

DEVELOPMENT OF AN INTEGRATED GEOTHERMAL
RESERVOIR MODELING SYSTEM
(DATABASE & MAPPING SYSTEM FOR RESERVOIR MODELING/SIMULATION/
MANAGEMENT, PRE-PROCESSOR SYSTEM AND POST-PROCESSOR SYSTEM)

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ABSTRACT

We developed the integrated geothermal reservoir modeling system on PC (Windows95/NT) or UNM that can combine database, pre-processor for a reservoir simulator, post-processor for a reservoir simulator and mapping system. The core of the system is database management & mapping system named "GEOBASE2.3" (Geoscience Exploration and Observation dataBASE) that was developed by authors. This system can provide geostatistical mapping and plotting for exploration & production data or simulation results that are queried on ORACLE database management system. The pre-processor for TOUGH2 family (K. Pruess, 1991) and SING (NEDO) named "GeoCAD3.0" was developed by authors. A post-processor for TOUGH2 named "GRAV/TOUGH2" to calculate micro-gravity change of a reservoir was also developed by authors. We hereby introduce the performance of the system using Yanaizu-Nishiyama geothermal field data (Okuaizu Geothermal Co., Ltd., Fukushima Prefecture, Japan).

INTRODUCTION

Geothermal reservoir modeling and the prediction of geothermal production behavior using numerical simulation based on geothermal reservoir modeling are important steps towards the construction of a geothermal power station. In geothermal reservoir modeling it is necessary to combine surface exploration results and well data obtained from various survey stages of rough to

detailed examination in order to form an integrated three-dimensional model of a geothermal reservoir. Since exploration data have been collected by many researchers in the fields of geology, geophysics, chemistry, drilling, logging, reservoir engineering, etc., over a long period of time, specialists in geology and reservoir engineering must make a great effort to find information essential for geothermal reservoir modeling out of a tremendous amount of data presented in various formats. Given this situation, construction of a consistent three-dimensional stereoscopic model is a time-consuming job requiring much skill if it is to be done in a human's head. Also, in forming a numerical model grid for ultimate numerical modeling simulation, a considerable amount of time is required to improve the accuracy of modeling because numerical modeling is also time-consuming and requires much skill. Therefore "computer-aided comprehensive analytic techniques" for geothermal reservoir modeling which use the latest in computer technology are becoming popular (Anderson et al., 1995; Stevens et al., 1995; Nakanishi et al., 1997).

In many existing geothermal power stations, history matching and numerical model review is continuously carried out, even after the start of operations, in order to optimize the numerical model of the geothermal reservoir so that steam can be generated satisfactorily and the accuracy of the production forecast can be improved.

In many geothermal power stations flow data from a specific well, or even from a specific flash separator connected multiple wells in extreme

cases, are mostly used for production history matching. Many geothermal power stations have some observation wells in which long-term changes in reservoir pressure are measured using a downhole capillary tubing system to provide data for production history matching; however, in areas where vaporization in the formation occurs (e.g., the area of the Yanaizu-Nishiyama Geothermal Power Station, owned jointly by Tohoku Electric Power Company and Okuizu Geothermal Co.) it may be difficult to measure reservoir pressure behavior due to vaporized areas. When a geothermal reservoir model is constructed from such poor information, it may be difficult to accurately predict the amount of production. In order to overcome such difficulties, it has been tried in actual geothermal areas to estimate the fluid behavior in a reservoir from changes in physical properties measured in surface surveys, e.g., micro-gravity surveys (Allis and Hunt, 1986; Motoyama et al., 1992; Sugihara, 1997) or streaming potential surveys (Ishido and Pritchett., 1996). This report describes application of the integrated geothermal reservoir modeling system developed in the present study, which uses an exploration and production database, a pre-processor for designing of a reservoir model, TOUGH 2 (Pruess, 1991), and a post-processor for micro-gravity, to the Yanaizu-Nishiyama geothermal field.

BACKGROUND

The Yanaizu-Nishiyama Geothermal Power Station, located in Yanaizu-cho in Fukushima Prefecture, is a single-unit geothermal power station with the largest steam turbine (of the single-flush type) in Japan, with an approved capacity 65MW. Tohoku Electric Power Company is responsible for the power generation section of the station, and Okuizu Geothermal Co. is responsible for the steam supply section. The station began operation in May 1995. A four-year joint study program was started in fiscal 1994 by Tohoku Electric Power Company and Okuizu Geothermal Co. A precision gravity survey was performed each year at 83 measuring points, including 8 benchmark points, in a 12 km² area for the purpose of monitoring the gravity change before and after the start of operation of the station and helping understand geothermal fluid behavior in a geothermal reservoir and how it is related to production and injection of fluid. Okuizu Geothermal Co., which is in charge of development of the station and management of the steam production facilities, started computer control of production-injection data immediately after the start of operation. Also, it has been

selecting data required for future reservoir control, developing an exploration and production database using GEOBASE (Sato et al., 1995) developed by the authors (K. Osato and T. Sato) and the pre-processor to be used for TOUGH2, and reviewing the production behavior which was predicted using the numerical geothermal reservoir model and TOUGH 2.

This paper describes the construction of the database for Okuizu Geothermal Co., compares the results of prediction of the micro-gravity change after the start of operation of the station and the measurement results, and gives a review of the modeling system in the future.

OUTLINE OF THE SYSTEM

The total structure of the system is shown below.

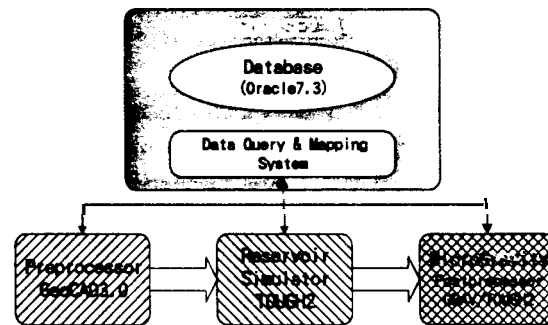


Figure 1. Total Structure of the System

The system consists of:

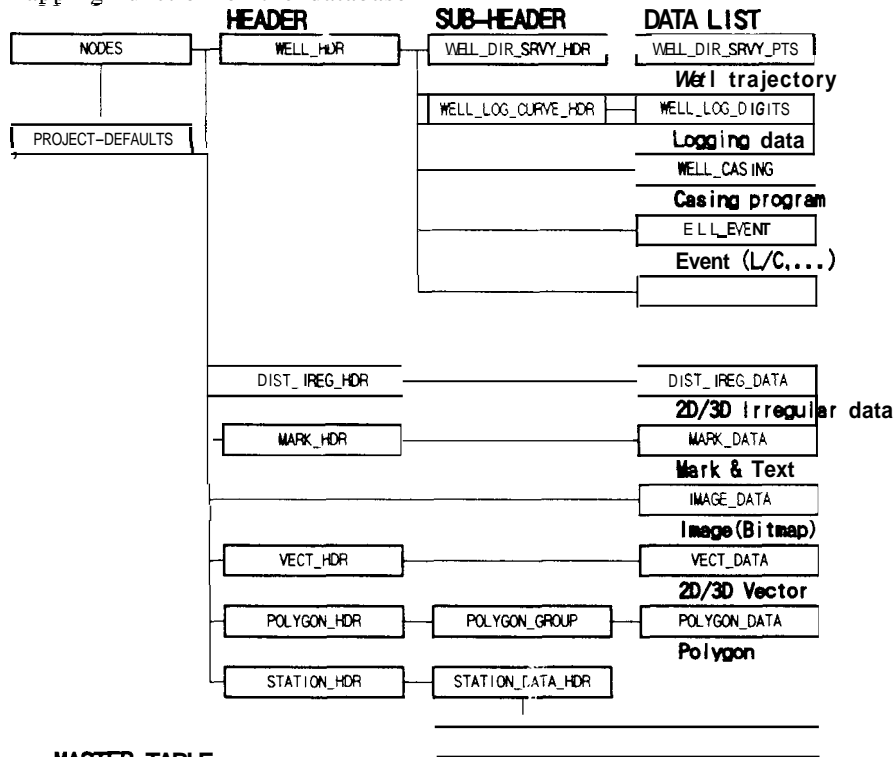
- (1) Exploration and Production database system GEOBASE2.3 for entering, querying, and displaying all the types of data in a comprehensive manner
- (2) Pre-processor GeoCAD3.0 for constructing a three-dimensional numerical model based on the conceptual model obtained by integrated data analysis from the database
- (3) Reservoir simulator TOUGH2, and
- (4) Micro-gravity post-processor GRAV/TOUGH2 for estimating gravity changes based on the physical properties calculated using the reservoir simulator.

GEOBASE2.3 runs on UNIX (HP9000/700, SUN, IBM/RS6000, SGI, PC/LINUX, etc.) or PC (Windows95/NT). GeoCAD3.0 runs on UNIX (HP 9000/700) or PC (Windows95/NT). TOUGH2 and GRAV/TOUGH2 can run on any machine with sufficient memory and CPU speed.

The database is based on Oracle (the current version is Oracle 7.2 or Personal Oracle 7.2), a decentralized relational database which is popular

all over the world. The database has a simple structure, and it is possible to redefine and enter all types of data which can be fitted in the structure into the database. If Oracle 7.2 is used, it is also possible to form a decentralized system (client-server system) using a LAN or WAN which can easily join PCs and UNM machines. The retrieval and mapping function of the database

allows a two-dimensional or three-dimensional representation of data to be obtained by using single data sets or superimposing various data sets, e.g., geological column diagrams, logging data, surface survey data, production/injection data, results of reservoir simulation. Figure 2 shows the data structure.



**MASTER TABLE
(Definitive)**

FORMATION	POLYGON	UNIT_CHANGE
Formation property		
ROCK	BUILDING	TABLE_COLUMN_NAME
Rock property		
FAULT		
Fault property		
TOPOGRAPHY		
Topographic property		

Figure 2. Data Table Structure of GEOBASE

CONSTRUCTION OF A NUMERICAL MODEL USING THE DATABASE AND THE PRE-PROCESSOR

Figure 3 shows the underground temperature distribution 1,500 m below sea level constructed using the database, the lost-circulation 'points, the feed points of production wells obtained by PTS logging, and the fault distribution at 1,200m below sea level. Figure 4 shows the NE-SW cross-sectional view onto which corresponding geological column diagrams are projected. According to the

underground temperature distribution, a range with underground temperature 200°C or higher, which is considered to be a promising reservoir, spreads from the northeast side of the Oizawa Fault towards the southwest side of the Onogawara Fault. In the high-temperature range, which is assumed to be the center of the up-flow, lost circulation frequently occurs and feed points of production wells are scattered. It was conjectured that there exists an up-flow from an underground high-temperature area along the faults under this high temperature range, and that the convection area extends from the northeast side of the Oizawa Fault

and from the southwest side of the Onogawara Fault at a width of approximately 1 km. In the numerical model, the NE-SW length of the area was taken to be 4.6 km so that the fault directions can be taken into consideration and the high temperature range can be covered. The NW-SE length was taken to be 3.2 km so that the Kitanosawa Fault and the Sudarezawa Fault, as well as the faults which are considered to restrict natural convection flow (Chinoikezawa, Sarukurazawa, Oizawa, Takiyagawa, and Onogawara Fault), can be covered. As for the internal grid, the area near the faults relating to production and injection was divided into smaller blocks and the surrounding area was divided into larger blocks.

In the numerical model, the first layer was taken to be the range between the surface level, which is about 500 m above sea level, and sea level, into which the heat flow test wells (T-1 to T-6) were drilled by NEDO. The range from sea level down to -2,000 m below sea level was divided into 500 m layers. As boundary conditions, the pressure and temperature on the ground surface was assumed to be constant, and closed boundaries were assumed on the side faces of the model. To reconstruct the underground temperature distribution, two recharge blocks were placed on the south side of each of the first to third layers, and one recharge block was placed to the west of the second layer. EOS2 (H₂O-CO₂) of TOUGH2 was used as the state equation to take the CO₂ of geothermal fluid into consideration.

In actual modeling, the pre-processor GeoCAD3.0 that had been developed by the authors (J. Burnell and S. White) was used. Since GeoCAD3.0 can readily form non-uniform (polygonal) grids taking advantage of the IFDM of TOUGH2, input data for TOUGH2 can be prepared by drawing quadrilaterals and polygons using a mouse and indicating the necessary physical properties in the center of each polygon. In this case, general rectangular grid division was made horizontally, and grid division in accordance with the inclination of the faults was made vertically. Figure 5 shows the sample display of GEOCAD3.0.

STEADY-STATE MODELING BY MEANS OF NUMERICAL SIMULATION

Since the numerical simulation was done just before the start of operation of the station, the model was optimized according to the steady-state. However, review of the numerical model based on the production history after the start of operation has not been done. The numerical model was constructed based on the base model used in the 1989 reservoir evaluation taking data from new

wells into consideration. Figure 6 shows the underground temperature distribution calculated using the steady-state-optimized numerical simulation, the actual underground temperature distribution (both at 1,500 m below sea level) with the grids of the fourth layer designed by GEOCAD3.0. Figure 7 shows the NW-SE cross-sectional view of Figure 6.

PREDICTION OF THE GRAVITY CHANGE USING THE POST-PROCESSOR

Based on the numerical model obtained above, the amount of production over a 30-year period after the start of operation of the station was predicted. This section describes the prediction of the gravity change based on the numerical model (Sato et al., 1993/1994, Takasugi et al., 1994). In calculating the gravity change, the Talwani method (Plouff, 1976) for estimating of anomalies in a polygonal prism with abnormal density was used.

To calculate the density change in the rocks, the porosity (ϕ), the mass percent in the vapor phase (S_g), the density in the vapor phase (δ_g), and the density in the liquid phase (δ_w) of each block rock, which are input/output values of TOUGH 2, are used. If the density change in the rocks is ignored, the density change is determined by the density change of geothermal fluid in the pores in the rock. The density of geothermal fluid in the rock density (ρ) is defined below.

$$\rho = [S_g \cdot \delta_g + (1 - S_g) \delta_w] \cdot \phi \quad (1)$$

According to the Talwani method, the gravity change in a polygonal prism under the ground (Figure 8), ΔZ in thickness and ρ in density, is given by the following equation:

$$g = \gamma \rho \sum_{i=1}^n \left\{ \begin{aligned} & S_p \left[Z_2 - Z_1 \right] + Z_2 \left[\tan^{-1} \frac{Z_2 d_1}{PR_{12}} - \tan^{-1} \frac{Z_2 d_2}{PR_{22}} \right] \\ & - Z_1 \left[\tan^{-1} \frac{Z_1 d_1}{PR_{11}} - \tan^{-1} \frac{Z_1 d_2}{PR_{21}} \right] - \text{Pit} \left[\frac{R_{22} + d_2, R_{11} + d_1}{R_{12} + d_1, R_{21} + d_2} \right] \end{aligned} \right\} \quad (2)$$

where g : gravity anomaly in the polygonal prism

γ : universal gravitation constant

ρ : density of block i

$S_m = 1$: the case in which the height of the center of gravity is lower than the observed value

$S_m = -1$: the case in which the height of the center of gravity is higher than the observed value

$S_p = 1$: the case in which P is a positive value

$S_p = -1$: the case in which P is a negative value

and $A, d_1, d_2, P, R_{11}, R_{12}, R_{21}, R_{22}$ are given as follows:

$$A = \cos^{-1} \left(\frac{X_1 X_2 + Y_1 Y_2}{r_1 r_2} \right) = \cos^{-1} \left(\frac{X_1 X_2 + Y_1 Y_2}{\sqrt{X_1^2 + Y_1^2} \sqrt{X_2^2 + Y_2^2}} \right)$$

$$d_1 = X_1 \frac{X_2 - X_1}{\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}} + Y_1 \frac{Y_2 - Y_1}{\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}}$$

$$d_2 = X_2 \frac{X_2 - X_1}{\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}} + Y_2 \frac{Y_2 - Y_1}{\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}}$$

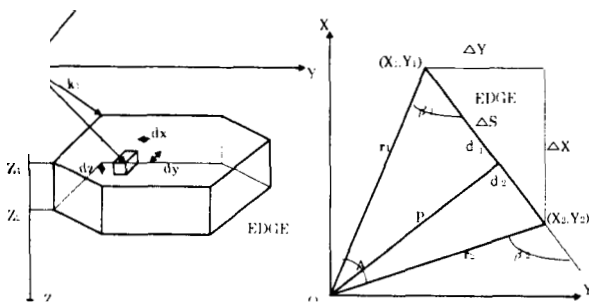
$$P = X_1 \frac{Y_2 - Y_1}{\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}} - Y_1 \frac{X_2 - X_1}{\sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}}$$

$$R_{11} = \sqrt{X_1^2 + Y_1^2 + Z_1^2}$$

$$R_{12} = \sqrt{X_1^2 + Y_1^2 + Z_2^2}$$

$$R_{21} = \sqrt{X_2^2 + Y_2^2 + Z_1^2}$$

$$R_{22} = \sqrt{X_2^2 + Y_2^2 + Z_2^2} \quad (3)$$



(Left) BASIC ELEMENT-POLYGONAL PRISM
(Right) PLAN VIEW OF ONE EDGE OF PRISM

Figure 8. Prism Model Used in the Talwani Method

Figure 9 shows the two-phase zone and the accompanied gravity change after five years of operation calculated based on production history. It can be seen from the figure that a two-phase (vapor-liquid) zone is produced below the cap rock above the production zone which causes a negative gravity change.

COMPARISON AND EXAMINATION OF REAL DATA

Figure 10 shows the gravity change due to the start of operation estimated from the differences between the data before and after the start of operation (1994 and 1995) obtained from periodic precision gravity measurements after normalizing for the effects of altitude and tide. In the figure, the results of the gravity change prediction after one year of operation, traces of wells, and the fault distribution at 1,200 m below sea level are shown for reference. The following can be seen from the figure.

- (1) In comparison with the predicted values (-10 or less), a much larger negative gravity change (-60 μ gal) occurred in the production zone and surrounding area. Such a large gravity change may be due to either a higher rate of

vaporization in the reservoir due to less recharge than expected before the start of operation, or a higher rate of steam up-flow through the faults than that used in the numerical simulation, or both.

- (2) Although the prediction gives a simple configuration of gravity changes due to the limitation of the division of blocks in the numerical modeling, according to the actual measurement, gravity changes occur according to the fault configuration which restricts the reservoir. This indicates the possibility that a steam phase is formed below the cap lock due to restriction by the faults.
- (3) Also in the injection zone, a larger positive gravity change (about +several tens of μ gal) occurred, compared with the predicted value (about +several μ gal).
- (4) As for differences from the numerical model, since the numerical model is basically a porous model, the rate of steam up-flow was less than in the actual reservoir which is restricted by longitudinal faults. Consequently, the rate of vaporized formation along the faults below the cap lock formation in the actual reservoir was lower than assumed in the numerical model.
- (5) Since the gravity value in the injection zone was increased, it may be possible that the underground water level had actually been raised. Since increased gravity values were also observed in areas surrounding the injection zone it may also be possible that the effects of the overall geological changes in the area covering the standard benchmark points are combined with those of the underground water level rise.

In 1996, the second stage of the numerical simulation has been done using the production history from the start of the plant and the production zone was divided more precisely using the location of the newest wells. The layers was also divided more precisely. Figure 11 shows the micro-gravity change after one year production that was calculated by the estimated model. We did not try to match the measurement of the micro-gravity data in this study but the shape and value of the gravity anomaly became more reasonable to the measurement than the last study. The result of calculated micro-gravity change shows the reservoir model was improved by the history matching from the start of the plant. However, the matching of the micro-gravity change is not completely and the more improvement of the numerical model study using both the production history and the micro-gravity change will be required.

CONCLUSIONS

In the above, the following facts were clarified.

- (1) It was proven that a integrated geothermal reservoir modeling system using a exploration and production database, a pre-processor for reservoir modeling, a reservoir simulator, and a post-processor for micro-gravity can be effectively used in the whole course of modeling, numerical modeling, numerical simulation, and evaluation using production history and micro-gravity monitoring.
- (2) Comparison of the results of precision gravity measurement using the post-processor with the results of the previous numerical modeling shows that precision gravity measurement may be used in conjecturing the fine structure inside a reservoir restricted by faults. Therefore, it was proven that precision gravity measurement can be effectively used in the future review of the numerical model.
- (3) Since the results of precision gravity measurements cannot explain detailed phenomena quantitatively, it will be necessary in the future to review both the details of the numerical model and to reexamine the measurement method..

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REFERENCES

- Allis R. G. and Hunt, T. M. (1986), "Analysis of exploitation -Induced gravity changes at Wairakei geothermal field.", *Geophysics*, 51, pp.1647-1660
- Anderson, E. B., Clark, G. B. and Ussher, G. N. H. (1995), "A Design and Implementation of the GDManager Geothermal Data Management System", *Proc. World Geothermal Congress 1995, Florence Italy*, pp.3005-3009.
- Ishido, T. and Pritchett, J.W. (1996), "Numerical Simulation of Electrokinetic Potentials associated with Natural and Production-induced Hydrothermal Fluid Flows", *GRC Transactions, Vol.20*, pp.323-329.
- Motoyama, T., Ehara, S., Mogi, T. and Akasaka, C. (1992), "Reservoir monitoring by observations of

gravity changes - A case history of Takegami geothermal field-", *Abstracts with Programs of 1992 Annual Meeting, GRCJ, A5*.

Nakanishi, S., Harada, M., Akasaka, C., Iwai, N., and Ebara, T. (1997), "Development of Support System for Geothermal Reservoir Analysis (INTEGRAS)", *CHINETSU, J.G.E.A, Vol.34, No.3*, 148, pp.1-14.

Plouff, D. (1976), "Gravity and magnetic fields of polygonal prisms and application to magnetic terrain corrections", *Geophysics*, 41, pp.727-741.

Pruess, K. (1991), "TOUGH2 - A General-purpose numerical simulator for multiphase fluid and heat flow.", Report LBL-29400, Lawrence Berkeley Laboratory

Sato, T., Osato, K., and Takasugi, S. (1993), "Parametric Study of Gravity Changes Accompanying Geothermal Reservoir Change Calculated by Numerical Simulation", *Proceeding of the 89th SEGJ Conference*, pp.99-103.

Sato, T., Osato, K., and Takasugi, S. (1994), "Study of gravity changes using numerical geothermal simulator", *Proceeding of the 90th SEGJ Conference*, pp.304-308.

Sato, T., Okabe, T., Osato, K., and Takasugi, S. (1995), "Graphical User Interface for TOUGH/TOUGH2 - Development of Database, Pre-processor and Post-processor", *Proceedings of the TOUGH Workshop'95, LBL*, pp.271-276.

Stevens, J. L., Garg, S. K., Luu, L., Barker, T. G., Pritchett, J.W., and Truesdell, A. H. (1995) "GEOSYS : An motif-based system for analysis and management of geothermal data", *World Geothermal Congress 1995, Florence Italy*, pp.2951-2953.

Sugihara, M. (1997), "Continuous Gravity Monitoring of Geothermal Activity", *Proceeding of the 96th SEGJ Conference*, pp.321-323.

Takasugi, S. (1994), "Parametric Study of Gravity Change Accompanying Geothermal Reservoir Change Calculated by Numerical Simulation", *Proceeding of 19th Annual Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Program*, pp.277-283.

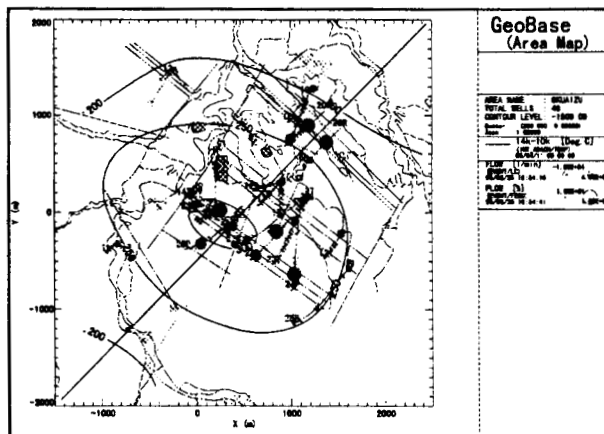


Figure 3. Underground temperature distribution (1,500 m below sea level) constructed from the database, lost-circulation points, feed points of production wells, and fracture distribution (1,206 m below sea level)

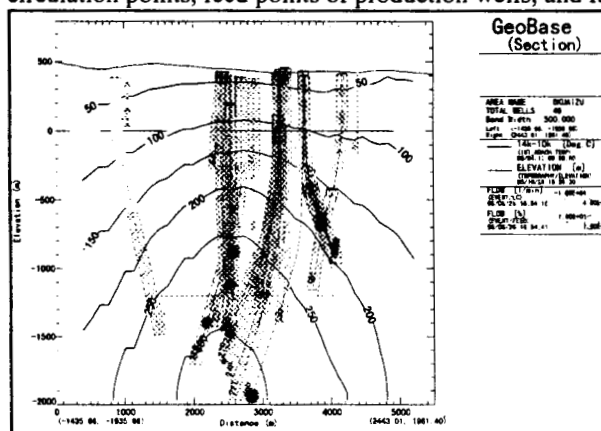


Figure 4. NE-SW Cross-sectional view of the underground temperature distribution, lost-circulation points, feed points of production wells, and projected geological columns

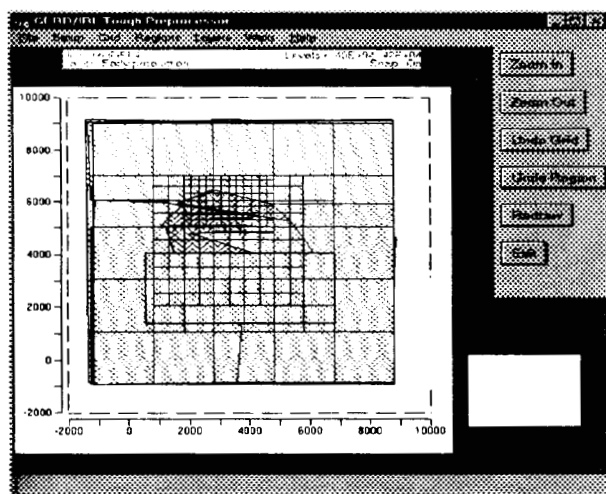


Figure 5. A sample display of GEOCAD3.0 on PC

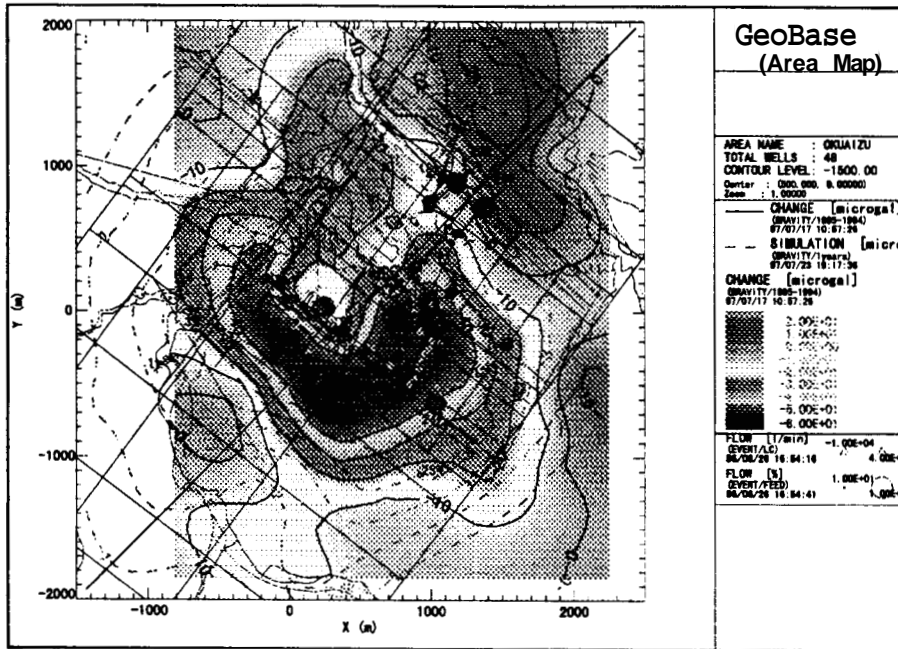


Figure 10 Gravity change predicted one year after the start of production (dash lines) and measured values (1994-1995)

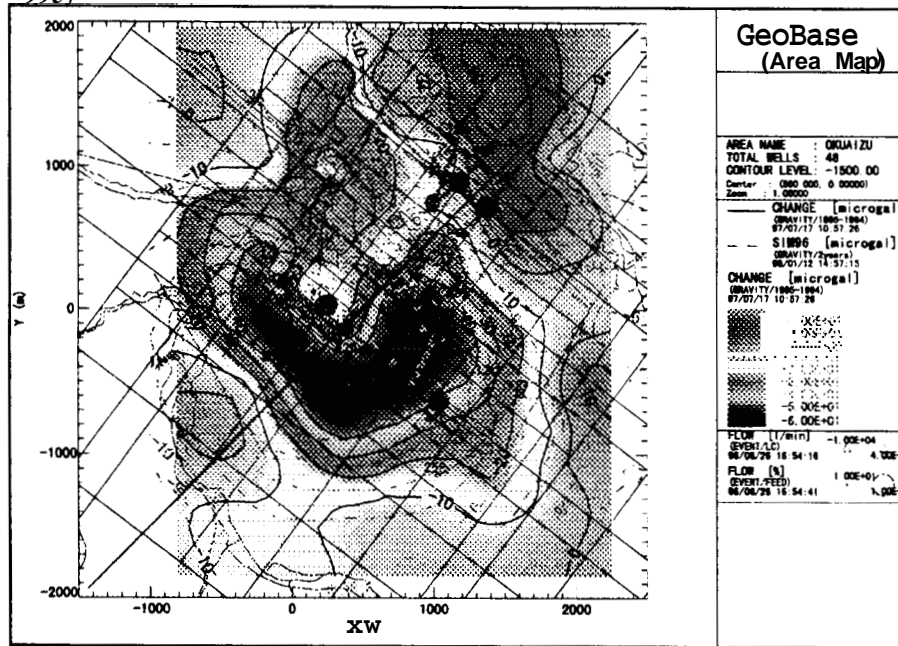


Figure 11 Gravity change predicted one year after the start of production (dash lines) and measured values (1994-1995) after the production history matching