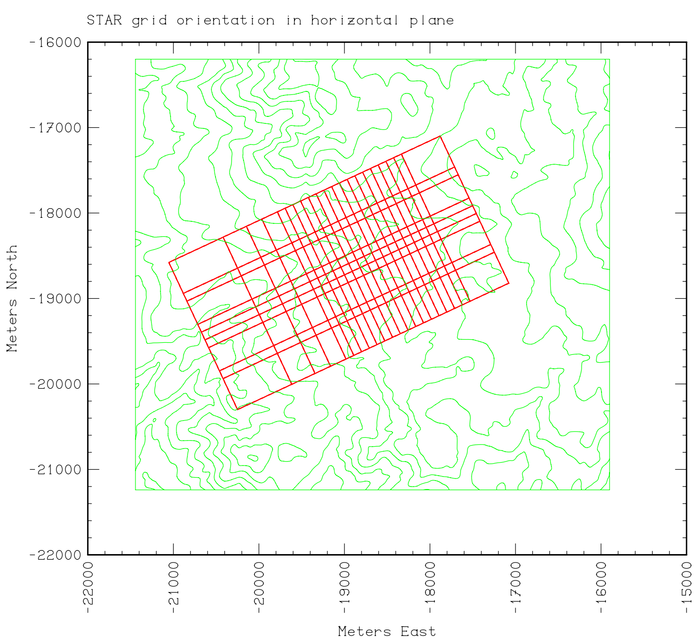

Figure 6. Area considered in mathematical simulation studies, showing computational grid spacing.

tion wells in addition to the natural state distributions of temperature and pressure (NEDO, 2002). We modified the model and used it for calculating changes in gravity during the field wide shut-in of production/reinjection wells in April 2003.

We considered 3500 m × 1900 m area shown in Figure 6. Figure 7 shows a vertical ENE-WSW cross-section along

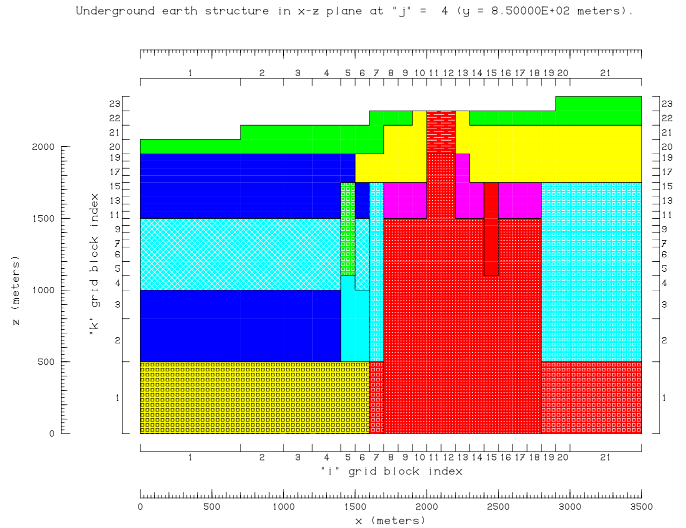

Figure 7. ENE-WSW vertical section through grid blocks along the Ginyu fault. Different colors separate grid blocks containing different rock formations.

the Ginyu fault zone (the vertical extent is changed from the original model and finer grid division is adopted). Seventeen rock formations are present, which differ in permeability. Other formation properties are uniform: porosity is 0.1, rock grain density is 2500 $kg/m^{3,}$ rock heat capacity is 1050 J/kg-°C, and thermal conductivity is 2 W/m-°C. Relative permeabilities are simple straight-line functions with residual water and steam saturations of 30% and 5% respectively. All vertical grid boundaries except the west-southwestern one (where pressure is held at prescribed value depending on the elevation) are impermeable and insulated. Pressure and temperature at the top grid surface are held at one bar and 20°C respectively. Most of the bottom surface (at -1600 m RSL) is impermeable, but an upward conductive heat flux of 0.4 W/m^2 is imposed over the entire bottom surface. Furthermore, 46 kg of hot (243-260°C) water flows upward per second into the reservoir through a few central areas of the bottom surface. (Rock properties and assignment of boundary conditions are also slightly modified from the original model.)

In the present calculation, we used the "STAR" geothermal reservoir simulator (Pritchett, 1995) and the STAR interface of "GEOSYS" database software (Stevens et al., 2000) to prepare the initial numerical model (such as assignment of rock formations to each grid blocks). To calculate the "natural state" of the system, an initial temperature distribution was first imposed which increases with depth from 20°C at the surface, with a corresponding hydrostatic initial pressure distribution. No steam is present initially. Next, a lengthy time-dependent STAR calculation was carried out representing 120,000 years of evolution – sufficient to reach a "natural state" that is steady for all practical purposes. Figure 8 (a) shows the final natural-state distributions of temperature, pressure and vapor-phase saturation in the vertical plane along the Ginyu fault. Heat transfer in the relatively impermeable basement and caprock layers (the permeability of the caprock layer is 0.01 millidarcy) is dominated by conduction, but the permeable zones along the Ginyu fault (where the largest permeability assigned is

1 darcy) etc. are dominated by natural convection, with a relatively homogeneous temperature distribution (~240 °C along the Ginyu fault).

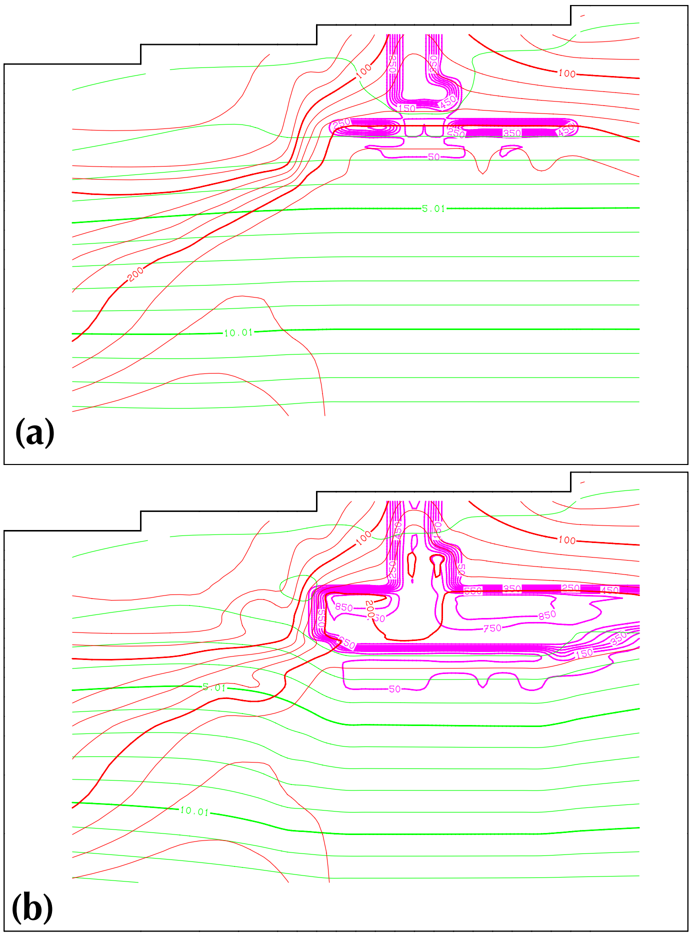

Figure 8. The distribution of pressure, temperature and vapor-phase saturation under (a) pre-exploitation state and (b) exploitation state after 10 years of operation. Contour interval is 10 bars, 25°C and 0.1 for pressure, temperature and vapor-phase saturation, respectively.

Next, starting with the "natural state" shown in Figure 8 (a) as initial conditions, a second STAR reservoir simulation was carried out which represents 10 years of 30 MW power production. Boundary conditions and formation properties are the same as for the natural-state calculation. Twelve production wells and seven injection wells were incorporated within the model. A constant total wellhead steam flowrate (sufficient to generate 30 MW of electricity) was assumed to be withdrawn from the production wells. A fixed separator pressure of 2.5 bars was used, and all separated liquid water (together with a small amount of steam condensate) was reinjected. Although the present model roughly reproduces the locations of the various wells and the total fluid production/reinjection rates, operation history and flow rate of individual wells (Figure 9) are not adjusted to reproduce the real situation. As for the short-term changes, only the shut-in operation in April 2003 is incorporated. Conditions at the end (10 years) of this exploitation calculation are shown in Figure 8 (b). The two-phase region has grown and expanded about 300 m downward owing to the pressure decline. Steam saturations have also increased markedly.

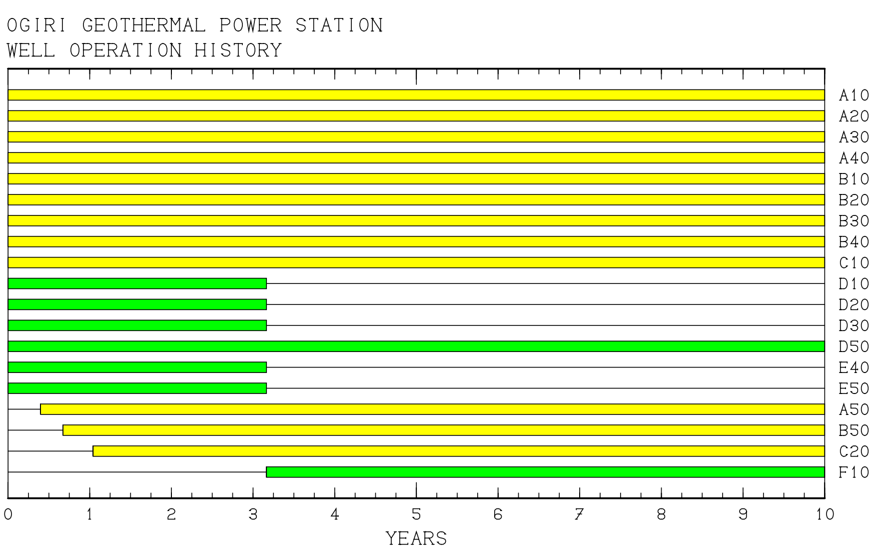

Figure 9. Well operation history assumed in the exploitation calculation. (Actual well name is not used in this figure.)

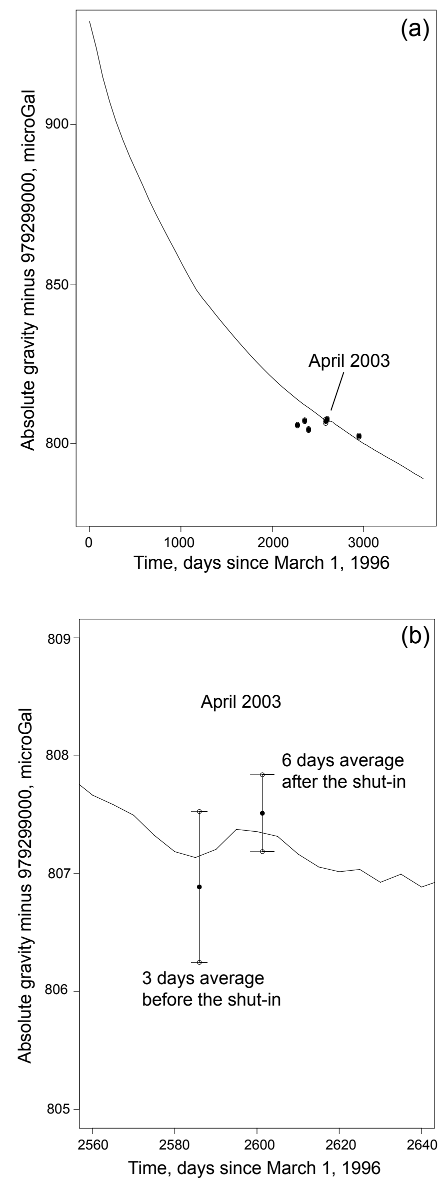

Figure 10. Calculated gravity change at the central station during 10 years of operation. The vertical location of the curve is adjusted so as to pass the observed values in March-April 2003. Absolute values obtained from the annual surveys are also shown in addition to the average values in March-April 2003.

Change in Gravity

STAR's "microgravity" postprocessor was used to calculate the gravity changes at the earth surface from the redistributions of underground fluid mass due to production and injection computed by the exploitation calculation. Figure 10 compares the calculated and observed changes in ground-surface microgravity at the central station where the absolute measurements were repeated. Several reliable absolute values obtained from the annual surveys are also shown in the figure in addition to the average values obtained from the surveys in March-April 2003.

As seen in Figure 10(a), the calculated gravity decreases more than 100 microGal over the seven years from 1996 to 2003. Although it does not explain the difference between the observed values in 2002 and 2003, it reproduces well the observed trend during about one year from April 2003. As seen in Figure 10(b), short-term recovery is calculated as ~0.3 microGal corresponding to the field wide shut-in of April 2003. Although this calculated recovery is smaller than the observed maximum change of ~2 microGal shown in Figure 3, it is in good agreement with the difference between the averages of observed values over several days before and after the shut-in. In addition, the calculated spatial pattern of gravity change shown in Figure 11 is consistent with the observed distribution shown in Figure 5.

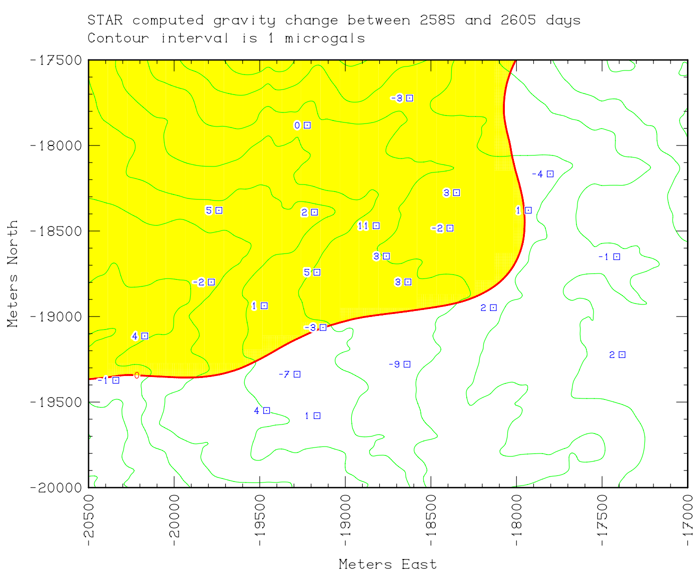

Figure 11. Gravity change at each station observed between the first survey on 28-31 March (before the shut-in) and the second survey on 12-14 April (latter half of the shut-in period). Red line separates the regions of gravity increase (yellow colored) and decrease computed by the reservoir simulation.

Concluding Remarks

NEDO carried out a SP survey of the Ogiri field in 1998. Comparing this result to that in 1987, decreases in SP were detected both in the production and reinjection areas. These changes are thought to be induced by the exploitation operation. In addition to repeat surveys, continuous SP monitoring was carried out by NEDO from 1998 through 2001. Total number of Pb-PbCl_2 electrodes involved in the measurement was more than 50. Changes in SP more than 20-30 mV were observed near the production and reinjection wells respectively.

In collaboration with NKG, GSJ carried out continuous SP measurement in addition to repeated gravity surveys in 2003 (e.g. Ishido et al., 2005). We will proceed history-matching studies based upon the reservoir model (described in this paper) using those long- and short-term SP data in addition to the changes in micro-gravity.

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