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DEVELOPMENT OF TECHNIQUES FOR RESERVOIR MONITORING - CURRENT STATUS OF THE PROJECT

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SUMMARY – Depletion of geothermal reservoirs and difficulties in increasing power output are serious problems for geothermal power stations in Japan. NEDO has been conducting a project entitled "Development of Technology for Reservoir Mass and Heat Flow Characterization" since 1997. In this project, techniques to stabilize electrical output fiom geothermal power stations and to explore the areas surrounding existing geothermal fields are being developed.

1. INTRODUCTION

Several geothermal power plants have difficulties in maintaining their designed electrical output. In some cases, too much production or lack of recharge water supply from the surrounding areas caused depletion in hydraulic pressure in the reservoirs. In other cases, too much reinjected water flowed into the reservoirs. It has become more and more important to estimate reservoirs correctly and to manage reservoirs better.

Development of energy from natural sources remains an important national policy. It is very-important to find new reservoirs and to increase electrical generating .capacity by geothermal energy. To do so, it is best to find a geothermal reservoir in the area surrounding an existing power plant, to avoid the difficulties associated with the legal restriction concerning natural parks, and the coordination with the hot spa owners nearby.

In response to these needs, NEDO has launched a project to establish techniques useful for reservoir management and exploration of areas around existing geothermal power stations.

2. STATE OF GEOTHERMAL POWER PLANTS IN JAPAN

It was 36 years ago that the first geothermal power plant, Matsukawa (9.5MW), began operating. Since then, geothermal plants have expanded to 17 locations and at present 19 plants exist with a total capacity of 533MW. Each geothermal power plant has been maintained at a high operation factor as base load power supply (Figure 1). However, the utilization factor shows a different trend at each plant because of declining production.

Operation factor is equivalent to:

$$\left[\frac{\text{Number of operating days}}{\text{Number of calendar days}}\right] 100\%$$

Utilization factor is equivalent to:

$$\left[\frac{\text{Average power through the year}}{\text{Authorized rated output}}\right] 100\%$$

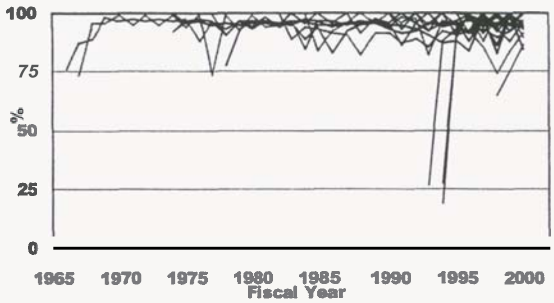


Figure 1. Annual operation factor

Figure 2 shows the history of utilization factor of 3 groups. Power plants can be separated into 3 groups based on their changes of utilization factor in the last 5 years, i.e. less than 5% (A-group), fiom 5 to 10% (B-group), more than 10% (C-group). The characteristics of each group are:

- The A-group has relatively small electrical outputs. (Onikobe: 12.5MW, Ogiri: 30MW, Takigami: 25MW)
- The B-group has relatively small outputs and long operation times; they have a significant amount of historical data and maintain a steady annual rate of decline. (Matsukawa: 23.5MW, Otake: 12.5MW, Onuma: 9.5MW, Mori: 28.8MW)
- The C-group has relatively large electrical outputs and short operation times. (Hachobaru 1st unit: 55MW, 2nd unit 55MW, Kakkonda ist unit: 50MW: 2nd unit: 30MW, Sumikawa: 50MW, Yanaizu-Nishiyama: 65MW, Yamakawa: 30MW).

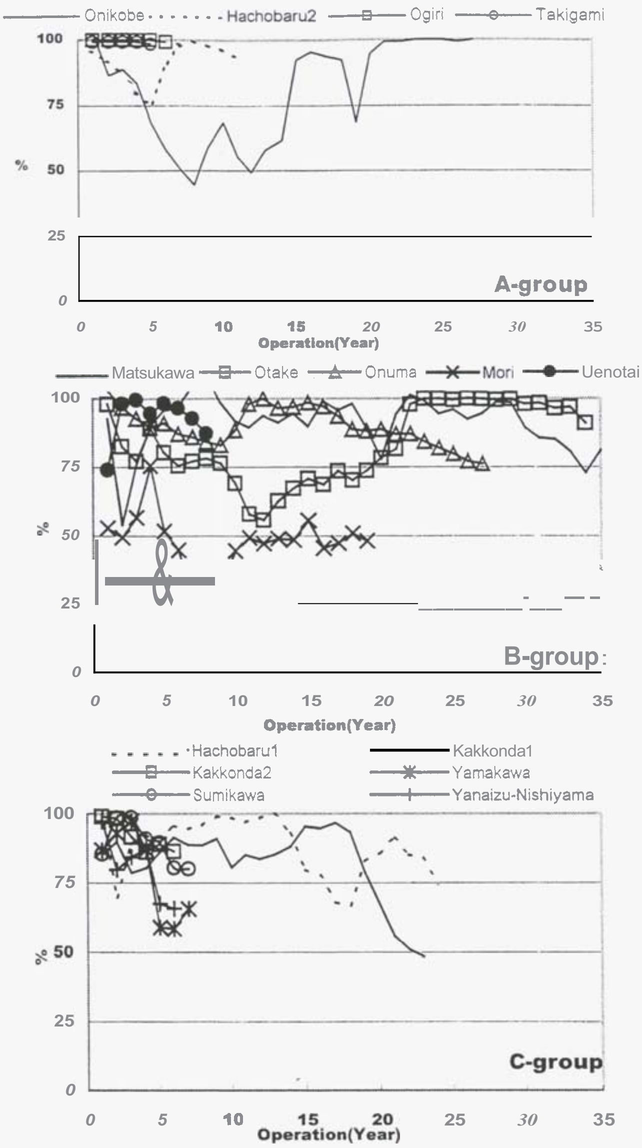


Figure 2. History of utilization factor

An investigation regarding actual the conditions of reservoir management was carried out on behalf of geothermal developers in 2001. This investigation was carried out in 14 geothermal areas: Mori, Sumikawa, Onuma, Matukawa, Kakkonda, Uenotai, Onikobe, Yanaizu-Nishiyama, Otake, Hachobaru, Takigami, Ogiri, Yamakawa, Hachijojima Island.

In the investigation, the main problems posed by each geothermal area are:

Production

Declining production caused by:
- Cooling reservoirs;
- Decreasing hydraulic pressure;
- Downhole scaling;
- Acid fluid damage in production wells;
- Increasing noncondensible gases (NCG).

Reinjection

Declining reinjection caused by:
- Downhole scaling;
- Reservoir scaling.

The countermeasures to be taken against these problems are:

Production

· Optimization of production wells;
· Silica scale inhibitor;
· Separation of production zones and reinjection zones;
· Artificial injection to sustain fluid-depleted reservoirs (EGS).

Reinjection

· Reaming, side-tracking;
· High-temperature reinjection method;
· Retaining tank method;
· Dilution method.

3. OUTLINE OF THE PROJECT

The project aims to develop techniques useful in capacity estimation of reservoirs, output stabilization of the electricity generation, and exploration in the surrounding areas of existing geothermal power stations.

The project started in FY1997 and ends in FY2002. The following three basic techniques are being developed (Figure 3).
1) Reservoir monitoring techniques such as gravity, SP, MT, and seismic monitoring techniques;
2) Integrated reservoir modeling and simulation techniques, and;
3) Techniques to improve reservoir models with hydrological property data, geological and geochemical data of reservoirs.

Geophysical monitoring techniques aim to perceive changes in a geothermal reservoir at or near the ground surface. Hydrological properties of the fracture system and geological and geochemical data will be used to improve the reservoir model. By using precise reservoir modeling, the present state of the reservoir will be reproduced through numerical simulation. Then, the numerical simulation results of the reservoir will be translated into changes measurable by surface geophysics, such as gravity, SP, resistivity, and underground seismic velocity structure using postprocessors. These calculated changes will be compared with those observed by geophysical monitoring. Next, the model will be modified through history matching to explain the present state of the reservoir. Through implementation of history matching, the reservoir model will become more accurate and the future state of the reservoir calculated by the reservoir simulator will be fairly

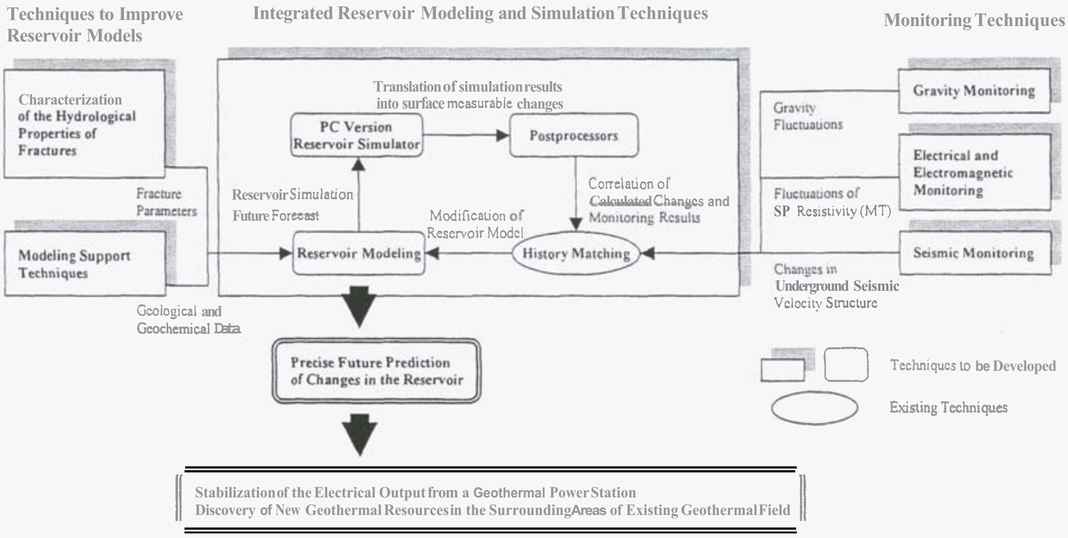


Figure 3. Project concept.

correct. The future state of the reservoir will provide us useful information on operation of the geothermal power plant and reservoir management.

The development of basic techniques is near completion. The test fields for development of basic techniques are shown in Figure 4.

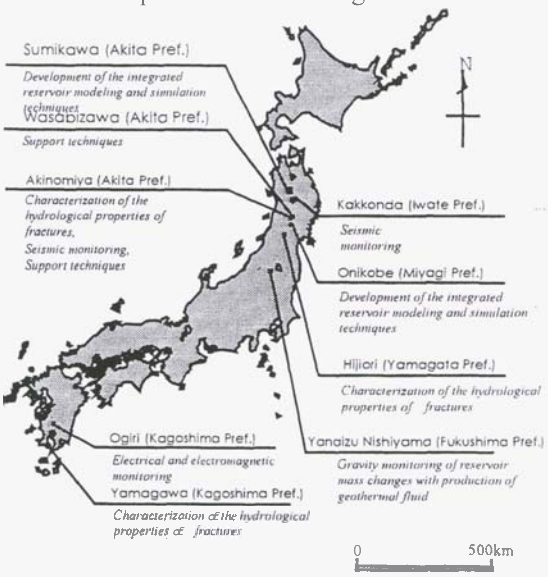


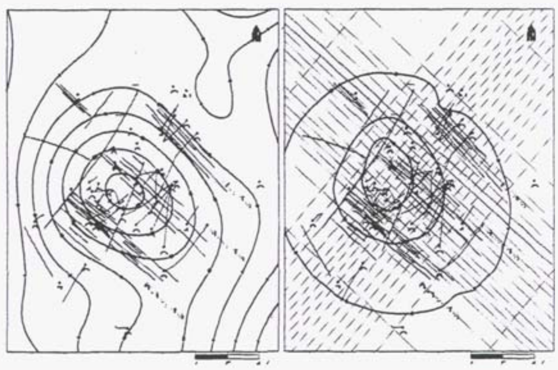
Figure 4. Location of study areas

3.1 Gravity monitoring

Surface gravity changes reflect underground mass redistribution caused by production and reinjection of geothermal fluids and the precise measurements and analysis of gravity changes can help to reveal changes in reservoir conditions. Development of a gravity monitoring system is being carried out in the Yanaizu-Nishiyama geothermal field, Fukushima Prefecture (Fig. 4).

Frequent gravity measurements (once every two or three weeks) and continuous groundwater measurements are carried out at ten gravity stations. Gravity, groundwater, temperature, barometric pressure, precipitation, and moisture content in the vadose zone are being continuously monitored in this field (Ohta et al., 2001).

Noise reduction techniques for gravity data were developed in order to isolate the gravity changes caused by mass movement in a geothermal reservoir. Precise noise reduction techniques to compensate for tidal effects and barometric pressure fluctuations were established using BAYTAP-G (Ishiguro et al., 1981, Tamura et al., 1991). Elevation checks of the gravity stations along with the seasonal gravity measurements and checks for vertical gravity gradient were also carried out at 8 sites in 1998. These investigations showed elevation changes and variations in vertical gravity changes were less important, at least at this particular field, over the period studied.



a) Observed gravity changes **b) Calculated gravity changes**

Figure 5. Comparison between the observed and calculated **gravity** changes **at the** surface

Figure 5a shows gravity changes observed around Yanaizu-Nishiyama geothermal power station over the period between 1994 and 1997. Negative gravity changes are clearly observed around the production zone and positive gravity changes are observed around the reinjection zone. The natural state geothermal reservoir model was constructed and the gravity changes at the surface after the commencement of operation was calculated using the reservoir simulator TOUGH2 (Pruess, 1991) and the gravity postprocessor (Figure 5b). The simulation result was similar to that of the present state observed by gravity monitoring; the history matching is being carried out. The development of the gravity monitoring system is almost completed.

3.2 SP and MT monitoring

Underground movements of geothermal brines reflect changes in SP at the ground surface, and underground resistivity is caused by changes in salinity and temperature of geothermal liquids and the distribution of two-phase zones in the reservoir. Precise repeat surface surveys of SP and resistivity can therefore yield information about fluid redistributions, flow rates and flow directions which prevail in the reservoir.

The development of a SP monitoring system and resistivity (MT) monitoring system was carried out in the Ogiri geothermal field, Kagoshima Prefecture (Figure **4**), where the production zone lies along the Ginyu fault system.

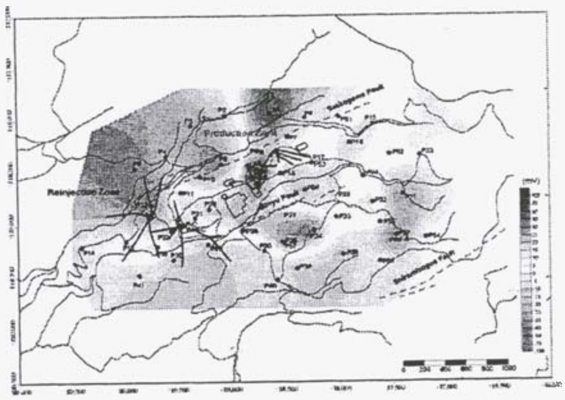


Figure 6. Observed **SP** changes **(1998 - 2001)**

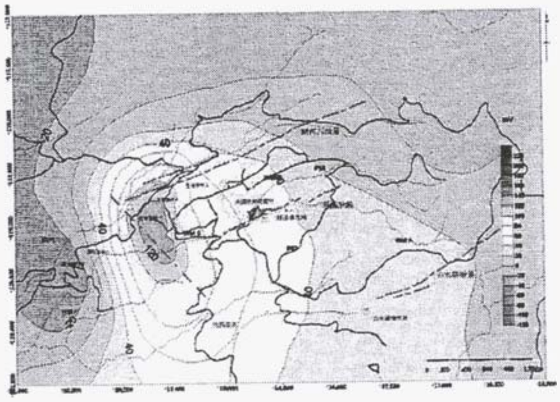


Figure 7. Calculated SP changes (postprocessor)

In the Ogiri geothermal field, 50 electrodes are placed in 1m deep holes and SP data are recorded continuously (Yokoi et al., 2001). Figure 6 shows observed fluctuations of SP between December 1998 and December 2001. Relative SP changes, +20mV at the production zone and –20mV at the reinjection zone, were observed.
A numerical reservoir model of the natural state of the field was constructed and a simulation was conducted which reproduced the present state of the reservoir using a reservoir simulator. SP changes at the surface calculated by the SP postprocessor showed good matching with the observed SP changes on the whole (Figure **7**). The development of the SP monitoring technique is almost completed.

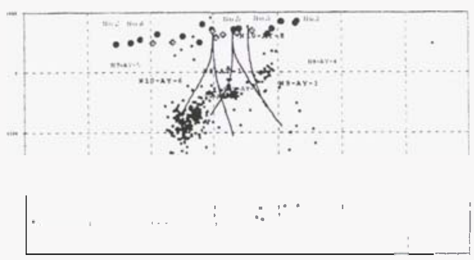
A resistivity monitoring network was set in the field from 1999 to 2002, and full-scale resistivity monitoring has been conducted since FY2000. **A** stationary MT monitoring network was installed across the production zone while repetitive MT stations were installed around the reinjection zone. Resistivity increases and decreases were observed at the Ginyu fault.

3.3 Seismic monitoring

Pressure changes in geothermal reservoirs caused by production and reinjection of geothermal fluid are expected to generate micro-earthquakes and to cause changes in the subsurface seismic velocity structure.

This research is composed of the following three main tasks: Development of a technique for micro-earthquake monitoring network system design, development of a seismic measurement technique for changes in seismic velocity structure, and development of history matching and prediction technique for changes of heat and mass flows in geothermal reservoirs.

The monitoring of **AE** (Acoustic Emissions) during the long-term production test in the Akinomiya geothermal field was carried out between June and October 2000.



We applied the one-dimensional velocity structure inversion method and joint hypocenter determination method (Frohlich, 1979). We confirmed that these methods result in a more precise source mapping.

The relationship between the hypocenter distribution and the reservoir changes was investigated. The result shows that most events were located around the bottom of the injection wells. This indicates AE occurred by the injection to these wells (Fig. **8**).

The improvement of the micro-earthquake processing and analyzing system (MEPAS), to make it running on Windows and friendlier to users, was completed (Tateno et al., 2000).

We applied a three-dimensional velocity structure analysis program (Zhao et al., 1992) to the Akinomiya geothermal field. We obtained precise hypocenter distribution and three-dimensional velocity structures that correlate with the geological structure. In addition, it was clear that the final velocity structures are depended on the initial velocity structure.

3.4 Integrated reservoir modelling and simulation techniques

This sub-theme aims to develop precise reservoir modeling techniques that employ both geological and geophysical data. These models can then be improved through history matching using measured gravity, SP, and resistivity changes from repeat field surveys to complement traditional reservoir data sets.

The effort incorporates the development of postprocessors to forecast changes in gravity, SP, resistivity and chemistry of discharges; development of a reservoir database management system; and conversion of the STAR (Pritchett, 1995), a UNIX-based geothermal reservoir simulator, to the PC platform. Also, practical modeling techniques have been developed using the Onikobe and Sumikawa systems as models of geothermal fields (Figure 4).

The conversion of the geothermal reservoir-simulator STAR has been completed and a new manual for the simulator is now being prepared. Patnaik et al. (2000) summarized the conversion procedure.

Gravity, SP, and geochemical postprocessors (and a prototype postprocessor for electrical resistivity changes using the DC method) were developed and manuals for each postprocessor are being prepared. Gravity and SP postprocessors are used in history matching in other sub-themes of the project. The postprocessor for the resistivity changes using the MT method was also developed.

3.5 Techniques to improve the reservoir model

To improve the reservoir model, modeling support techniques to provide geological and geochemical data and techniques to provide hydrological properties of the fractures were developed in the project.

The modeling support technique comprises three items to be examined:

- Application of fluid inclusion measurements to estimate temperature and chemical conditions of reservoir fluid;
- Practical use of rock-dating techniques for altered and fresh rocks to estimate thermal history of geothermal activity; and
- Application of chemical analysis of trace chemical components in secondary minerals to estimate chemical characteristics of reservoir fluid.

The homogenization temperature and melting point of ice have been measured simultaneously with gas composition determined using the laser Raman spectrometer. The thermoluminescence (TL) method was tried for zircon. Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) succeeded in quantitative chemical analysis of trace elements in minerals.

Figure 9 is an example of the application of the techniques to the existing geothermal field (the Wasabizawa and the Akinomiya geothermal fields (Figure 4)).

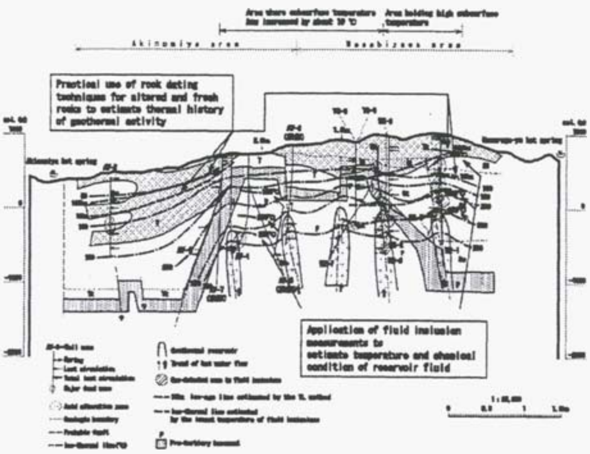


Figure 9. Geothermal Reservoir Model of the Wasabizawa and the Akinomiya geothermal fields

To determine the precise hydrological properties of fractures that form a geothermal reservoir, a computer-controlled pressure transient test system has been developed. The hydrological properties of the fracture system are determined by monitoring pressure changes in the injection well or in the observation wells nearby. To improve injection testing and downhole pressure monitoring technologies, a computer system that enables precise water injection rate control and downhole pressure control was incorporated in the test system. Software to analyze the measured pressure-transient test data to obtain pertinent reservoir properties is also being developed.
The system will permit injection of water into a well at any specific rate or rate-history (e.g. at a sinusoidal rate), air pressurizing of a well at any desired rate, and simultaneous precise measurements of downhole pressure in the injection and observation wells. The data analysis software permits precise estimation of fracture permeability. An example of a sinusoidal injection test in the Mori geothermal field (Figure 2) is shown in Figure 10.

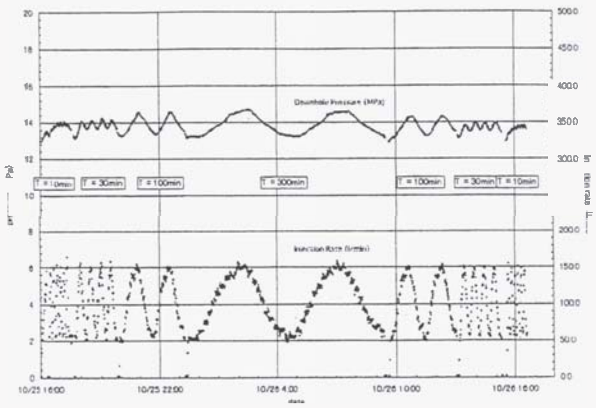


Figure 10. Sinusoidal injection test

4. INVESTIGATION REGARDING THE APPLICABILITY OF EACH TECHNIQUE

An investigation regarding the applicability of each developed technique was carried out on behalf of geothermal developers in Japan, (Which technique do they have interest in? Do they want to apply it to their own fields?)

According to the investigation, the high-ranking techniques that each geothermal developer estimates to be effective are shown below:

1) Gravity monitoring: 5 areas
2) SP monitoring: 4 areas
3) Two-phase flow metering system : 4 areas
4) Micro-earthquake monitoring:3 areas
5) Integrated reservoir modeling and simulation techniques: 3 areas
6) Modeling support technique: 1 area
7) High precision tilt-meter method: 1 area
8) Pressure transient test: 1 area.

The reasons for their selections are given below: (i.e.: Why do they select it among the developed techniques?)

1) Gravity monitoring.
- Useful for assessing the mass changes in the reservoir that accompany production and reinjection.
- Stability and high precision.
- Simple and easy to understand.

2) SP monitoring.
- Useful for assessing the fluid flow in the reservoir.
- Simple and easy to understand.
- Low cost.

3) Two-phase flow metering system.
- Indispensable to reservoir management.

4) Micro-earthquake monitoring.
- Cost-effective.
- Micro-earthquake is monitored for environmental monitoring at the present, and it is useful.

5) Integrated reservoir modeling and simulation techniques.
- Gravity and SP postprocessor are of practical use.

5. CONCLUSIONS

NEDO's project on Development of Technologies for Reservoir Mass and Heat Flow Characterization is in the final stage, with basic techniques being developed.
These basic techniques will be integrated and made suitable for practical use for geothermal reservoir monitoring and management. In the course of history matching, the monitoring results of each method will be compared with the simulation results of each geophysical characteristic calculated by postprocessors. The reservoir model will subsequently be modified so that it can explain all monitoring results.
Using this highly precise model, future changes in the reservoir will be predicted through reservoir simulation. By analyzing the future state of reservoirs, measures against problems and the best plan for steam production will be presented.

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