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RECENT RESULTS OF "DEEP-SEATED GEOTHERMAL RESOURCES SURVEY" PROJECT IN THE KAKKONDA GEOTHERMAL FIELD, JAPAN

Toshiyuki Tosha[1], Kazuo Koide[1], Takao Ohminato[2], Kohei Akaku[3], and Nobuo Doi[4]
[1] The New Energy and Industrial Technology Development Organization (NEDO),
Sunshine 60, 30F, 3-1-1 Higashi-Ikebukuro, Toshima, Tokyo, Japan
[2] NEDO (Now at Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo, 113-0032, Japan)
[3] NEDO (Now at Japan Petroleum Exploration Co. Ltd., 1-2-1 Hamada, Mihama, Chiba, 261-0025, Japan)
[4]Japan Metals and Chemicals Co. Ltd., Sasamori 72, Ukai-aza, Takizawa-mura, Iwate-gun, Iwate, 020-0172, Japan

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ABSTRACT

During flow tests conducted at the well WD-1b in the Kakkonda geothermal area, geothermal fluid from a deep reservoir was successfully produced. The total flow rate and its vapor-liquid content at WD-1b suggest that a two-phase feeding condition is developed in the deep reservoir. The chemical characteristics of the water from well WD-1b are slightly different from those of the other deep production wells in Kakkonda possibly owing to high temperature and relatively low permeability of WD-1b.

Although the stress field around WD-1a and WD-1b estimated from the DTF analysis is approximately in good agreement with the local stress field, no straightforward relationship between orientations of fractures and measured stress field.

Isotopic analyses of fluid inclusions in quartz, tracer tests, and pressure monitoring using five shallow wells and a deep well give hydrologic property of the Kakkonda geothermal system. Using reservoir parameters obtained by the pressure monitoring, flow tests, and other various surface and borehole surveys, numerical simulations of the Kakkonda reservoir was conducted. The natural state simulation can reconstructs the observed temperature profile when the permeability in the shallower reservoir is two to three orders of magnitude higher than that of deep reservoir.

The results of the collapsing analysis on microearthquake location confirms that the base of the seismogenic zone roughly corresponds to the isothermal contour of 300 to 350°C. The joint analysis of various types of electric resistivity measurement techniques, such as MAIL, VEMP, and conventional MT shows much higher resolution of resistivity structure in the vicinity of the well. Applicability of the synthetic fluid inclusion logging as a deep fluid sampler is confirmed by a series of laboratory tests.

By exposing various types of test pieces of casing and pipings to the flow of geothermal field both in WD-1a and in the surface facilities, corrosion and erosion properties of metallic materials were investigated. The results obtained in the Kakkonda field will be used to make guidelines for the development of deep-seated geothermal resources.

1. INTRODUCTION

Since deep-seated geothermal resources are expected to contribute immediately to the growth of the capacity of the geothermal power generation in Japan, several studies on exploitability of such deep geothermal resources which exist beneath already-developed shallow reservoirs have started recently. Deep-seated geothermal resources (approximately at a depth of 2,000 m and deeper from ground level) are considered promising because of their advantages over shallower reservoirs, such as their larger size, lower initial cost of development, and lower environmental damage. As a target depth increases, however, exploration difficulties increase exponentially. Several technical difficulties in drilling are also expected. There still be uncertainty in dealing with highly corrosive geothermal fluid from a deep reservoirs. Considering these difficulties, it is still risky to proceed to develop deep subsurface resources.

"The deep-seated geothermal resources survey" is planned so as to meet the following three indispensable factors in order to promote the development of deep geothermal resources;

- an investigation of the three basic factors of geothermal resources : heat supply, geothermal fluid supply, and highly developed fracture systems that constitutes geothermal reservoirs, so that the overall geothermal system including both shallow and deep reservoirs is well depicted,
- a research on the applications of drilling techniques, which have been already used in drilling wells targeting for shallow reservoirs, to the condition of extremely high temperature and high pressure in deep geothermal reservoirs,
- an investigation of a possibilities of utilizing deep geothermal fluid which is expected to be highly acid, aiming to put the deep-seated geothermal resources under practical use.

The final goal of the project is promoting the development of geothermal resources in the deep subsurface in order to increase the capacity of geothermal power generation by establishing the technological guidelines necessary to reduce development risks.

The deep-seated geothermal resources survey project started in fiscal 1992* and is scheduled to complete at the end of fiscal 2000* (* the first day and the last day of fiscal year in Japan are April 1 and March 31, respectively). This project is divided into two phases, phase I: detailed field survey in the Kakkonda geothermal field including drilling exploration wells named WD-1a and WD-1b (Figure 1), phase II: based on both the research results obtained in the Kakkonda area and the information which have been obtained in other geothermal fields, a guideline which can be applicable to various types of geothermal field all over Japan will be developed. The first phase was completed at the end of calendar year 1999 and the second phase is now on-going.

The progress of the project has been reported constantly and regularly by Sasada et al. (1993), Yagi et al. (1994a, 1994b, 1995), Muraoka et al. (1995), Yasukawa et al. (1995), Uchida et al. (1996a, 1996b, 1997), Kamenosono et al. (1997a, 1997b), Yanagisawa et al. (1997), and Fujimoto et al. (1998). As the project proceeds, the geological setting of the Kakkonda area, drilling progress of WD-1a and WD-1b, the results of various geophysical and geochemical surveys have been reported in detail in the papers mentioned above.

The main topic of this paper is to show the latest results of the first phase of the project conducted in the Kakkonda geothermal field. We start with reviewing the project plan. We then introduce the recent results of the project conducted in the Kakkonda area obtained during the fiscal 1998. Finally, we briefly mention the future plan of the project.

2. THE PROJECT PLAN

The survey area is the Kakkonda geothermal field in Iwate Prefecture, northeastern Japan, where sufficient amounts of the shallow subsurface data on the geothermal resources are available and the existence of a deep geothermal reservoir has been already confirmed by several wells deeper than 2,500 m. In this area, a 4,000-m-class exploration well is drilled. Various types of surveys, such as borehole geological surveys including sample analyses, well loggings, and flow tests are conducted. The work program of the project is categorized into the following four groups:

• Modeling of a deep geothermal system:
To conduct various types of surveys based on geology, geochemistry, geophysics, and reservoir engineering. To build a model of geothermal system useful for exploration and development of deep-seated geothermal resources by integrating the results of the data analyses.

• Development of deep reservoir survey methods:
To improve survey and analysis methods using micro-earthquakes or electromagnetic signals so as to increase an accuracy of the methods for both deep and shallow geothermal reservoirs far more better than that of conventional methods.
In addition, to investigate practical applicability of the synthetic fluid inclusion methdas logging for measuring extremely high temperature that cannot be reached by conventional techniques.

• Systematization of deep drilling technologies:
To apply the latest drilling technologies, such as a mud cooling system, drill bits for high temperature, and directional drilling techniques, to the drilling of the deep exploration well in order to clarify the advantages and disadvantages of these technologies. On the basis of investigation results, technologies for drilling exploration wells are systematized.

• Research on deep geothermal fluid utilization technologies:
To conduct corrosion and erosion tests of casings and pipes for surface facilities during a flow test conducted at the exploration well in order to clarify the corrosion and erosion resistance of various kinds of metallic materials to deep geothermal fluid. To investigate galvanic corrosion between different types of metals, as well. On the basis of the investigation results, a guideline of the optimum selection and combination of metallic materials in utilizing the deep geothermal fluid is put in shape.

3. SUMMARY OF THE SURVEY RESULTS IN 1998

3.1 Flow Test

Before starting a flow test, damages of the 9-5/8" casing pipes of WD-1b were repaired. At the same time, a cement bridge was also removed which was left in the borehole and prevented steam from being discharged smoothly.

Although interrupted for about 50 days by an earthquake which occurred in the vicinity of the survey area, a total of 100 days of the flow test was conducted at WD-1b from July 1 to November 26, 1998. At the beginning of the flow test, the flow rate of steam and liquid were about 10 tons/hour, 3 tons/hour, respectively, at a well-head pressure of 0.25MPa. These figures declined gradually to 6.6 tons/hour, 0.4 tons/hour, and 0.25MPa, respectively, at the end of the flow test (Figure 2). As the flow rate of liquid declined, the total discharged enthalpy increased and finally reached 2,500-2,600kJ/kg. The enthalpy increase can be explained by an increase of dryness of wet steam.

3.2 Geochemical Analyses

During the flow test, the chemical composition of the fluids discharged from WD-1b was continuously monitored. Isotope composition monitorings and PTS loggings were conducted, as well.

Yanagiya et al. (1996) reported that the discharged water from shallow production wells in the Kakkonda area is slightly alkaline (pH = 8-9), whereas the water from the deep wells is acid (pH = 3.2-4.5). The pH of the fluid discharged from WD-1b is 2-3, that is even lower than that from other deep wells. It is observed that the higher the enthalpy of the discharged water, the lower the pH of it. Chloride concentration in the water is as high as 10,000 mg/l. From the result of analyses of isotopic composition of the water, the origin of the fluid from WD-1b is estimated to be meteoric, same as fluids from other deep production wells in the Kakkonda area. The gas composition suggests no significant contribution from magmatic water.

Differences in chemical composition between the water samples from WD-1b and those from other deep wells in the Kakkonda area can be explained by the following mechanism. Under the low permeable condition, a vapor phase flows into a well preferentially than a liquid phase and thus a salt concentration into the water left in the reservoir occurs. Concentrated salts are decomposed and produce HCl under high temperature and the existence of water, causing low pH (Kasai et al., 2000).

3.3 DTF Analysis

Drilling-induced Tensile Fractures (DTF) indicate the stress field around the well. The orientation of DTF is analyzed taking into account the effect of thermal stress and pressure of drilling fluid. Directions of the maximum principal stress axis are obtained around WD-1a and WD-1b as follows (Figure 3):
• Shallower part of WD-1 (700-1,300m from GL) :
The direction of the axis is nearly EW with no inclination.
• Deeper part of WD-1a (1,900-2,650 m):
The axis are inclined at 60° to the WNW.
• Deeper part of WD-1b (2,600-2,910 m):
The direction of the axis is ENE-WSW with no inclination.
• Between WD-1a and WD-1b (2,500-2,910m):
The direction of the axis is ENE-WSW with no inclination.

These results are in good agreement with the direction of the maximum principal axis of the regional stress field obtained by using other techniques such as an analysis of micro-earthquake mechanisms .

Based on the FMI** (** the trademark of Schlumberger) data, the relationship between the stress field near the well deduced by the DTF analysis and the permeable fractures observed in the well WD-1b are investigated. No clear relationship between the distribution of permeable fractures and stress field was observed (Kato et al., 2000).

3.4 Isotope Composition of Fluid Inclusions in Quartz

An isotopic fraction of fluid inclusions in quartz grains is analyzed. The results suggest two types of water behavior. One is that the water, of which the present-day hydrothermal system in the Kakkonda field is composed, is metric and possibly permeate into the Kakkonda granite at isolated points where permeability is relatively higher than its surroundings. The other is that there exist water in the Kakkonda granite which are isolated from the present-day hydrothermal system.

3.5 Micro-earthquakes Monitoring

Continuous monitoring of micro-earthquakes using ten seismic stations was completed on March 31, 1999. The number of microearthquakes observed from January 1 to December 31, 1998 is approximately 16,500 which is extremely larger than usual (3,500 events in 1995, 6,400 events in 1996, and 7,200 events in 1997). This unusual seismicity is interpreted as the activity associated with the volcanic activity of Iwate volcano which has started since February 1998.

Microearthquakes are relocated by using the Joint Hypocentral Determination (JHD) method and the collapsing method (Figure 4). The hypocenter relocation makes it clearer that the hypocenter distribution has significant relationship with geological structure, electrical resistivity structure, depths at which lost circulations are encountered, and so on. Detailed comparisons of the hypocenter distribution and geothermal contour confirm the relationship between the bottom of the hypocenter distribution and 300-350°C geothermal contour.

3.6 Tracer Tests

The existence of flow paths between the deep wells in the Kakkonda geothermal field is confirmed for the first time by a series of tracer tests. It is also discovered that the flow pattern in the Kakkonda area has been changed significantly in last 6 years. When a series of tracer test was carried out in 1992, trace elements were detected at the wells whose completed depths are almost the same as the depth at which tracers are injected. On the other hand, the tracers are detected only at a well deeper than the depth of the tracer injection during the tracer test in 1998. This means that the re-injected water have been pulled down to much deeper portion of the hydrothermal system than in 1992.

3.7 Pressure Monitoring and Reservoir Evaluation

Pressure monitoring was conducted using five existing shallow wells at depths from 590m to 1,270m from March 1996 to October 1999. The pressure monitoring using WD-1b was also performed from November 1998 to October 1999 to investigate the existence of the pressure interference inside the deep-seated geothermal reservoir and between shallow and deep reservoirs. The pressure monitoring data are re-examined and events of pressure change extracted from the data are compared with each other. The short-term pressure changes are analyzed based on the method of type-curve matching so as to calculate permeability and storativity of the reservoir. A pressure interference due to the shut-in of production wells during the regular inspection of the geothermal power plant is similarly analyzed. As a result, permeability of an order of magnitude of 10-14 m2 is obtained.

Taking into account the pressure reduction trend in the reservoir in the Kakkonda area as a result of the steam production for the Kakkonda No. 2 power station, a closed system model is applied to compute the total mass of hydrothermal fluid in the reservoir including both shallow and deep. The derived mass of geothermal fluid in the Kakkonda geothermal field is of an order of 1012kg that is several tens of times larger than that of the net hydrothermal fluid production in the past.

Permeability anisotropy in the shallow reservoir is also analyzed. The high-permeability direction is N19°W and almost horizontal. The orientation of the axis of high permeability is in good agreement with the direction of shallow reservoir elongation.

The parameters of the shallow and deep reservoirs obtained by a pressure monitoring, flow tests, and other hydrological measurements, are used for reservoir simulation studies. The natural state simulation well reconstructs the observed temperature profiles which is characterized by the existence of temperature discontinuity at a depth of around 1,500m (Figure 5). The temperature discontinuity, which has been interpreted as a boundary between the shallow and deep reservoirs, is simulated only when the permeability in the shallow reservoir is two to three orders of magnitude higher than that in the deep reservoir (Sakagawa et al, 2000).

Numerical simulation of the geothermal reservoirs, both history matching and prediction of future behavior of reservoirs, have been performed at the time when this manuscript is written.

3.8 Electromagnetic Survey

In this project, Multi-frequency Array Induction Logging (MAIL) tool, Vertical ElectroMagnetic Profiling (VEMP) tool, and an joint inversion technique are developed. In the joint analysis, data obtained by above two logging tools, conventional electric logging techniques, and a conventional MT method are analyzed simultaneously.

In fiscal 1998, MT data were obtained using 4 survey lines. 3D analysis of MT data using the results of MAIL and VEMP analyses as a constraint of the resistivity model were conducted in 1999. Intermediate results shows fairly good agreement with other geological and geophysical data. The Kakkonda granite are detected as a high resistivity body, while shallow reservoir corresponds to moderate resisitivity region with much higher precision than that obtained by conventional techniques.

3.9 Synthetic Fluid Inclusion Logging

The synthetic fluid inclusion logging is a new technique for temperature measurement and fluid sampling in geothermal wells. It can be applied to very high temperature (above 500°C) geothermal wells deeper than 3,000m in which conventional logging tools do not work (Sawaki et al, 1995). The applicability of the method as a temperature measurement tool has been confirmed in the early stage of this project. In order to confirm and evaluate the other function as a geothermal fluid sampler, a series of laboratory tests is conducted. It is proved that enough amounts of synthetic fluid inclusions are formed within a day when the temperature exceed 350°C.

3.10 Corrosion and Erosion Tests of Metallic Materials for Casings and Pipings for Surface Facilities

Corrosion test in the well : After the initial flow test, the metallic corrosion test pieces that were set in WD-1 at a depth of 2,100m were pulled up. Detailed inspections of these test pieces show that at the boundary between different metallic materials, weight losses possibly due to galvanic corrosion are detected.

Corrosion test for surface piping : Test pieces that were set in the pipings of the surface facilities were retrieved after the completion of the flow test. Among the two types of test pieces made of stainless and carbon steels, only carbon steel pieces suffered from slight corrosion. The estimated corrosion rate is

0.2 mm/year.

3.11 Guidelines for Developing Deep Geothermal Reservoirs

In order to establish the guideline for the exploitation of deep-seated geothermal resources, the results of the first phase of this project conducted in the Kakkonda geothermal field are re-examined and rearranged. The guideline consist of three parts; the guideline for deep reservoir exploration techniques, the guideline for deep drilling techniques, and the guideline for deep fluid production technologies. The guideline for exploration technology for deep geothermal reservoirs is further divided into two parts; guidelines for each individual exploration technique, and guidelines for each individual subsurface target.

Additional data collection has been conducted in order to extend the guidelines which are established based solely on the data of Kakkonda geothermal field so that they are applicable to other geothermal systems.

4. FUTURE PLAN OF THE PROJECT

Based on the results obtained in the Kakkonda geothermal area, exploration technologies, drilling and production technologies effective for the development of deep geothermal resources will be established. Important know-hows on the utilization of individual technologies (such as specifications necessary for actual applications) will be put together to establish the guidelines for exploiting deep-seated geothermal resources taking into account not only effectiveness of technologies but also an economical point of view. On the basis of the data obtained by exploration and development in other geothermal fields, various types of geothermal systems in Japan will be categorized, how the deep-seated geothermal resources in other fields exist will be estimated, and applicability of the guidelines for exploitation formulated on the basis of all the survey results in the Kakkonda field to other geothermal fields will be investigated.

5. CONCLUSIONS

Important conclusions obtained during fiscal 1998 are as following.

• The well WD-1b, which was drilled in the Kakkonda geothermal field succeeded in flow tests producing geothermal fluids from a deep reservoir. The well's flow rates of steam and liquid are about 6.6 tons/hour and 0.4 tons/hour, respectively, at a wellhead pressure of 0.25 MPa. Total discharged enthalpy is as high as 2,500kJ/kg, suggesting that a two-phase feeding condition is developed in the deep reservoir.

• The chemical characteristics of the water collected at WD-1b are slightly different from those of the other deep production wells in the Kakkonda field possibly owing to high temperature and relatively low permeability in WD-1b.

• Although the stress field estimated by the DTF analysis approximately coincides with the local stress field, no straightforward relationship between orientation of fractures and inferred stress field is observed.

• Various exploration techniques, such as microearthquake monitoring and electromagnetic survey, have been conducted in the Kakkonda field. The result of the collapsing analysis on micro-earthquake location confirms that the bottom of the hypocentral distribution roughly corresponds to the isothermal contour of 300 to 350°C. The electric resistivity measurement techniques including MAIL, VEMP and conventional MT method gives much higher resolution of electric resistivity structure in the vicinity of the well.

• The applicability of the synthetic fluid inclusion logging as a sampler of deep water is confirmed by the laboratory experiments.

• Isotope composition analysis of fluid inclusions in quartz suggests two types of characteristic behavior of deep geothermal water in the Kakkonda field. Tracer tests reveal the existence of flow paths between wells deeper than 2,500m.

• An order of magnitude of the permeability in the shallow reservoir is 10-14m2. Permeability anisotropy with higher permeability direction in N19°W is also calculated using pressure monitoring data.

• Hydrological characteristics of geothermal reservoirs in the Kakkonda area obtained through various methods including tracer tests and pressure monitoring, are used for numerical simulations of the geothermal reservoir. It is shown that the permeability in the shallow reservoir need to be two to three orders of magnitude more permeable than that in deep reservoir in order to explain the discontinuity in the temperature profile of deep wells.

• In the corrosion tests conducted in the well WD-1a, galvanic corrosion between different metallic materials was detected. Corrosion rate of 0.2 mm/year is obtained by the corrosion test for pipings for the surface facilities.

• The results at Kakkonda will be used to make guidelines for the development of deep-seated geothermal resources, which can be applicable not only to the Kakkonda type geothermal systems but also to other geothermal systems in Japan.

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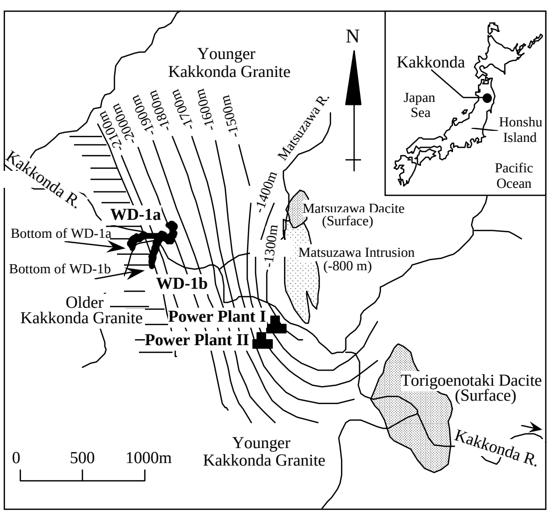

Figure 1. Location of the Kakkonda geothermal field. The traces of the deep exploration well WD-1a and the well WD-1b sidetracked from WD-1a are also shown. Contour lines corresponds to the top of the Kakkonda granitic pluton at depths in meters below sea level (modified from Kato and Doi, 1993)

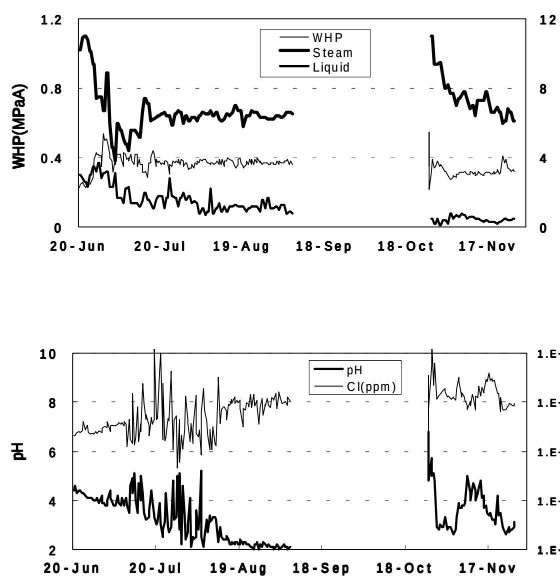

Figure 2. Results of the flow test and related geochemical analysis: (Top) Wellhead pressure change and flow rate of both steam and liquid from WD-1b. (Bottom) Changes in pH of and Cl concentrations in liquid phase (after Kasai et al, 2000).

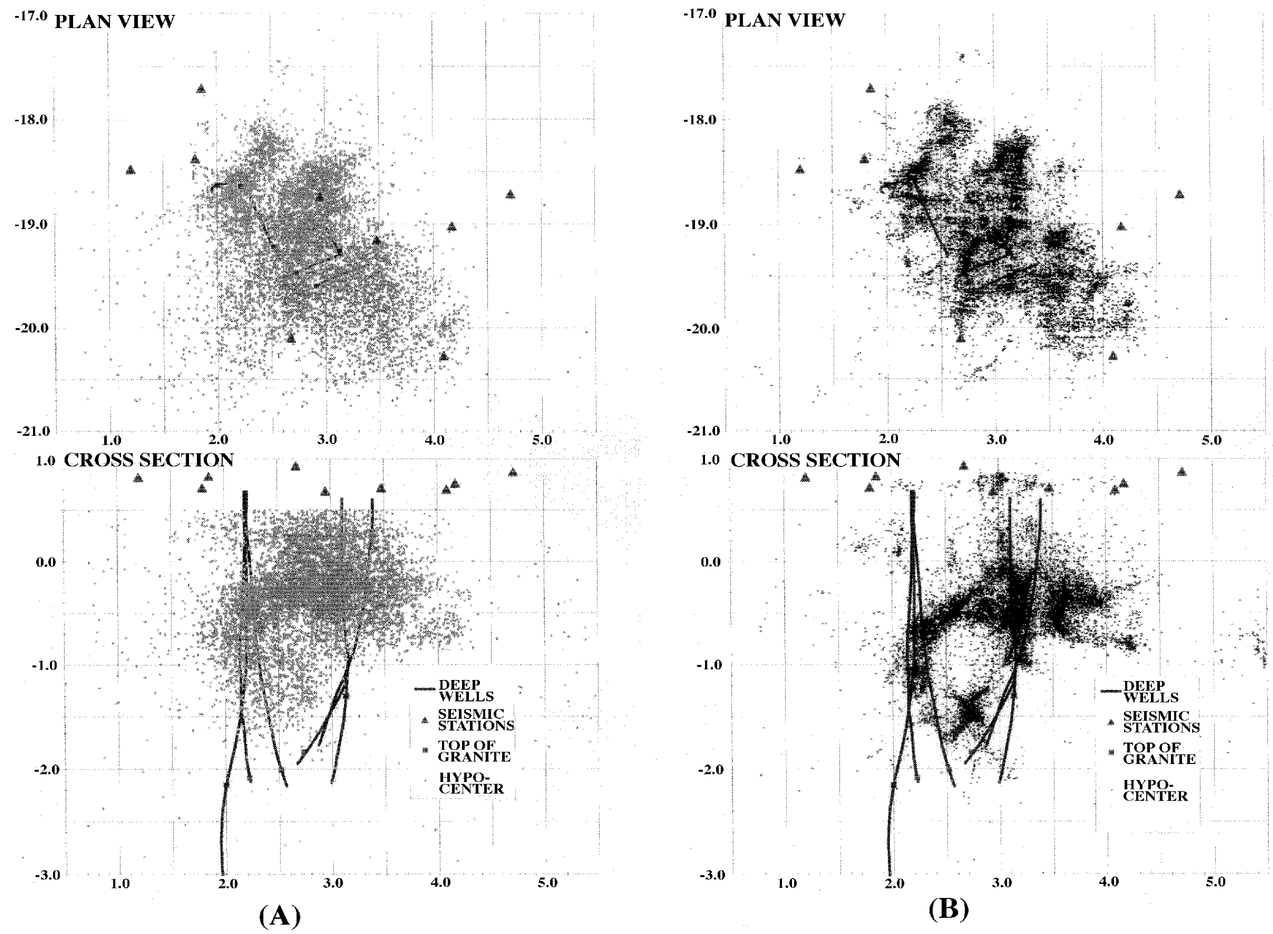

Figure 4 Hypocenter distributions using (A) conventional method, and (B) the collapsing method.

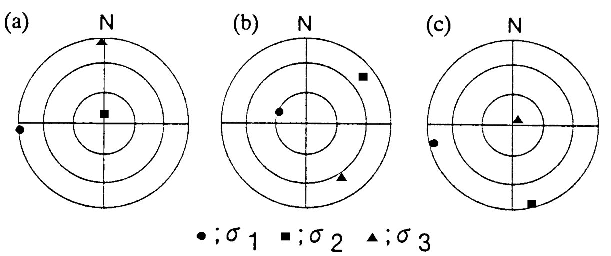

Figure 3. Results of DTF analyses showing in situ stress field near WD-1. (a) Shallow reservoir (700-1,300m in WD-1), (b) Deep reservoir (1,900-2,650 m in WD-1a), (c) Deep reservoir (2,600-2,910 m in WD-1b). s1 > s2 > s3 (modified from Kato et al., 2000)

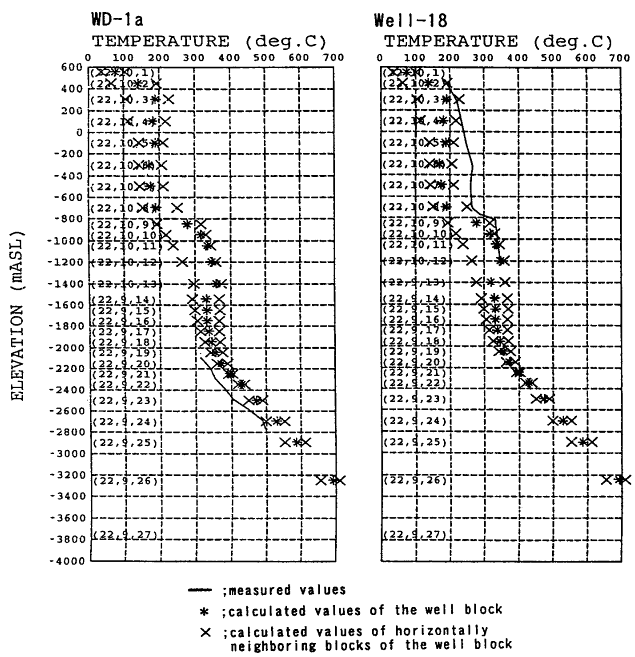

Figure 5 Comparison between observed temperature profiles(--) and the result of the natural state simulation of geothermal reservoir(*, x) (after Sakagawa et al, 2000).