STUDY ON RESERVOIR BEHAVIOR FROM MICRO-GRAVITY CHANGES MONITORED IN THE HATCHOBARU GEOTHERMAL FIELD, JAPAN

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Abstract

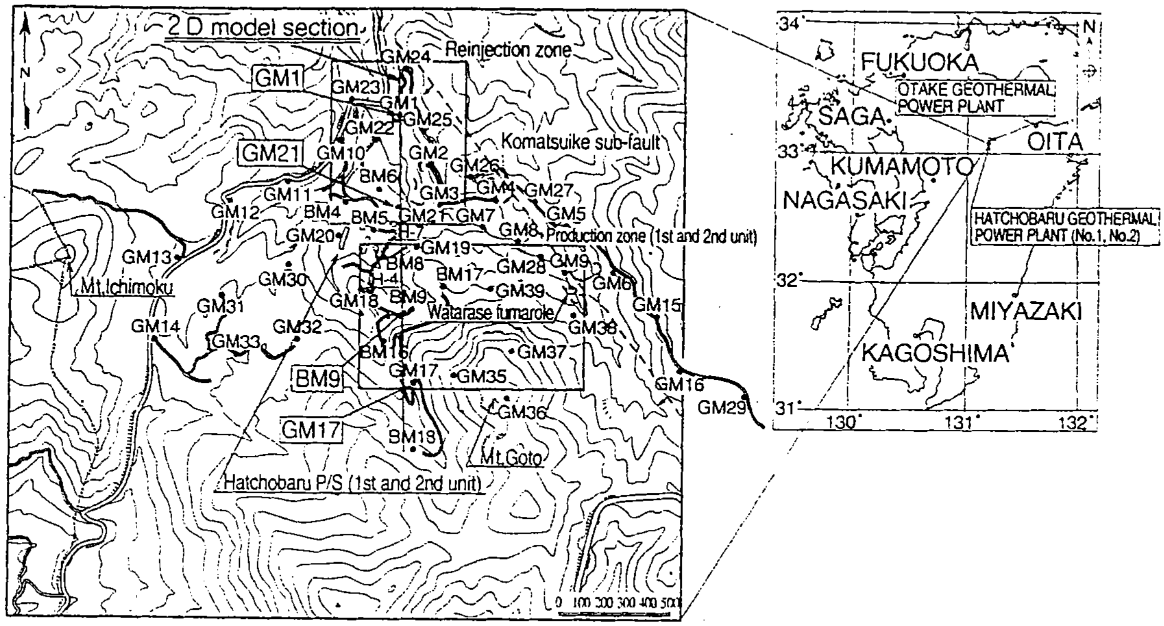
In the Hatchobam geothermalfield, gravity changes at 46 benchmarks have been monitored since May 1990 to study the correlation between gravity and reservoir pressure changes that have been measured using three observation wells with capillary tubes. From the data monitored during 1990 to 1993, a close correlation between these two changes was recognized, and the area was divided into three zones, such as northern, central and southern zone, from the pattern of gravity changes. In the northern and the central zones, the value of gravity at each point showed a steep increase just after the commercial operation of the Hatchobaru N0.2 unit (55 MW) was commenced, after that, it turned to decrease to the initial level in the northern zone and to lower level than the initial level in the central zone. In the southern zone, gravity has decreased without any initial increase tendency. From a two-dimensional modeling analysis, gravity changes in each zone are considered to reflect the change of reservoir mass behavior that had been caused by production and reinjection of geothermal fluids in the reservoir.

1.0 INTRODUCTION

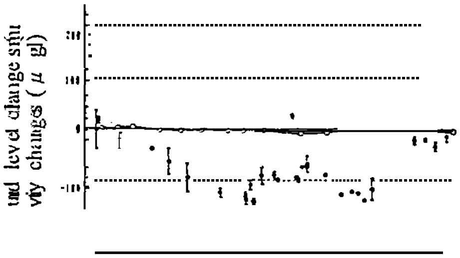
In June 1990, the Hatchobaru N0.2 unit (55 MW) owned and operated by Kyushu Electric Power Company Inc. (KEPCO) started its commercial operation in addition to the No.1 unit (55 MW) that started its commercial operation in June 1977. The maintenance of geothermal reservoir for the generation of 110 MW in stable conditions was one of the important subjects after the N0.2 unit operation was added to the previous unit. To monitor the mass change being occurred in the reservoir due to the pressure change that would be induced by the change of production and reinjection rates with shifting the output from 55 MW to 110 MW, micro-gravity measurements at fixed locations were introduced with a suggestion by Prof. Sachio Ehara of Kyushu Univ. Recent gravimeters have sensitivities sufficient to reliably measure differences in gravitational acceleration of about between 5 and 10 μgal (10^{-8} $m/sec/sec$), though the acceleration of gravity is actually a function of numerous factors including mass distribution beneath the measuring point and its absolute elevation. In this paper, referring to the first practical test of precision gravimetry in geothermal studies at the Wairakei field established by Hunt (1970, 1983, 1988), and Allis and Hunt (1986), the authors will describe the interpreted results regarding the reservoir behavior for 1990 - 1993 (partially 1990 - 1995) from gravity changes, taking other effects such as elevation changes, ground motions related to local seismic activity and etc. into account. A result of two-dimensional modeling study will be also discussed that might guide us to maintain the reservoir in stable and the most appropriate conditions.

2.0 GRAVITY MEASUREMENTS

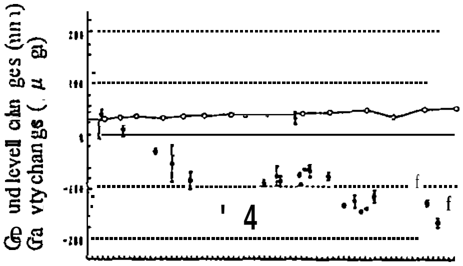
Repeated gravity measurements have been made since 1990 on 46 benchmarks (Figure 1) using Sintrex CG-3 gravimeter. The instrument has a reading accuracy of 1 μgal showing with standard errors statistically computed using about 120 sampled values for two minutes at each benchmark in the field. It also has a function to correct for changes in the gravitational attraction of the sun and moon automatically in real time. Looping techniques have been adapted to minimize errors associated with instrument drift and the least squared method was applied to obtain the most reliable gravity values. We calculated the correction values for



We repeated leveling surveys in and around the Hatchobaru geothermal field after 1979 for three to four times a year aiming at monitoring topographic changes associated with the withdrawal of geothermal fluids. Those leveling benchmarks have also been used for gravity measurements to interpret



correspond to about -11 to +5 μgal in gravity changes using 0.3086 $mgal/m$ as elevation correction value. Figure 2 shows the values of gravity at BM9 and BM16. Around January 1993, those decreased by about -150 μgal comparing with respective values first measured in June 1990. This large change of gravity decrease is hardly explained only from the



3.0 CORRELATION OF GRAVITY CHANGES WITH RESERVOIR PRESSURE CHANGES

At the initial phase of this *study,* it was uncertain about whether repeat measurements of gravity could provide the information reflecting **mass** behavior in geothermal reservoirs. For this reason, to check the effectiveness of the technique, the gravity data at benchmarks beside observation wells were correlated to the reservoir pressure changes that had been monitored with capilary **tubes** inserted into the wells.

3.1 Correlation between BM8 and H-4 observation well

The values of pressure observed in the H-4 observation well (Figure 3), provided that the pressure monitored **just** after helium gas charged should be considered as intrinsic values reflecting geothermal reservoir pressure, started to decrease in the middle of 1990 and showed the **minimum** at the first quarter in 1992. Thereafter, the changes seem to be recovering with a gentle fluctuation to date. The curve of gravity changes drawn with a broken line in the lower part of the figure, which was obtained from the polynomial approximation, shows a harmonious correlation with that of pressure Changes. The coefficient of correlation between these two curves is 0.93.

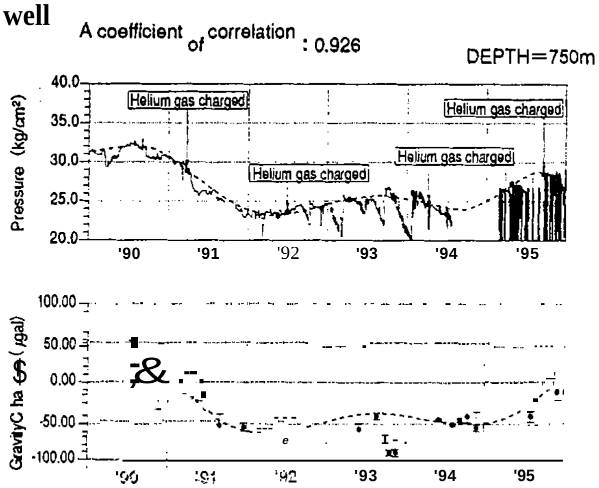


Figure 3: Comparison between pressure changes in H-4 observation well and gravity changes at BM8.

3.2 Correlation between BM5 and H-7 observation well

The values of pressure observed in the **H-7** observation well (Figure 4) show a similar curve as well as that of BM8, but started to increase from the **early** middle of 1992 with a relatively steep gradient. After 1993, the values show close values with the **first** measured pressure in 1990. The curve of gravity changes (shown in the lower part of the figure) also shows a harmonious correlation with that of pressure changes. The coefficient of correlation between these two curves is 0.82.

The resultant coefficients of correlation between gravity and pressure changes at two benchmarks beside the observation wells were higher than 0.8. This proves that, the changes in gravity at points in and near the Hatchobaru geothermal field, which are detectable and have been monitored, can be regarded as the reflection of changes of reservoir pressure. The changes of reservoir pressure is regarded as changes in rock density in turn caused by changes in mass distribution in the reservoir.

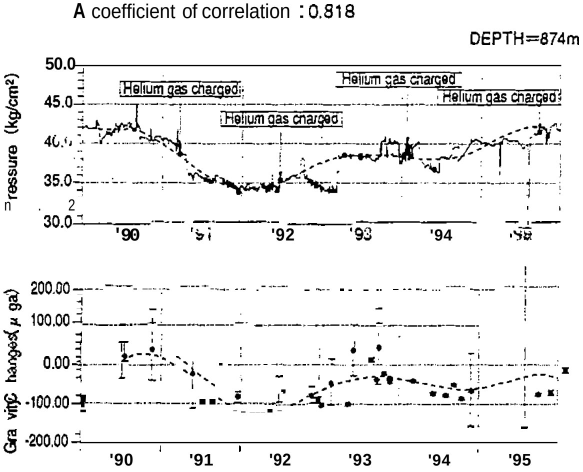


Figure 4: comparison between pressure changes in H-7 observation well and gravity changes at BM5

4.0 RESERVOIR BEHAVIOR FOR JUNE 1990 - MAY 1993

4.1 Types of Gravity Change Curves

Figure 5 shows the zones divided into **four** (*A* to *D*) groups **from** the characteristics of curves in gravity change for 1990 June - May 1993. ***Groups A**, **B*** and *C* were relatively easy to distinguish from curve characteristics. However, the rest of points except ***A*** to *C* group were put together **to *Group D*** temporarily. Roughly, ***Group D*** represents the points installed after one to **two years** for the additional measurements, therefore they are naturally difficult to classify into *A* to *C* group due to the lack of data for a short period. Judging from surrounding groups, ***Group D*** in the western part might be classified into ***Group*** *E*, on the contrary ***Group*** D in the eastern part might be classified into ***Group*** C. The features of Group *A*, *E* and *C* are summarized as follows.

4.1.1 Group A

The feature of this group is that the gravity increase occurred for about six months just after the reinjection for the N0.2 unit was started. After the six months, the gravity stopped to increase, then it started to decrease until the middle of 1992, but not to negative levels supposing that the first gravity changes are zero. From 1993, the values of gravity have increased again to date. The benchmarks classified to ***Group A*** are located only in a small part of the north of Hatchobaru where most reinjection wells are under operation.

4.1.2 Group B

As well as ***Group A***, the gravity increase occurred for about six months just after the reinjection for 110 MW generation was started. However, after the six months, the gravity started to decrease until the middle of 1992 to negative levels around -100 *μgal* below the first zero level. From 1993, the values of gravity have changed to increase to date, but show still negative values. The benchmarks classified to ***Group*** *B* surround that of ***Group A***.

4.1.3 Group C

Differing from the pattern of gravity change in ***Group A*** and *B*, this group did not show a clear increase after the No.2 unit was started. From the beginning of 1991 until around the beginning of 1993, the values of *gravity* decreased by less than -100 *μgal* with a relatively steep gradient. After that, the values of gravity have changed to increase slightly to date. The benchmarks classified to ***Group C*** are located in the south of ***Group*** *B*, and the feature of gravity change in respective points in ***Group C*** can be clearly recognized at points further located to the south.

As described above and shown in Figure 5, the location of ***Group*** *A* is almost coincident with the reinjection area. Besides, the area classified to ***Group C*** can be regarded as almost production zone. The area of ***Group B*** is the intermediate zone in between reinjection and production zone.

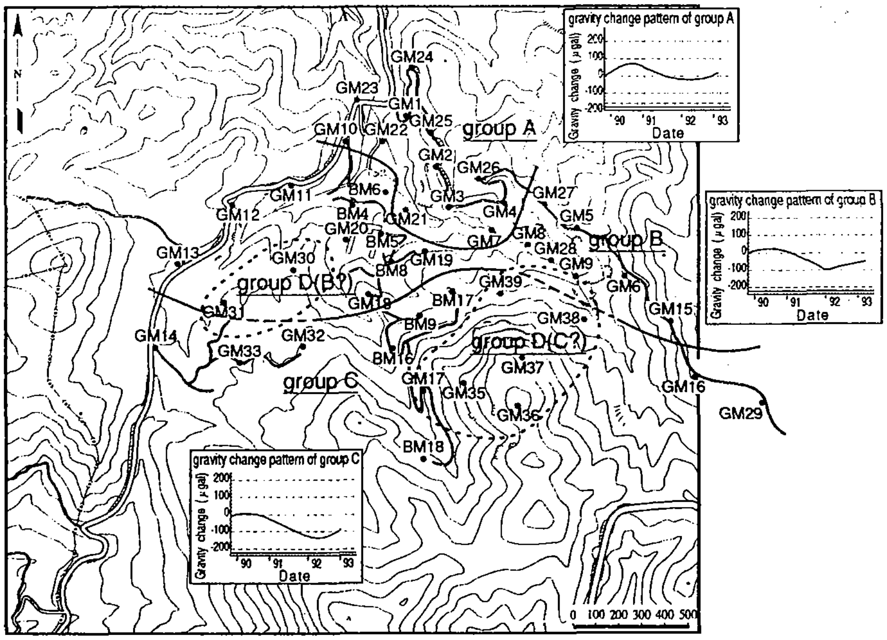


Figure 5: Distribution of A, B, C and D groups derived from patterns of gravity changes

4.2 Reservoir Behavior deduced from Gravity Changes for June 1990 - May 1993

From the distribution of gravity change patterns as previously discussed, the reservoir behavior in terms of reservoir pressure (water table) changes is studied from June 1990 to May 1993 (Figure 6). This period corresponds to the initial significant *three* years that the greatest change of reservoir mass had occurred after the production and reinjection for the **N0.2** unit was added to the No. 1 unit.

Before the commencement of commercial operation by the **N0.2** power plant unit, suppose the water table corresponding to the reservoir pressure was of condition as shown in the uppermost graph of Figure 6. From the middle of 1990 to the first half of 1991, the reinjection rate to the northern zone had necessarily increased because the steam for 110 MW instead of previous *55 MW* were required and separated hot water was reinjected. In this phase, because **most** of reinjection wells were located in a limited small part known as the main reinjection field, a clear and sudden increase of the reservoir pressure, in other words a rise of water table of observation well, occurred as shown in the second graph from the top of the figure. The production rate of *steam* and **hot** water to maintain 110 MW power was assumed to be enough in this phase. From the Iatter half of 1991 to the first half of 1992, the production rate of *steam* and hot water had gradually decreased with time, then the generating output resulted in dropping to 90 *MW*. That is, the pressure of production reservoir declined, with the consequence that the pressure of reinjection aquifer was also declined as shown in the third graph in the figure. After 1993, it seems that the mass balance in the production reservoir has been almost settled with the conditions of 90 MW generating output, and the supply of geothermal fluids from surroundings at depth has gradually getting larger, which was reflected as slight increases of gravity change at the points in production zone as shown in the lowermost graph in the figure.

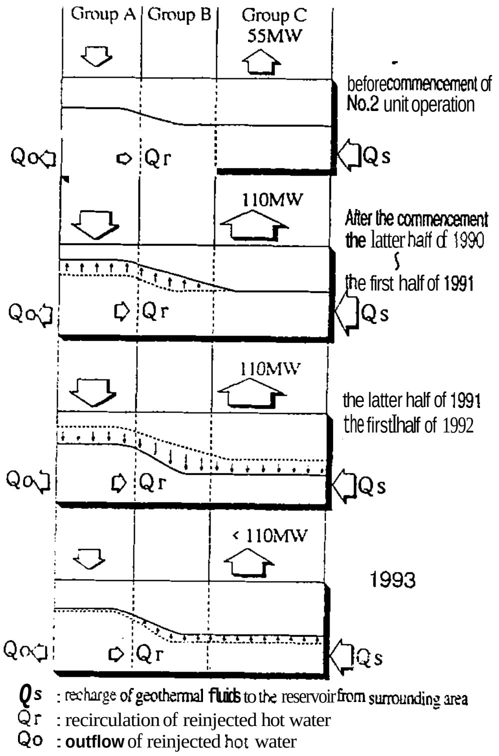


Figure 6: Reservoir behavior deduced from gravity changes in the Hatchobaru geothermal field (I990 - 1993)

4.3 Gravity Change Distribution

4.3.1 Gravity Changes from August 1991 to November 1992

Gravity changes during this period are thought to reflect the reservoir conditions when the generating output dropped to 90 MW after 110 MW operation by the No. 1 and No.2 unit (Figure **7**). The values of gravity change are in a range -20 to -120 *μgal* (max. -8 *μgal/month*), which **may** represent the degree of substantial mass change in the geothermal aquifer, The southern area near Mt. Goto (e.g. GM-36) shows a remarkable negative values. On the contrary, the northern area does not show such large negative values. The least negative zone around **GM-7** and **GM-8** shows a contour distortion in the direction of **NW-SE** which is coincident with a geological fault named Komatsu-ike fault. The distortion of the contour in gravity changes, therefore, *can* be regarded as the reflection of fluid movement in nearby reinjection aquifer and re-circulating effect to production zone along the fault.

4.3.2 Gravity Changes from November 1992 to November 1993

The gravity changes during this period are shown in Figure **8.** The values of gravity change are in a range -20 to +100 *μgal* (max. +8.3 ***μgal/month***), which correlates with the mass loss from geothermal aquifer, **had** stopped and *starts* to recover. In the northern and western areas, the gravity changes range less than ±20

μgal, which represents that the **mass conditions** under these local zones have been almost balanced. On the contrary, in the southern area, the gravity changes show bigger than +40 μgal. **This** suggests that a large recharge zone might exist in the **direction** of **N-S (from BM-8** to the **BM-8).** The geothermal fluids **mainly** along **this** zone are considered to be recharged at depth after a sudden withdrawal of geothermal fluids accompanied **with** the **operation** by the No. 2 power plant unit.

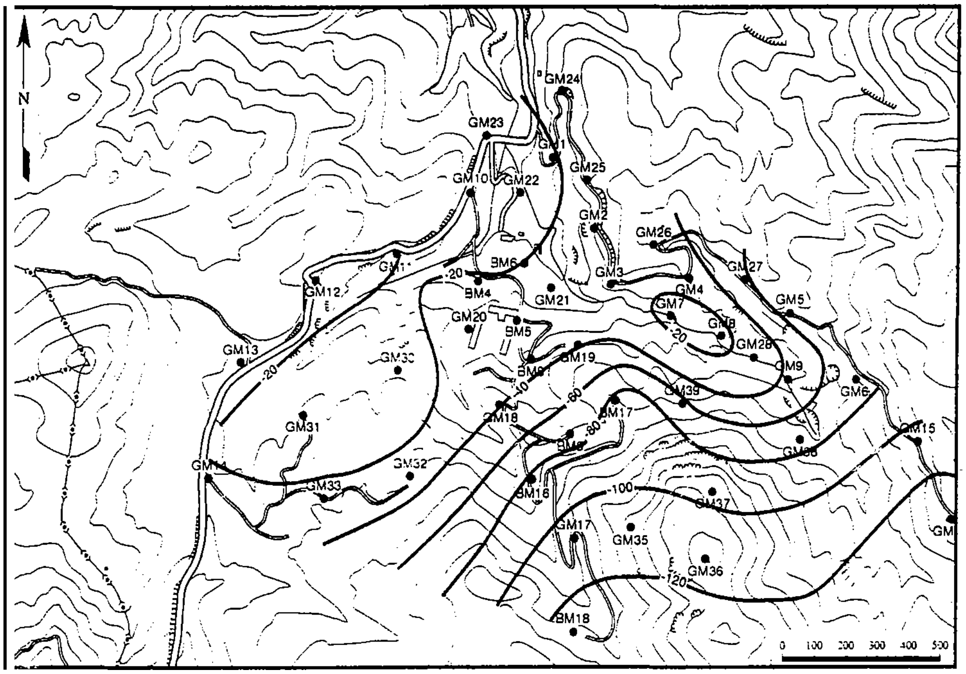


Figure 7: Gravity changes (μ gal) in the Hatchobam geothermal field from August 1991 to November 1992

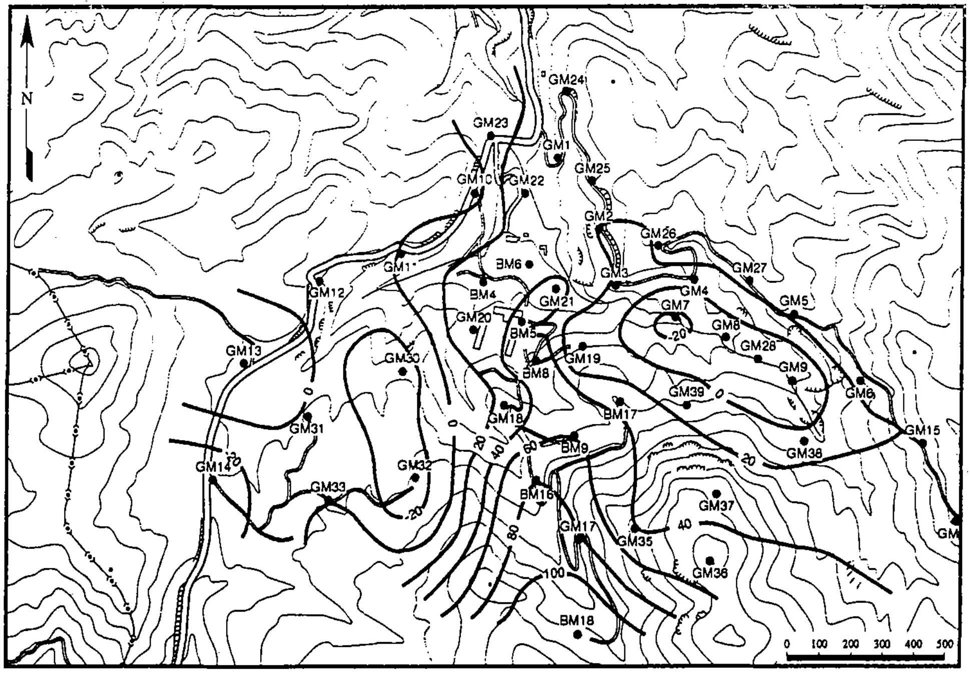
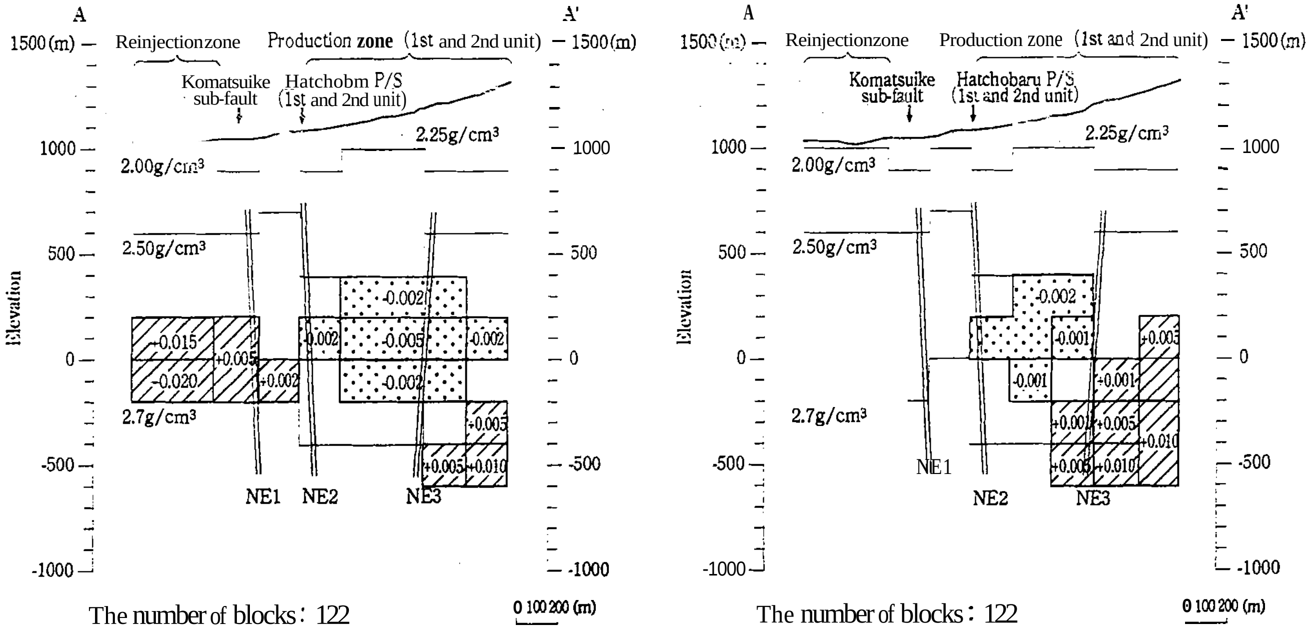


Figure 8: Gravity changes (μ gal) in the Hatchobaru geothermal field from November 1992 to November 1993

5.0 2-DIMENSIONAL MODELING

To check the phenomena previously discussed, a two-dimensional density model was constructed and was studied. To cover the area from reinjection to production zone, a section along N-S direction (shown in Figure 1) was selected. We constructed an original density model which reflects the density structure in August 1991, referring to the results of the detailed gravity survey conducted in the middle of the same year. The model consists of four density layers from the top such as Kuju volcanic group (2.25g/cm^3), the upper and middle layer of Hohi volcanic group (2.00g/cm^3), the lower layer of Hohi volcanic group (2.50g/cm^3), and Usa formation and Re-tertiary rocks as the gravity basement (2.70g/cm^3). These density values are based on the results measured in a laboratory from core and rock samples. Figure 9 shows the results of modeling analysis, which reflect the density change conditions in November 1992 and November 1993, respectively. From figures 10 (a) to (d), the calculated gravity changes (shown with squares) fairly correspond with the observed gravity changes, which mean that the accuracy of models is relatively good.

For November 1992, the modeling analysis shows a density increase by about 0.005 to 0.020g/cm^3 in the layers between -200 to 200m A.S.L. in the reinjection zone. On the contrary, in the production area, a density decrease by about 0.002 to 0.005g/cm^3 was obtained in the layers between -200 to 400m A.S.L., where most of production wells encountered circulation losses. It is interesting that the modeling analysis revealed a density increase at depth of the production area in southern edge. We expect that this result shows a possibility of a new recharge zone at depth. And it plays a important role to supply geothermal fluids to the reservoir. This fluid supply at depth can be recognized more remarkably from the modeling result based on the data for November 1993. In addition, the results by these two models proved that an increase of the density in the reinjection zone is getting small with time, as well as a decrease of the density in the production zone is also getting small with time to date. The modeling results depict that the mass change in the aquifer associated with the N0.2 unit operation added to the No.1 is getting to be gradually balanced after three years, and that geothermal fluids are being recharged to the reservoir at depth to supplement the mass loss caused by exploitation.



('91.8—'92.11) ('92.11—'93.11)

Figure 9: Density changes obtained from two-dimensional modeling analysis for August 1991 - November 1992 on the left side, and for November 1992 - November 1993 on the right side. NE1, NE2 and NE3 represent faults. and predominant productive fractures are well developed along the faults.

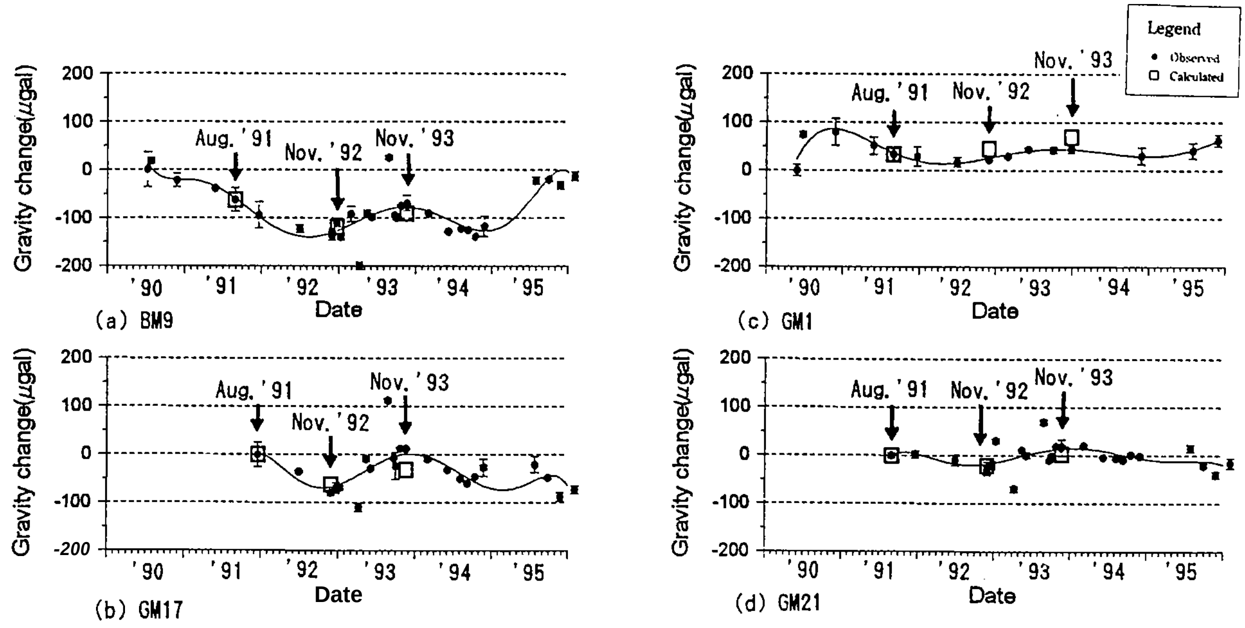


Figure 10 (a) - (d): Comparison between observed gravity changes and gravity changes calculated from two-dimensional density model at BM9, GM17, GM1 and GM21.

6.0 CONCLUSION

In the Hatchobaru geothermal field, gravity changes are considered to reflect the reservoir mass changes including mass loss by production wells and mass gain by reinjection wells. The Hatchobaru area can be divided roughly into three zones, such as northern, southern and central zone. A two-dimensional modeling analysis revealed a new recharge zone at depth under the present production zone, and showed that the mass conditions of the area has been gradually balanced after three years from when the commercial operation of the No. 2 unit was commenced.

Repeated gravity change measurements are considered to be effective to monitor the behavior of geothermal reservoir in the Hatchobaru geothermal field. It is expected that this technique can be applied to other hydrothermal geothermal fields to maintain the power output and to estimate the most adequate operating conditions to the reservoir. In conjunction with other reservoir data, gravity changes can be expected to eventually allow for ideas which will lead to informed management of reservoirs.

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