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CHARACTERIZATION OF RESERVOIR MASS AND HEAT FLOWS -A MAJOR JAPANESE RESEARCH PROGRAM-

Tomonori Ide, Shigeyuki Yamazawa, Shozo Ichikawa and Toshiyuki Tosha
New Energy and Industrial Technology Development Organization,
3-1-1 Higashi-Ikebukero, Toshima-ku, Tokyo 170-6028, Japan

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ABSTRACT

Since 1997, the New Energy & Industrial Technology Development Organization (NEDO) has been developing technologies which will be useful for geothermal reservoir characterization and management. The program has two main R&D themes: development of technologies for (1) Characterization of the hydrological properties of fractures, and (2) Monitoring and modeling of reservoir mass and heat flows. The objectives of the first theme are to improve injection testing technology and techniques for downhole pressure monitoring in order to characterize hydrological properties of fractured reservoirs, and to develop new logging technology for estimating properties of fractures intersected by boreholes. The objectives of the second theme are to improve the technologies for precise measurements of changes in gravity, SP (self-potential), resistivity, micro-earthquakes and other events which occur when geothermal fluid is withdrawn from geothermal reservoirs or reinjected into the ground. It also aims to develop techniques for performing integrated analysis of various types of reservoir data, and to develop quantitative numerical reservoir modeling to forecast mass and heat flow changes. These technologies could contribute to minimizing the decrease of power generation output which often occurs during production history, and to increasing the overall power generating output by indicating geothermal fluid location in surrounding areas.

1. INTRODUCTION

Most geothermal reservoirs in Japan consist of fracture systems containing steam and hot water. In conducting geothermal development, it is necessary to locate not only the fractures, but also the behavior of the fluid within those fractures, because isolated or sealed fractures do not contribute to geothermal fluid production. It is also necessary to identify the physical and hydrological changes which occur in the reservoir during production. Such technology could contribute to both minimizing the decrease in power generating output, and increasing overall power generating output by helping to develop the geothermal fluids in the surrounding areas. A decrease of generating output occurs in some of Japanese geothermal plants and the technology to overcome the problem is needed. In response to these needs, NEDO launched a new R&D project in 1997, as part of MITI's New Sunshine Program, for developing technology to characterize and forecast the mass and heat flows in geothermal reservoirs. In this paper, the outline of the project is described first and the details and some of the recent results of each task are then presented. The general structure of the project is illustrated in Fig. 1. Some results of the project were also presented in a previous paper (Horikoshi et al., 1998).

2. PROJECT OUTLINE

2.1 Characterization of the hydrological properties of fractures

This theme seeks to improve injection testing technology, techniques for downhole pressure monitoring and flow measurements on the surface, to better characterize the hydrological properties of fractured reservoirs. It also seeks to develop new logging technology for estimating the properties of fractures that are intersected by boreholes. This part of the program consists of two tasks:

1) well testing for hydrological properties
2) logging for fluid permeability

2.2 Monitoring and modeling of reservoir mass and heat flows

The objective of the second theme is to improve the technologies for precise measurements of changes in gravity, SP, resistivity, micro-earthquakes and other events which occur when geothermal fluid is withdrawn from geothermal reservoirs or reinjected into the ground. It also aims to develop techniques for performing integrated analyses of various types of reservoir data, and for quantitative numerical reservoir modeling to forecast mass and heat flow changes. This second theme involves several tasks, as indicated in Fig. 1:

1) gravity monitoring
2) electrical and electromagnetic monitoring
3) seismic monitoring
4) integrated reservoir modeling and simulation techniques

Preliminary surveys were carried out in 1997 and since then fundamental tests have been carried out.

2.3 Schedule of R&D

The project is scheduled to be accomplished in two phases. The first phase consists of five years, beginning in fiscal year (FY) 1997 and ending in FY 2001. The second phase consists of three years, beginning in FY 2002 and ending in FY 2004 (Fig. 2). Until FY 2001, cost-effective and useful techniques will be selected from all of these R&D tasks. In the second phase, various monitoring techniques will be combined to permit an integrated reservoir analysis.

3. CHARACTERIZATION OF THE HYDROLOGICAL PROPERTIES OF FRACTURE

3.1 Well testing for hydrological properties

<u>Development of computerized pressure transient testing system</u>
The objective of this task is to develop a computerized

pressure transient testing system which will enable injection of water into a well at any specific rate (e.g. at a sinusoidal rate). The system consists of an injecting device with feed-back control system, downhole pressure and well temperature profile monitoring devices, various surface sensors, a test controller and data interpreting software.

A prototype of the pressure transient testing system was constructed and a sinusoidal injection test was carried out at Hijiori field in 1998. As a result of the field test, the prototype will be improved to become practical and software for analysis will be developed (Ide et al., 2000) .

Development of accurate tiltmeter measurement method

The objectives of this task are to examine the use of tiltmeters in fracture mapping, and to establish a method for the analysis of fracture orientations by means of tiltmeters.

A field test has been carried out with ten tiltmeters distributed around the injection well used for the pressure transient test at Hijiori, and good responses to water injection were detected. A preliminary inversion analysis of the tiltmeter data showed that a small amount of volumetric change was detected in the southeast region of the Hijiori field during the injection test. Analysis of the data is continuing (Nakagome et al., 2000).

Two-phase flow measurement system

Measuring the precise volume of two phase flow in each well contributes to effective reservoir management. The aim of this research task is to develop a cost-effective, two-phase flow measuring system which can be employed directly on the two-phase line.

We measured the amount of two-phase flow using vortex flow and steam quality meters and simultaneously checked the result with the tracer dilution method. The test result suggests that scaling might affect the measuring system, and so a new measuring system which can be removed easily needs to be developed. In FY 1999 a prototype of such a two-phase flow measurement system will be developed (Yasuda et al., 2000).

3.2 Logging for permeability

Hydrophone VSP

Since the tube-wave amplitude varies with the hydraulic characteristics of the fractures, vertical seismic profiling (VSP) using hydrophones can yield the fracture characteristics through analysis of the tube-waves. A tube-wave is a Stonely wave generated by body waves in a water-filled well. The aim of this task is to develop a hydrophone VSP tool which can operate in high-temperature geothermal wells to measure tube-waves.

Theoretical investigations of hydrophone VSP were carried out in FY 1998. As a result of this study, more theoretical investigations were found to be needed to increase the precision of determination of fracture permeability .

Doppler borehole televiewer (DBHTV)

To measure the volume of fluid produced from each single fracture in a well, ultrasonic waves can be employed. When ultrasonic waves enter the flowing fluid, the frequency of waves reflected by small particles is modulated according to the fluid velocity (Doppler shift). In this task, a high-temperature DBHTV will be developed together with a method for measuring the flux of fluid in a fracture.

Doppler signal processing algorithm and the design of the DBHTV are investigated by simulation and laboratory experiments. Even if several technical problems are settled, a high cost is still required to develop the DBHTV under high temperature conditions.

4. MONITORING AND MODELING OF RESERVOIR MASS AND HEAT FLOWS

4.1 Gravity monitoring

Gravity values may change due to mass flows caused by production and reinjection of geothermal fluids. Precise gravity measurements and their analysis can help to reveal present and future reservoir conditions, and so monitoring of gravity is of importance and the development of the practical method for the gravity monitoring is required to improve reservoir management capability.

Three sub-tasks are included in this task:

a. development of a gravity monitoring system
b. analysis and evaluation of gravity monitoring data
c. study of a borehole gravity meter

The goal of the first sub-task is to establish a practical method for precise gravity measurements. In the second sub-task, gravity analysis methods will be improved by taking groundwater and tidal effects into account. A computational post processor, which forecasts gravity change based upon a mathematical reservoir model will be applied to history matching of the survey results in this sub-task. The goal of the third sub-task is to evaluate the practicability of a borehole gravimeter in reservoir monitoring.

Field measurements on this task are carried out at the Yanaizu-Nishiyama geothermal field in Fukushima prefecture, northeast Japan. The Yanaizu-Nishiyama geothermal power plant commenced operation in May 1995. A gravity survey in and around the field was made in 1994 by Okuaizu Geothermal Co. Ltd. (the developer of the field). NEDO carried out a gravity survey in 1997. By comparing the data obtained in 1997 with those in 1994, the mass change due to the production and the reinjection of the geothermal fluid was clearly observed. The gravity decreases, which imply mass depletion were found along faults in the production zone, and gravity increases, reflecting mass increases were found in the reinjection zone (Horikoshi et al., 1998, Yamazawa et al., 1999, Takemura et al., 2000).

4.2 Electrical and electromagnetic monitoring

SP and resistivity anomaly mapping are useful for monitoring the movement of the geothermal fluid, the salinity changes and the distribution of two-phase conditions in the reservoir. The precise measurement and analysis of changes in SP and resistivity would therefore indicate the present state of a geothermal reservoir.

This task aims to develop practical monitoring and analysis techniques to map SP and resistivity anomalies caused by the production and the reinjection of the geothermal fluid.

Field surveys are being carried out at the Ogiri geothermal field in Kagoshima Prefecture, Kyushu Island. By comparing SP distribution in the Ogiri area in 1987 (measured by NEDO and Geological Survey of Japan) with that measured in 1998, an apparent SP change of negative polarity was observed in the reinjection and production zones.

Positive SP anomalies were found associated with high temperature upflow zones. These positive anomalies are thought to be caused by upward hydrothermal fluid flow through electrokinetic coupling. The natural fluid circulation is disturbed by the withdrawal of the fluid for production, resulting in the decrease of the positive SP anomaly in the production area.
The fluid is injected at the reinjection area and the downward fluid flow is expected at the area. The negative anomalies are found around the area (Horikoshi et al., 1998, Ide et al., 1999).

4.3 Seismic monitoring

The production and reinjection of geothermal fluid sometimes trigger micro-earthquakes. A precise analysis of hypocenter distribution of these micro-earthquakes can delineate a geothermal reservoir and the flow path of geothermal fluid. By monitoring the seismic waves, it is possible to evaluate changes in such reservoir characteristics as temperature and fluid phase.

The main objectives of this research are to develop:
a. a micro-earthquake monitoring network system
b. a seismic measurement technique to detect changes in seismic velocity structure
c. history-matching and prediction techniques to detect changes in heat and mass flow

Equipment for a micro-earthquake monitoring system has been designed and improvements have been made to the Micro-earthquake Processing and Analysis System (MEPAS). A feasibility study of the analysis method for three dimensional seismic velocity structure is also underway (Shigehara et al., 2000, Kuwano et al., 2000, Tanaka et al., 2000).

4.4 Integrated reservoir modeling and simulation techniques

This task aims to develop the reservoir modeling techniques for carrying out an integrated analysis of the various types of data such as geological, geophysical and geochemical field data and to develop technology for modeling geothermal reservoirs in order to forecast the mass and heat flows.

This task consists of the following sub-tasks:
a. developing computational "postprocessors" for calculating changes in gravity, resistivity, SP, seismic phenomena and fluid chemistry
b. developing precise reservoir modeling and reservoir simulation techniques

Gravity postprocessor has been improved to calculate subsurface gravity changes and the SP postprocessor has been modified to improve the graphic output. A new geochemistry postprocessor has been developed to facilitate the simulation of tracer experiments in an operating geothermal field. Feasibility studies for the numerical postprocessors using electrical and seismic monitoring data are being performed. The STAR geothermal simulator, a core reservoir simulator, is being converted to operate in a PC environment (Nakanishi et al., 2000a, b, Stevens et al., 2000a, b, Pritchett et al., 2000).

4.5 Modeling support technique

This task focuses on the establishment of new technologies for obtaining geological and geochemical information which will be help reservoir modeling:
a. A practical tool for determining the age of altered and unaltered rocks
b. A tool for measuring homogenization temperatures and determining the fluid and gas composition of fluid inclusions
c. A tool for investigating fluid flow paths through the analysis of minor chemical components in rocks

The thermoluminescence (TL) method was adopted for determining the rock age and fundamental experiment of the TL intensity measurement was carried out. A linear relationship in a logarithm diagram between the TL intensities and the known ages of rock was obtained using quartz grains in the wavelength range from 550 to 700nm. The age of the weakly altered dacite in a geothermal field was estimated by the TL method, and the result was close to the reported age.

The formation temperature, which is normally obtained by temperature logs, can be estimated from the homogenization temperature of fluid inclusions. The lowest temperature estimated from quartz grains gave the best estimation of the formation temperature among these observed. Fluid inclusions in calcite grains, however, showed lower homogenization temperatures than those estimated from quartz grains, implying that the formation temperature was lower than that at present.

Minor elements in quartz grains obtained from several wells were measured using an Inductively Coupled Plasma - Mass Spectrometer (ICP-MS) and the variation of the elements with depth was obtained. The sodium/potassium ratio fluctuates intensely near the point of circulation losses; by comparing the ratios between wells, the flow paths will be determined (Maeda et al., 2000).

5. SUMMARY

Technology to characterize the mass and heat flows in the geothermal reservoir is being developed under a NEDO project in Japan. The project consists of two themes, which are “Characterization of the hydrological properties of fractures” and “Monitoring and modeling of reservoir mass and heat flows”. In this project, pressure transient testing system, tiltmeter measurement method, two-phase flow measurement system, gravity monitoring method, SP monitoring method, electromagnetic monitoring method, seismic monitoring method, simulation techniques and modeling support techniques are being developed. These techniques are under testing in the Sumikawa, Kakkonda, Wasabizawa, Akinomiya, Onikobe, Hijiori, Yanaizu-Nishiyama, Ogiri and Yamagawa geothermal fields in Japan (Fig.3).

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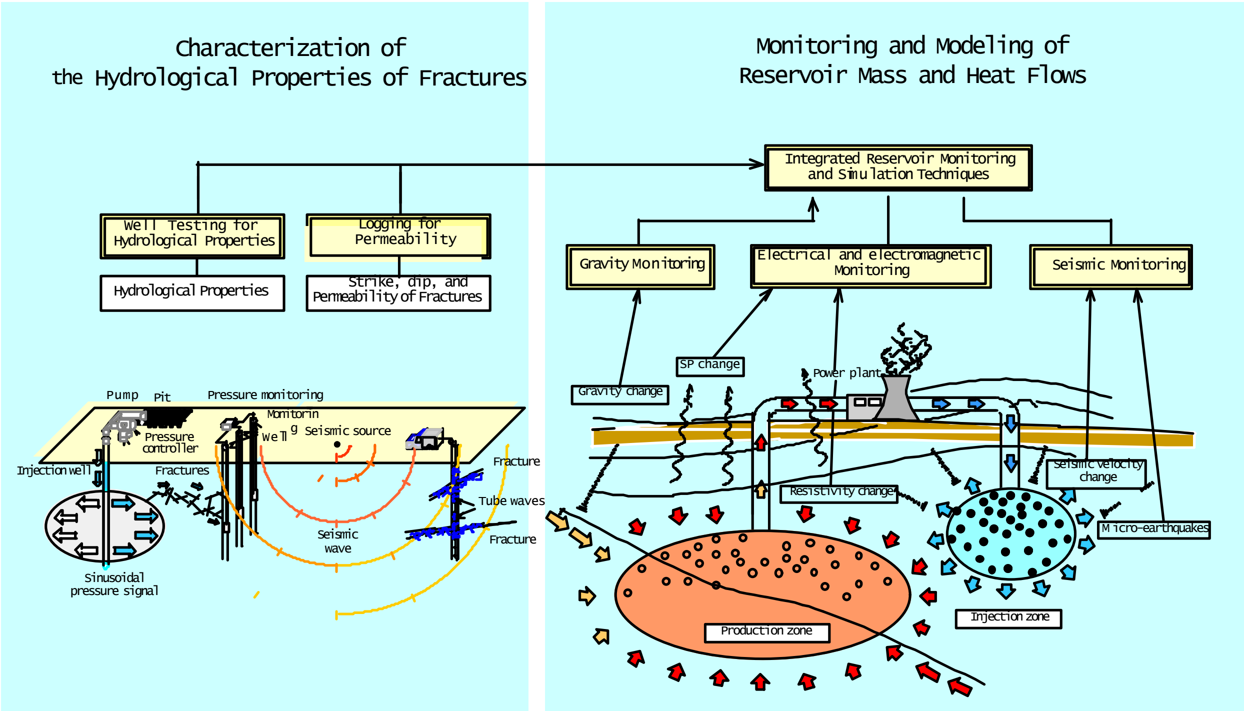

Figure 1. Elements of the technology development program

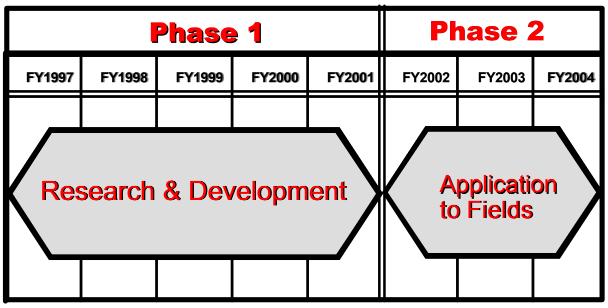

Figure 2. Timing of the program

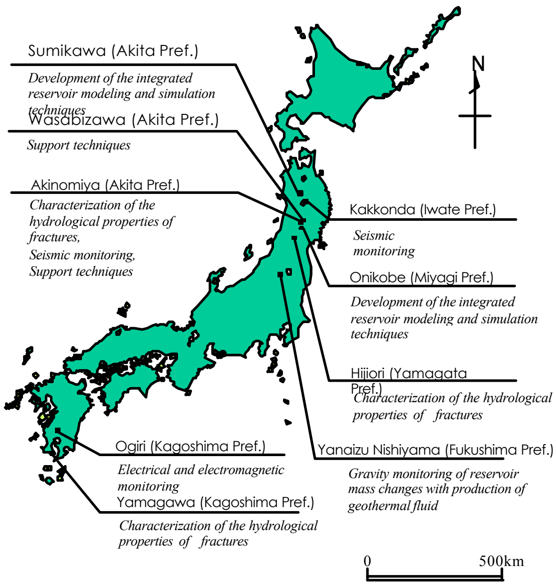

Figure 3. Location of study areas