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ABSTRACT

NEDO has drilled WD-1 in the Kakkonda geothermal field, as a part of the "Deep-Seated Geothermal Resources Survey" project. We performed temperature measurements and fluid inclusion study of WD-1. The logging temperatures above 414°C were confirmed at 3,600 and 3,690m depths for S.T.=82h, and the temperatures above 500°C were also confirmed by using temperature melting tablets at 3,700m depth for S.T.=129h and 159h. This temperature is the highest recorded for a geothermal bore hole in Japan. Formation temperature in the Quaternary Kakkonda Granite can be evaluated roughly from homogenization temperature of the liquid-rich inclusion which has minimum salinity at every depth. As a result of temperature measurements, we found the boundary between the hydrothermal convection zone and the heat conduction zone at about 3,100m depth. Data obtained by fluid inclusion study is also judged to be consistent with this conclusion.

INTRODUCTION

The New Energy and Industrial Technology Development Organization (NEDO) started the "Deep-Seated Geothermal Resources Survey" in FY-1992 to investigate the characteristics of deep geothermal systems. As a part of the project, NEDO drilled WD-1 in the Kakkonda geothermal field, located about 500km north of Tokyo (Fig.1). Kakkonda is one of the most active liquid-dominated geothermal fields in Japan. The first power plant, Kakkonda Unit-1, 50MWe, has been in operation since May, 1978. Moreover, Kakkonda Unit-2, 30MWe, has been in operation since March, 1996.

WD-1 was drilled to a depth of 3,729m in July, 1995. This is the deepest recorded for a geothermal bore hole in Japan (Yagi et al., 1995; Uchida et al., 1996). After drilling to 3,729m depth, we carried out a temperature build-up test to understand the thermal structure in Kakkonda. Microthermometry and gas analysis of fluid inclusions were also performed. As a result, we determined important information about the thermal structure and fluid flow in the Kakkonda Granite, which is a part of heat source in the Kakkonda geothermal system (Doi et al., 1993).

In this report, we describe the bottom of the hydrothermal convection zone, i.e. the boundary between the hydrothermal convection zone and the heat conduction zone, found by temperature measurements, which include results of temperature melting tablets and fluid inclusion study.

DRILLING HISTORY OF WD-1

WD-1 was drilled to a 3,729m depth in July, 1995. During drilling below 3,642m depth, mud with a high content of H₂S gas started to return to the surface. After the drilling operation was terminated, WD-1 was plugged back below 2,400m depth because of safety concerns (Kasai et al., 1996). The temperature build-up test had to be run for short standing time for the above reason. Before WD-1 was plugged back, temperature measurements which used a PTS tool, Kuster tools and temperature melting tablets were carried out a total of 7 times.

GEOTHERMAL MODEL IN KAKKONDA

The geothermal model in the Kakkonda field is shown in Fig.1. There are two reservoirs with different temperature and permeability in the Kakkonda geothermal field (Hanano and Takanohashi, 1993; Hanano, 1995). The shallow reservoir is permeable and at 230 to 260°C, while the deep reservoir is less permeable and at 350 to 360°C. However, they are hydraulically connected to each other. The deep reservoir consists of Pre-Tertiary, Tertiary formations and the Kakkonda Granite. There are permeable fractures at the margin of the Kakkonda Granite (Kato et al., 1993).

TEMPERATURE LOGGINGS BY TOOLS

A temperature build-up test was carried out during circulation above 2,510m depth, because we feared a high content of H₂S gas would blow out. Therefore, temperature tools were run within the drill pipe to 2,510m depth.

(1) TEMPERATURE BUILD-UP TEST BY A PTS TOOL

Temperature logging by a PTS tool using armored-cable was carried out 5 times. Figure 2 shows the results of PTS tool logging, Kuster tool logging and temperature melting tablet measurement. PTS tool logging ran until 310°C considering the armored-cable heat resistance limit.

(2) TEMPERATURE BUILD-UP TEST BY KUSTER TOOLS

Temperature logging by Kuster tools using a stainless-steel wireline was carried out twice. These logs surveyed temperatures at a distance of every 100m below 2,500m depth.
in order to measure temperatures below the circulation zone. The result of the first log showed that the temperature increased linearly from 2,500 to 3,500m depth, and a temperature of 414°C was recorded at a 3,500m depth. Moreover, temperatures greater than 414°C, which was the limit of this Kuster tool, were confirmed at 3,600m and 3,690m depths. This 414°C is the highest recorded by the logging tool in Kakkonda.

During the second logging run, we could not survey below 3,300m depth, because the Kuster clock broke down due to the high temperature. However, the temperature above 418°C, which was the limit of this Kuster tool, was confirmed below 3,300m depth.

TEMPERATURE MEASUREMENT BY TEMPERATURE MELTING TABLETS

Temperature melting tablets were used twice in order to confirm high temperature which could not be measured by Kuster tools. These tablets are made by pressing of irreversible substances that fuse at a specific melting temperature. The tablets for measurements had 12 kinds of melting points ranging between 399 and 550°C (Table 1). The tablets are made of various inorganic fusion compounds. For example, the main materials of these compounds are chromium, molybdenum, tungsten, barium, sodium and potassium.

Each tablet was packed into a steel container or crucible, and furthermore, was installed into a steel vessel (O.D.=45mm). The steel vessel was sealed and was run into the bore hole using a stainless-steel wireline. The steel vessels were held at a depth of 3,700m for one hour. Two measurement runs on successive days were conducted.

Table 1. Temperature melting tablets using temperature measurements.

<table>
<thead>
<tr>
<th>Date</th>
<th>Melting point of temperature melting tablets</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/23/1995</td>
<td>399°, 427°, 482°, 500°, 510°, 538°, 550°</td>
</tr>
<tr>
<td>7/24/1995</td>
<td>434°, 471°, 485°, 499°, 427°, 430°, 460°, 482°, 500°, 510°, 520°, 538°, 545°, 550°</td>
</tr>
</tbody>
</table>

An engineer of the company which manufactured the tablets inspected them whether they had melted or not. As a result, the surface of the tablets rated below 500°C were found to have melted in both measurement runs (Fig.3). Therefore, the temperatures of 3,700m depth at S.T.=129h and 159h are estimated to be above 500°C.

To corroborate the above measurements, we tested melting points of the same specification tablets, in a furnace. In these tests, we used the same tablets, crucibles and vessel as those in the temperature measurements of WD-1. These tests were carried out at temperatures of 475, 490, 500, 510 and 520°C respectively. We spent two hours when we heated the tablets to the target temperature, we then kept them at the target temperature for one hour in the furnace. This temperature change was similar to what the tablets experienced in WD-1. As a result, the surface of the tablets rated below 500°C were judged to have melted in the 510° and 520°C tests by inspector of the producer of the tablets. Therefore, we confirmed that the temperatures at 3,700m depth for S.T.=129h and 159h were above 500°C by these tests.
Figure 2. Compiled column showing casing design, geology, lost circulation and temperature logging data of WD-1.
Before measurement

After measurement

DATE: 7/24/1995
Thermo crayon-M: 490°C

280 μm

Before measurement

After measurement

DATE: 7/24/1995
Tempil-pellet 510°C

280 μm

At the same time of the temperature measurement using temperature melting tablets, Sasada et al. (1996) also tried to measure temperature of WD-1 by using other materials. Four kinds of pure materials, metal lead, potassium dichromate, metal zinc and metal tellurium, were installed into steel vessels. After the measurement, they found that the metal tellurium had melted at 3,700m depth for S.T.=129h and 159h. Those indicated temperatures exceeded 449°C that was the melting point of metal tellurium.

ESTIMATED STATIC FORMATION TEMPERATURE

Estimated static formation temperatures were analyzed using the 5 FTS tool logging data sets and the two Kuster tool logging data sets by use of Homer plots (Fig.4). The estimated static formation temperature at 3,500m depth was analyzed to be 501°C.

The highest temperature measured in a bore hole, to the best of our knowledge, was in excess of 1,070°C in the melt zone of Kilauea Iki lava lake in Hawaii (Hardee and Hills, 1981). The previous record of the highest temperature in a geothermal bore hole was 419°C, which was determined by the melting of zinc in San Vito, Italy (Bruni et al., 1983). In Japan, the highest recorded temperature by a logging tool was 373°C, which was measured at Fushime geothermal field (Yoshimura and Ito, 1994). The highest estimated static formation temperature in Japan was 412°C, which was analyzed at Kakkonda geothermal field (Saito, 1994).

Therefore, this is the first time we obtained 501°C for the estimated static formation temperature at 3,500m depth in a geothermal bore hole. Moreover, we applied the temperature melting tablets to temperature measurement in WD-1 for the first time. As a result, 500°C at 3,700m depth was positively confirmed.

Figure 3. Temperature melting tablet photographs.

Figure 4. Estimated static formation temperature (Homer plots).

MICROTHERMOMETRY AND GAS ANALYSIS OF FLUID INCLUSIONS

We studied fluid inclusions for WD-1. Most samples of Quartz, Calcite, Anhydrite and Sphalerite were taken from cuttings, some samples were veinlets in cores. We observed liquid-rich inclusions, vapor-rich inclusions and polyphase inclusions with Halite in the samples. The liquid-rich inclusions were dominant at shallower depths. On the other hand, the polyphase inclusions and vapor-rich inclusions increased at greater depths. Few liquid-rich inclusions were observed below 3,450m.
We measured final melting points of ice (Tm(ice)) of the liquid-rich inclusions and vapor-rich inclusions by the freezing method. Then, we measured their homogenization temperatures (Th(L-V)) by the heating method. We also measured disappearance temperatures of the bubble (Th(L-V)) and those of Halite (Tm(Halite)) in polyphase inclusions by the same method. These data were measured using a FLUID INC. adapted USGS Gas-Flow Heating/Freezing System.

The distribution of homogenization temperatures of the fluid inclusions is shown in Fig.5. The number of samples was 47. Roughly speaking, homogenization temperatures increase at greater depths, especially, below 3,350m. The relation between salinities of the fluid inclusions and depths is also shown in Fig.5. To obtain salinities from Tm(ice) of the liquid-rich inclusions and vapor-rich inclusions, we used the data of Bodnar(1993). When we obtained salinities from Tm(Halite) of the polyphase inclusions, we used the data of Bodnar and Vityk(1994). If Tm(Halite) is greater than Th(L-V), the salinity of the polyphase inclusion is not obtained. One feature of the results is that the minimum salinities of the liquid-rich inclusions increase below 3,250m.

Furthermore, we analyzed gases in the fluid inclusions by laser Raman microprobe (LRM) spectroscopy, a Ramanor T6400 produced by Jobin Yvon. All the samples were Quartz taken from cuttings and cores, and they were polished on both sides. We focused a laser beam of 1 micron in diameter on the bubble in individual fluid inclusions, and then detected Raman scattering. As a result, we could determine if N2, CO2, CH4 and H2S were present in the fluid inclusions (Table 2). The shallowest depth for these samples at which CO2 and H2S existed was 3,350m. N2 and CH4 were not detected in any samples.

Table 2. Results of gas analysis for fluid inclusions.

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Sample</th>
<th>CO2</th>
<th>N2</th>
<th>H2S</th>
<th>CH4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,150.0</td>
<td>Qz-v</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
</tr>
<tr>
<td>2,750.0</td>
<td>Qz-v</td>
<td>-X-</td>
<td>-X-</td>
<td>-X-</td>
<td>-X-</td>
</tr>
<tr>
<td>2,900.0</td>
<td>Qz-ph</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
</tr>
<tr>
<td>3,150.0</td>
<td>Qz-ph</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
</tr>
<tr>
<td>3,350.0</td>
<td>Qz-ph</td>
<td>OXO</td>
<td>XXX</td>
<td>XXX</td>
<td>OXO</td>
</tr>
<tr>
<td>3,450.0</td>
<td>Qz-ph</td>
<td>X-X</td>
<td>X-X</td>
<td>X-X</td>
<td>X-X</td>
</tr>
<tr>
<td>3,550.0</td>
<td>Qz-ph</td>
<td>X-X</td>
<td>X-X</td>
<td>X-X</td>
<td>X-X</td>
</tr>
<tr>
<td>3,700.0</td>
<td>Qz-ph</td>
<td>O-O</td>
<td>X-X</td>
<td>O-O</td>
<td>X-O</td>
</tr>
<tr>
<td>3,728.1</td>
<td>Qz-v</td>
<td>O-O</td>
<td>X-X</td>
<td>X-O</td>
<td>X-X</td>
</tr>
</tbody>
</table>

Qz : Quartz, v : vein, ph : phenocryst.

THERMAL STRUCTURE AND FLUID FLOW

In the temperature build-up test by a PTS tool, we confirmed that the temperature profiles changed slope at about a 3,100m depth (Figs.2 and 6). WD-1 was drilled from the same drilling pad as Well-18. If we extrapolate the temperature profile of Well-18 below 1,890m depth, it intersects the estimated static formation temperature of WD-1 at about 3,100m (Figs.5 and 6). The slope of the estimated formation temperature below 3,100m is apparently larger than that of the extrapolated temperature for Well-18 above 3,100m. Therefore, we conclude that hydrothermal convection exists above around 3,100m, and that heat conduction zone exists below that depth.

We also discuss whether the fluid inclusions can be applied as a geothermometer in the Kakkonda Granite. We propose that the lower the salinity, the younger the fluid. The reason is that Sasaki et al.(1995) described the fluids circulating in the Kakkonda Granite had continuously changed from highly saline fluid to low salinity fluid. Homogenization temperatures (Th) of the liquid-rich inclusion with minimum salinity at every depth below 2,800m are shown in Fig.6. Between 2,800 and 3,250m, Th of the liquid-rich inclusions, whose minimum salinities are less than 1.7wt.%, are lower than the extrapolated temperature for Well-18 by about 10°C. Below 3,250m, Th of the liquid-rich inclusions are lower than estimated formation temperature for WD-1 by about 40-50°C, however, Th follows the increase of estimated formation temperatures. Thus, formation temperatures can be evaluated roughly from Th of liquid-rich inclusion which has minimum salinity at every depth in the Kakkonda Granite.

According to the result of mud logging for WD-1, the CO2 content increased rapidly to several thousand ppm at 3,350m (Fig.6). Part of the CO2 surely derived from the formation. H2S was presumed to have flowed into WD-1 from the formation below 3,642m (Kasai et al., 1996). According to the result of gas analysis for fluid inclusions, the shallowest depth at which CO2 and H2S were detected was 3,350m (Fig.6). Neither gas was detected above a 3,150m depth. We may relate the existence of CO2 and H2S with formation permeability and degassing from the fluid. That is, below 3,250m in the heat conduction zone, CO2 and H2S were not likely to separate from the fluid, because formation permeability was lower. On the other hand, above a 3,150m depth, degassing from fluid which had flowed up from the heat conduction zone was likely to continue upward, because formation permeability above about 3,100m in the hydrothermal convection zone is higher.

Sasaki et al. (1995) described that salinities of a part of polyphase inclusions (Type P2) in the Kakkonda Granite were between 60 and 75 wt.%, and that those inclusions were considered to have trapped hydrothermal fluids equilibrated with the Kakkonda Granite. Salinities of the polyphase inclusions in the Kakkonda Granite we measured (Fig.5) are lower than those of the Type P3 inclusions. We therefore propose that the polyphase inclusions of WD-1 have trapped fluids generated by mixing of highly saline fluids just like the Type P3 inclusions with meteoric water. In other words, meteoric water has also permeated slightly into the heat conduction zone below 3,100m.

BOTTOM OF HYDROTHERMAL CONVECTION ZONE

Productive fractures exist at the margin of the Kakkonda Granite and its neighboring pre-Tertiary formation.
Figure 5. Result of microthermometry for fluid inclusions of WD-1. The symbols of geology are the same as Fig. 2.
Hydrothermal convection is apparently active at least to the margin of the Kakkonda Granite. On the basis of the results and discussions about WD-1 as mentioned above, the boundary between the hydrothermal convection zone and the heat conduction zone is around 3,100m depth in the Kakkonda Granite (Fig.7). The following data support this:

(a) Temperature profiles of PTS tool logging for WD-1 inflect at about 3,100m depth (Fig.2). (b) If we extrapolate the temperature profile of Well-18 below 1,890m depth, it intersects the estimated static formation temperature of WD-1 at about 3,100m depth (Figs.6 and 7).

We also consider that the other data are very consistent with the conclusions: (c) Minimum salinities of the liquid-rich inclusions are near 0wt.% above 3,250m, however, they increase below 3,300m (Fig.5). (d) Homogenization temperatures of the liquid-rich inclusion, which has minimum salinity, increase just slightly between 2,800 and 3,250m, however, they increase rapidly below 3,250m (Fig.6). (e) According to the result of gas analysis for fluid inclusions by LRM spectroscopy, CO2 and H2S were not detected above 3,150m, however, they were detected below 3,350m (Fig.6).

Thus, we derived the thermal structure model of the Kakkonda geothermal field shown in Fig.7. The slope of the estimated static formation temperature is about 32°C/100m between 3,200 and 3,500m. If we extrapolate the estimated static formation temperature below 3,500m, the temperature is evaluated to be 574°C at 3,700m.

CONCLUSIONS

We performed temperature measurements and fluid inclusion studies of WD-1 in the Kakkonda geothermal field. For temperature measurements, we used temperature melting...
tablets in addition to temperature logging tools. Concerning fluid inclusion studies, we performed microthermometry and gas analysis by LRM spectroscopy. As a result, the bottom of hydrothermal convection zone, that is the boundary between the convection zone and the heat conduction zone, was found in the Kakkonda Granite.

(1) By utilizing temperature melting tablets, we confirmed that the temperatures at a 3,700m depth for S.T.=129h and 159h were above 50°C.

(2) The temperatures greater than 414°C, which was the limit of the Kuster tool, were confirmed at 3,600m and 3,690m depths for S.T.=82h. The temperature greater than 414°C is the highest recorded by a logging tool in Japan.

(3) Formation temperature in the Kakkonda Granite can be evaluated roughly from homogenization temperature of the liquid-rich inclusion which has minimum salinity at every depth.

(4) As a result of temperature measurements, the bottom of the hydrothermal convection zone of WD-1 is at about 3,100m depth in the Kakkonda Granite. Data obtained by fluid inclusion study is also very consistent with this conclusion.

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REFERENCES


* in Japanese with English abstract