NUMERICAL RESERVOIR MODELING COUPLED WITH REPEAT GEOPHYSICAL SURVEY DATA

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SUMMARY - Integrated reservoir modeling and simulation technology has been developed which will improve the quality of mathematical reservoir models by taking account of repeated geophysical survey data sets (and/or continuous geophysical monitoring data) in addition to the conventional data sets usually employed in reservoir engineering studies. Various computational "postprocessors" were developed in order to couple these geophysical survey data with numerical reservoir simulations. These geophysical survey data sets involve changes in surface microgravity, downhole microgravity profiling, self-potential, and electrical resistivity (monitored by repeated DC, MT and/or CSAMT surveys). A computational feasibility study of reservoir monitoring using geophysical survey techniques was performed based on a numerical model of the Oguni geothermal reservoir. Starting with the steady-state natural condition of the system, an exploitation strategy involving a 20MWe geothermal power station was devised and further numerical calculations were performed, which induced changes in underground pressure, temperature, steam saturation and the underground flow pattern. Then, various mathematical "postprocessors" were applied to the computed reservoir history to appraise changes that could be observed using various surface geophysical measurement techniques. The results suggest that these techniques have considerable promise for monitoring of geothermal reservoir evolution. The "postprocessors" can help develop more robust reservoir models, because more constraints (based on more field measurements) can be imposed upon the model during model calibration (history matching). The postprocessors are also useful for designing an appropriate reservoir-monitoring program.

1. INTRODUCTION

The New Energy and Industrial Technology Development Organization (*NEDO;* a Japanese government agency) has carried out various projects over the years to promote geothermal energy. NEDO recently initiated a new effort: "Development of Technology for Reservoir Mass and Heat Flow Characterization" (Horikoshi *et al.*, 2001). As part of this new project, "Integrated Reservoir Modeling and Simulation Techniques" (Nakanishi *et al.*, 2000a) have been pursued. This involves developing new analysis techniques for various geophysical data sets and combining them with traditional reservoir engineering practice. Existing mathematical ***microgravity*** and ***self-potential*** postprocessors (see Ishido *et al.* (1995), and Ishido and Pritchett (1999)) were enhanced, and ***geochemistry, DC*** and ***MT-CSAMT electrical resistivity*** postprocessors were newly developed.

Along with the software development, we carried out various "feasibility studies" to appraise the practicality of using these geophysical techniques to detect and characterize subsurface changes induced in geothermal reservoirs by field operations. These feasibility studies involved (1) adopting a particular mathematical "reservoir model" for the system, (2) using that model to perform calculations of changes in underground conditions over many years of operation, and then (3) using the mathematical "postprocessors" to calculate the changes that will be observable at the surface using the various geophysical survey techniques. Pritchett et *al.* (2000) describe the results of such a study for a hypothetical high-enthalpy geothermal reservoir. Nakanishi *et al.* (2000b) describe a feasibility study of Onikobe, a mature field which has been supplying power to the grid since 1975.

Nakanishi *et al.* (2001) have also performed a similar feasibility study for the Oguni reservoir, a field which has been extensively explored but has not yet been placed into production. In this paper, an overview is provided of notable features of the various postprocessors, using the Oguni study as a case history. The utility of the "postprocessors" for characterizing reservoir evolution is outlined and appraised.

2. RESERVOIR EVOLUTION

A detailed description of the hydrogeologic and hydrothermal characteristics of the Oguni field is beyond the scope of this paper, but Yamada *et al.* (2000) provide a general description of structure and hydrogeology. Oguni is located in central Kyushu, southwestern Japan (Figure 1). The reservoir is extensively fractured, horizontally layered, and may be subdivided hydrologically into northern and southern portions. Both the "northern" and "southern" reservoirs contain dilute. NaCl liquid brines at temperatures from 200 to 240°C. A small steam zone is present at the top of the reservoir. The northern reservoir covers a large area including the Takenoyu Fault Zone and has relatively high permeability (kh ≈ 100-250 darcy-m). The southern reservoir covers a smaller area and has limited transmissivity. The undisturbed stable reservoir pressure in the southern reservoir exceeds that in the northern reservoir by about 1 MPa, indicating little connectivity between them.

A numerical model of the field has been constructed to forecast future performance (see Pritchett and Garg, 1995). The computational volume considered has a surface area of 45 km^2 (Figure 2) and is subdivided into 16 layers (each 200 meters thick) and 3456 individual grid blocks. Some of the blocks in the upper part of the grid are "void" since the ground surface elevation is

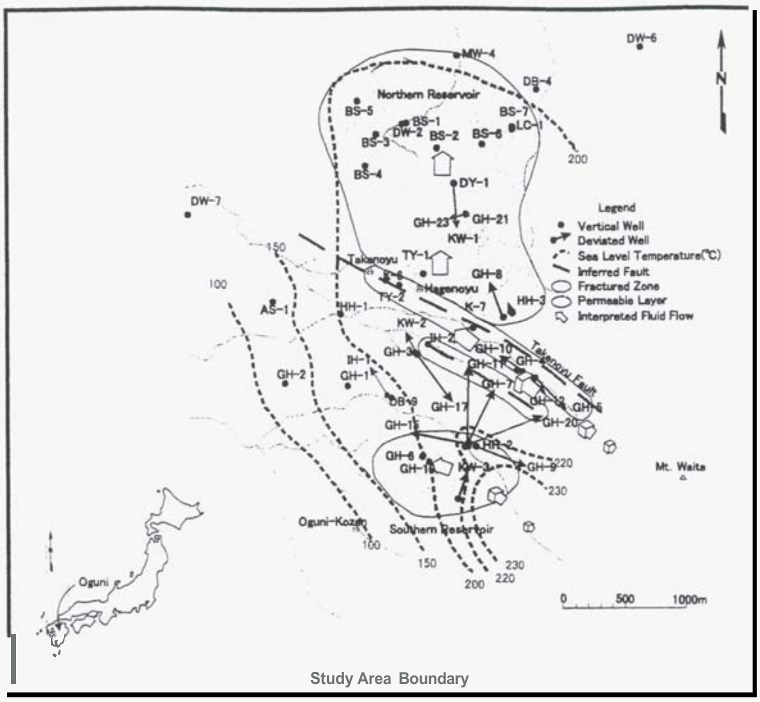

Figure 1 – The Oguni study area and well locations.

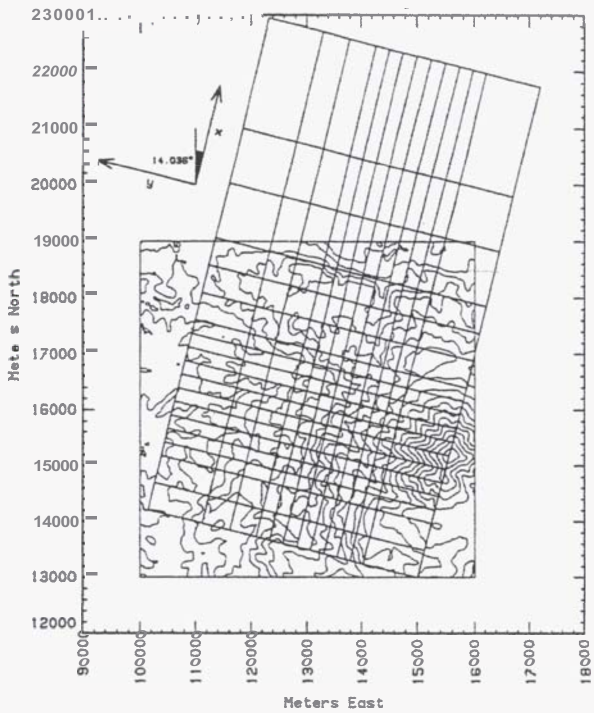

Figure 2 – STAR computational grid orientation relative to study area.

generally less than +1300 m ASL (top surface of the model). The total number of non-void blocks is 2878. The STAR reservoir simulator (Pritchett, 1995) was first used to carry out a series of long-term calculations representing the natural development of the hydrothermal system over geological time (250,000 years) to provide steady-state underground temperatures, pressures, etc. This repetitive sequence of calculations continued until a satisfactory match was found with existing reservoir conditions (Pritchett and Garg, 1995).

The STAR simulator was then used to perform a 50-year forecast of the effects of production and injection, using the natural-state model as the initial conditions. A 20 MWe (gross) double-flash geothermal power station was considered. Six existing production wells were selected to supply the steam required by the plant: GH-10, GH-11, GH-12, GH-19, GH-20 and IH-2. Their locations are indicated in Figure 1, and initial productivity indices for these wells were assigned based on actual measurements. The southernmost of these wells (GH-19) is located in the southern "high-pressure reservoir": the others are all in the northern "low-pressure reservoir". Three injection wells (GH-21, GH-23 and one other planned well) in the Sugawara area to the extreme north reinject spent 105°C brine from the flasher. Two injection wells located in the western part of the field inject 45.5°C steam condensate.

The forecast indicates that there should be no problem sustaining 20 MWe electrical generation throughout the 50-year period considered, even though the calculation predicts that well IH-2 will cease discharging after 47 years (owing to condensate injection nearby). The combined initial steam discharge capacity of the six production wells is enough to generate 38 MWe, so considerable excess capacity is available at first. Accordingly, it was assumed that all six production wells will be "throttled" by the same factor to provide just enough steam for 20 MWe.

Because of reservoir pressure decline, the total volume of underground steam increases with time. After the first five months (during which steam volume actually decreases slightly due to the proximity of injection wells to the two-phase zone), total steam volume increases from about 15 million cubic meters initially to about 26 million cubic meters after 50 years.

3. CHANGES IN MICROGRAVITY

3.1 Changes in Surface Microgravity

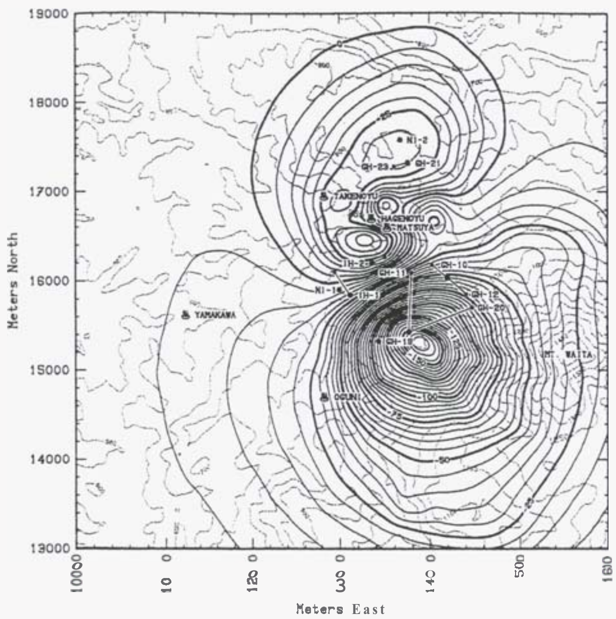

Figure 3 – Computed gravity change after 50 years of field operation (contour interval is **5** microgals). Shaded area denotes where gravity increases.

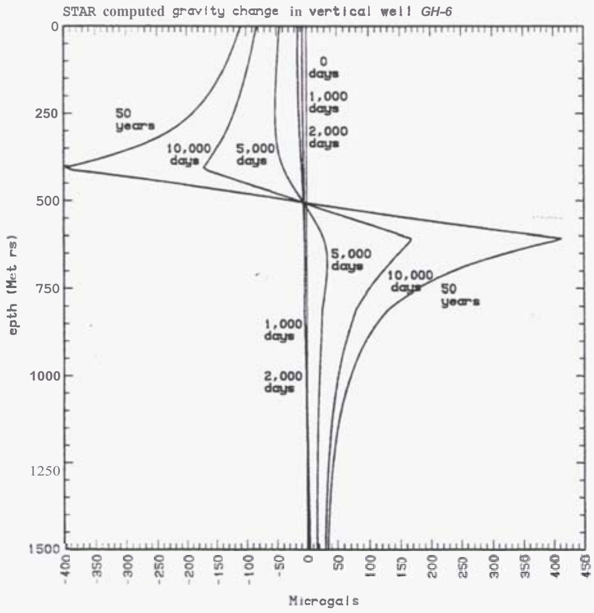

Figure **4** - Computed downhole gravity changes from natural state in monitor well GH-6.

STAR's microgravity postprocessor (Pritchett, 1995) was used to estimate earth-surface gravity changes due to the underground fluid mass redistributions caused by fifty years of field operation. Figure 3 shows the spatial distribution of computed 50-year microgravity change relative to pre-production conditions. This gravity change map exhibits increases (about +40 microgals) in the Sugawara re-injection wellfield caused by cooling-induced liquid densification. Relatively large gravity decreases (about –170 microgals) centered on the middle of the production wellfield are also predicted, caused by boiling arising from production-induced local pressure decline. The shutdown of well IH-2 at about **47** years causes a significant local increase in gravity. This is because pressures rise locally after IH-2 stops discharging, cold water from the nearby condensate injection wells floods in, and all the steam around well IH-2 condenses back to liquid.

Since the proposed Oguni power plant is small and the reservoir is very permeable, production-induced gravity changes are limited. Even so, these gravity changes should be detectable by properly-conducted gravity surveys. The forecasts obtained from the gravity postprocessor were very useful for planning this monitoring program.

3.2 Changes in Downhole Gravity Profiles

The original STAR microgravity postprocessor was extended to permit forecasting the response of a subsurface downhole gravity meter (in addition to surface measurements). Figure **4** shows the computed vertical distribution of microgravity change (relative to natural state conditions) in a shut-in monitor well (GH-6) located in the southern "high pressure" reservoir after 1000, 2000, 5000, 10,000 and 18,250 days of field operation. These changes are mainly due to the intensification and migration of the underground steam zone caused by fluid production from well GH-19. The gravity signal amplitudes in the downhole profiles substantially exceed their expressions at the ground surface. This calculation indicates that it should be feasible to accurately delineate regions where production-induced subsurface boiling is taking place if it is possible to develop and deploy instrumentation to accurately measure downhole microgravity changes in operating geothermal fields.

4. SELF-POTENTIAL CHANGES

A postprocessor has been developed for the STAR geothermal reservoir simulator to calculate distributions of electrical self-potential ("SP") along the ground surface, and how they change in response to changes in underlying reservoir conditions (Ishido and Pritchett, 1999). To calculate the SP distribution, a second "SP grid" is superimposed on the STAR grid used to compute reservoir flow. For Oguni, the SP grid covers 900 km^2 (30 km x 30 km), centered on the middle of the study area. Vertically, the SP grid extends from the ground surface down to –10 km ASL.

A model for *in-situ* underground electrical resistivity is an essential prerequisite for carrying out SP calculations (and also for the DC, MT and CSAMT calculations discussed below). For this purpose, in all cases electrical resistivities throughout the entire volume were assigned to the various major geological formations based on the results of a CSAMT survey. Archie's law was adopted for calculating the electrical resistivity distribution within the STAR grid volume:

$$R = R_w / A\,[\phi(1-S)]^2$$

where R is effective resistivity, ϕ is rock porosity, S is steam saturation, R_w is the electrical resistivity of 2500 ppm NaCl brine (representative of Oguni reservoir waters; a function of tmeperature), and "A" is a

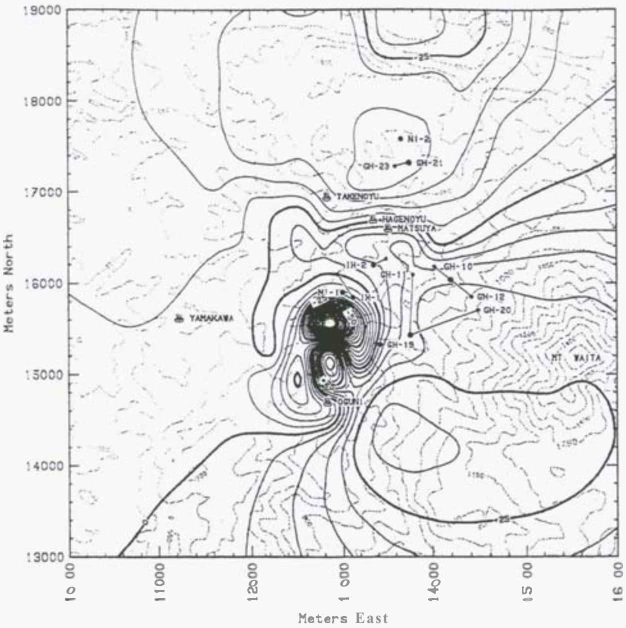

Figure 5 – Computed self-potential change **from** initial state after one year of operation (Contour interval **is 5** mV). Shaded area denotes where potential increases.

location-dependent coefficient established from field measurements.

Figures **5** and 6 show changes in computed ground surface self-potential compared to the initial **SP** distribution after one and 50 years of operation respectively. **SP** generally increases in the southeastern part of the study area and decreases to the north and northwest. The progressive SP decrease is presumably associated with injection at Sugawara. In addition, **an** intense small-scale feature – a dipole-like structure oriented north-south and less than one kilometer in size – lies to the south of the condensate injection wells. This feature forms immediately upon field startup. Potential increases to the south and decreases to the north. The peak-to-trough amplitude of this dipole feature exceeds 150 mV after only one year, then gradually increases to around **220** mV after **50** years. The feature appears to be related to changes induced in the reservoir by "high-pressure" production well GH-19, located about 600 meters to the east. **GH-19** causes substantial disturbances in the underground distributions of fluid flow and of pressure in the relatively small "high-pressure reservoir".

The forecast suggests that significant SP changes will occur very early in the field exploitation program, and will most likely occur near the boundary between the "high-pressure" and "low-pressure" reservoirs. Careful measurements of these early changes will be of great potential value in elucidating the character and extent of the barrier separating these two hydrologically disjoint systems in the field.

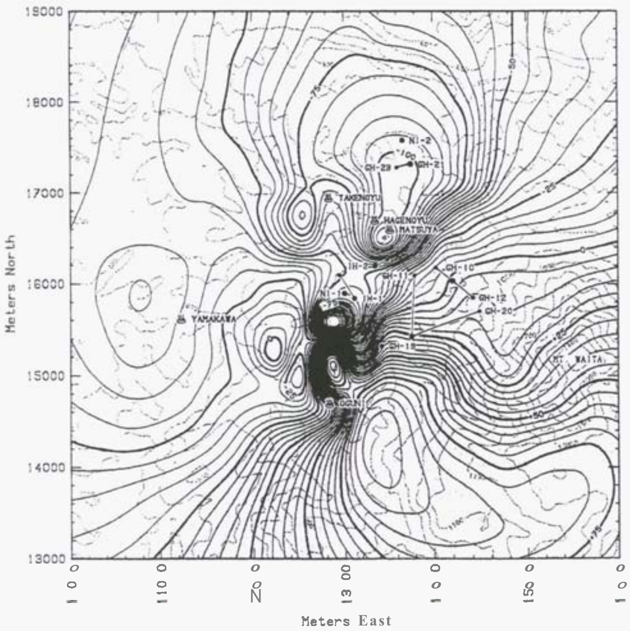

Figure 6 - Computed self-potential change from initial state after 50 year of operation (Contour interval is **5** mV). Shaded area denotes where potential increases.

5. DC RESISTIVITY SURVEY CHANGES

A "DC resistivity" postprocessor has been developed for the **STAR** geothermal reservoir simulator to calculate distributions of apparent resistivity which would be detected by surface DC electrical surveys, and how they change in response to changes in underlying reservoir conditions (Pritchett, **2000).** Like SP, to calculate the apparent resistivity distribution a second "EP **grid"** (used to calculate electrical potential) is overlaid on the **STAR** grid (used to calculate changes in reservoir mass and heat **flow).** The Oguni EP grid covers **144 km^2 (12 km x 12 km),** centered on the middle of the study area, and extends from the ground surface to **–3.5** km **ASL.**

The electrode array geometry used for the DC resistivity survey must also be specified. The postprocessor will accept an arbitrary electrode arrangement. **A** Wenner electrode array oriented east-west with **1200** meter voltage electrode spacing was used for these calculations. The electrode array, with fixed orientation and spacing, is moved from place to place within the central 16 km^2 "survey area" during the calculation to construct the spatial distribution of apparent resistivity.

The apparent resistivity distribution was calculated for the "natural state" and also after fifty years **of** field operation. Figure **7** shows the 50-year change in apparent resistivity, expressed as a percentage of the initial "natural state" value. The main causes of underground electrical resistivity change in a geothermal reservoir due to field operations will usually be (1) underground steam saturation changes (steam increase causes resistivity increase), and **(2)** temperature changes (cooling causes resistivity increase). Large increases **(>12%)** in apparent resistivity are predicted in the

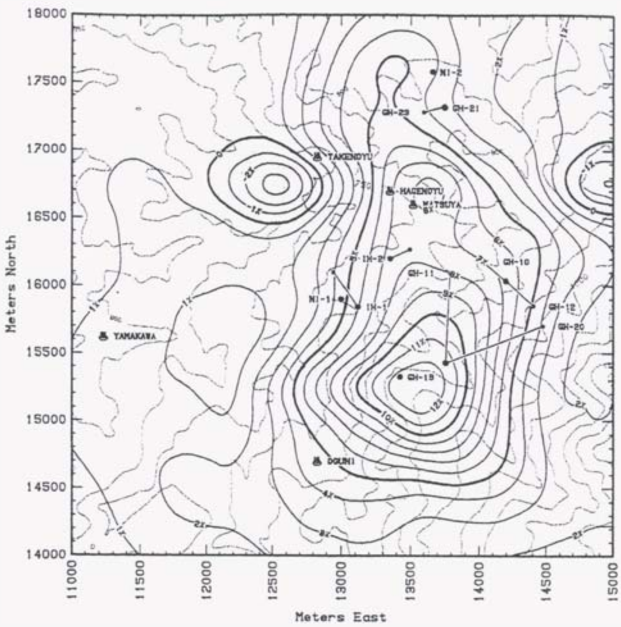

Figure 7 – Percentage increase in apparent resistivity using Wenner electrode array (east-west orientation, voltage electrode spacing 1200m) after 50 years of field operation. Contour spacing is 1 % with bold contours every *5%.* Shaded area indicates regions where resistivity decreases.

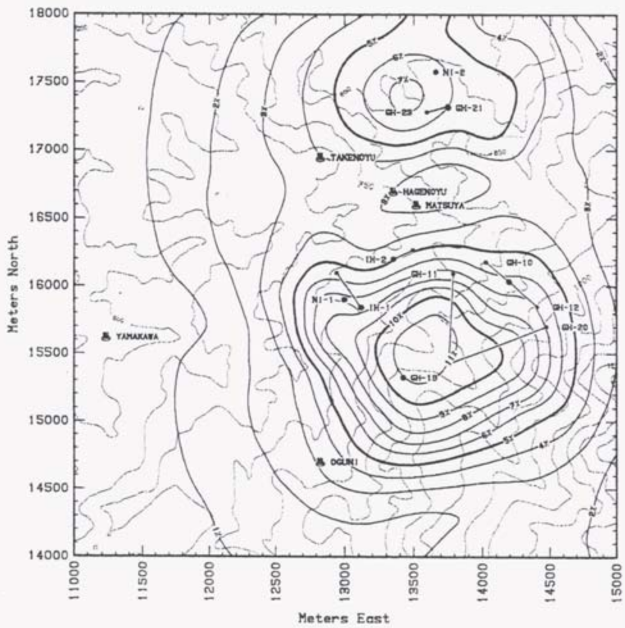

Figure 8 - Percentage increase in apparent resistivity using Wenner electrode array (north-south orientation, voltage electrode spacing 1200m) after 50 years of field operation. Contour spacing is 1 % with bold contours every *5%.*

Oguni production wellfield due to local growth of the steam zone, and smaller apparent resistivity increases **(8%)** are likely in the northern Sugawara reinjection wellfield due to temperature decline (Figure 7). The predicted apparent resistivity changes at Oguni are fairly small, but should be detectable by careful survey experiments. Again, the main reason for relatively weak signals is simply that Oguni is a very permeable geothermal system with abundant natural recharge, and the projected electricity production rate (20 MWe) is rather low.

Figure **8** shows similar distributions of percentage increases in apparent DC resistivity, but this time the electrode array is oriented north-south instead of east-west. The differences between Figures 7 and **8** are due to complex underground geological structure which causes resistivity heterogeneity. These calculations suggest that DC resistivity monitoring should be conducted very carefully. It **is** essential that electrode locations be replicated precisely for the surveys to be compared to appraise temporal change. For Oguni, the entire 50-year temporal change in resistivity is small compared to the differences in apparent resistivity obtained from the differing electrode orientations.

6. CHANGES IN MT SURVEYS

An "MT resistivity" postprocessor has been developed for the STAR geothermal reservoir simulator to calculate distributions of apparent resistivity (and impedance phase) which would be detected by surface magnetotelluric (MT) surveys, and how they change in response to changes in underlying reservoir conditions (Pritchett, 2001). Electromagnetic modeling of complex 3-D earth structures is required to calculate MT response based on a reservoir simulation. Sasaki's (1999) finite difference program (which solves initially for secondary electric field) was chosen among several **3-D** MT modeling algorithms after an examination of program accuracy, versatility and run time (Wannamaker, 2000), and was modified to interface seamlessly with the STAR simulator.

Figure **9** shows the calculated spatial distribution of changes in apparent resistivity (at **1** Hz) after 50 years of Oguni production, expressed **as** a percentage of the initial "natural state" MT resistivity. Qualitatively, MT resistivity changes are broadly similar to those obtained from DC surveys (Figure. 7). Relative apparent resistivity increases reach 40%, and should be readily detectable with careful repeat MT surveys. Corresponding phase difference anomalies around 3" are also predicted.

7. CONCLUDING REMARKS

Results **of a** new R & D program to develop novel techniques for monitoring **and** modeling reservoir mass **and** heat **flows** are described. Calcuiations were performed to estimate changes in quantities observable using geophysical survey techniques (gravity, SP, DC and MT resistivity) at Oguni caused by field exploitation operations based on a numerical reservoir model. It appears that these "postprocessors" will help in devising more robust reservoir models, **as** more constraints **(based** on more

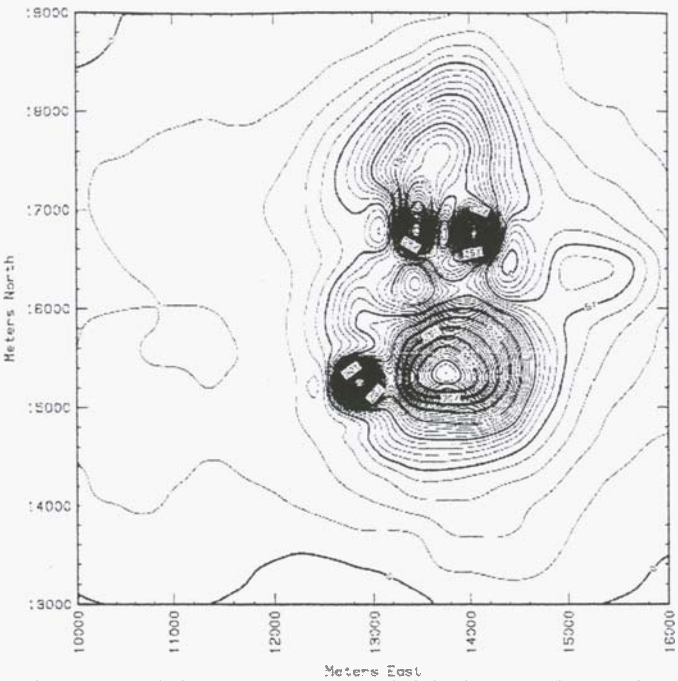

Figure 9 – Relative 1 Hz apparent resistivity increase (in %) after 50 years of field operation. Contour spacing is 1 % with bold contours every 5%.

field measurements) can be imposed during model calibration (history matching) if pertinent repeat geophysical survey data are gathered. The postprocessors should also aid the planning of suitable reservoir-monitoring survey programs.

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