NEDO "DEEP-SEATED GEOTHERMAL RESOURCES SURVEY": A LINK OF IGNEOUS, METAMORPHIC AND HYDROTHERMAL PROCESSES

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ABSTRACT Since FY 1992, NEDO has been conducting the Deep-seated Geothermal Resources Survey to confirm the existence of deep geothermal reservoirs (>2,000 m deep) in basement and/or intrusive rocks beneath the already utilized shallower reservoirs (<2,000 m deep). A primary means of this program, a 4,000 m class drillhole Wedge-I (WD-1), actually started to be dnlled from early January 1994 at the Kakkonda geothermal field, Northeast Japan. This program also involves mud logging, cuttings and core surveys, various kinds of electrical logging. micro-earthquake activity monitoring, synthetic fluid inclusion, vertical electro-magnetic profiling surveys and flow tests at 3,000 m and 4,000 m depths. The WD-1 has been drilled down to 1,505 m until May 1994 and the result is briefly summarized in this paper. Before completing this program in FY 1997, the WD-1 may reach a rim of the neo-granitoid pluton at about 3,000 m depth in FY 1995 and may reach about 400 ˚C at 4,000 m depth in FY 1996. Nature of the plutonic reservoir and several other scientific objectives are expected to be clarified in the remaining course of this program.

Key words: ***Kakkonda geothermal field, Neo-granitoid pluton, Deep geothermal drilling, Deep geothermal reservoir, Geothermal Model***

INTRODUCTION

In order to increase the geothermal power generation using deep geothermal resources in Japan, the NEDO started the Deep-seated Geothermal Resources Survey as a part of the New Sunshine Project of the Ministry of International Trade and Industry (MITI). This program is scheduled from FY1992 to FY1997. A primary goal of this program is to drill a drillhole down to 4,000 m depth; with projected temperature of 350-400˚C, and this would be the deepest and hottest geothermal well in Japan. The drillhole Wedge-I (WD-1), which stands for "Well for Deep Geothermal Evaluation", was started in early January 1994 at the Kakkonda geothermal field, Northeast Japan (Figure 1). The purposes of the survey are to delineate the deep-seated geothermal resources, to understand the overall geothermal environment including shallow systems, and to evaluate the possibility of utilizing deep hydrothermal fluids. The final goals of the survey are to define directions for the development of deep geothermal resources, to reduce the risk of deep resource exploration, and to put deep geothermal energy into practical use.

For this survey, the Kakkonda geothermal field, where a shallower reservoir system had already been investigated, was selected. A 50 MWe power plant has been in operation since 1978, and the

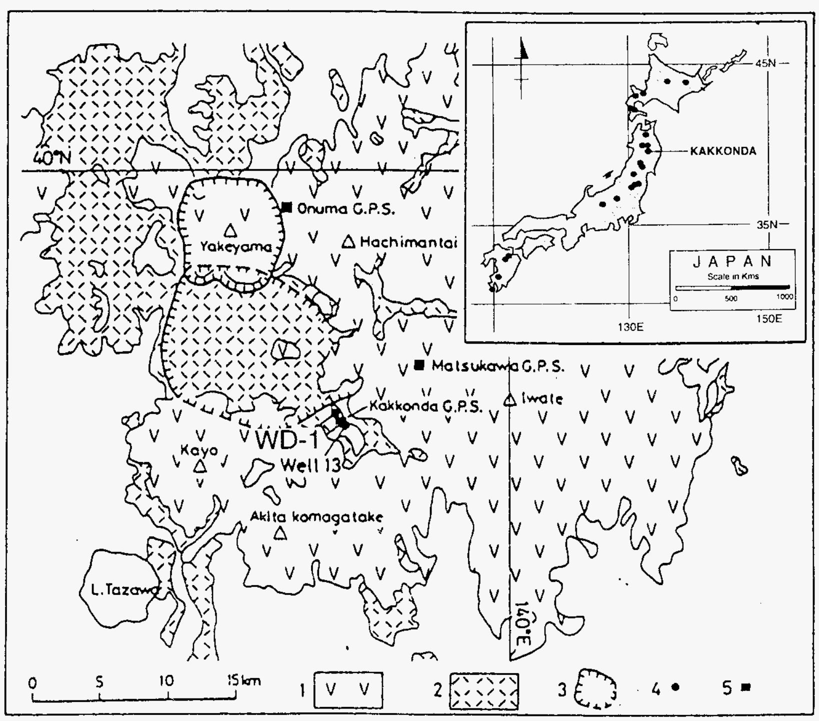


Figure 1. Generalized geological map of the Hachimantai geothermal field (Kato and Doi, 1993). 1: Quaternary volcanic rocks, 2: Tamagawa Welded Tuffs, 3: Calderas associated with Tarnagawa Welded Tuffs, 4: Geothermal wells, 5: Geothermal power plants.

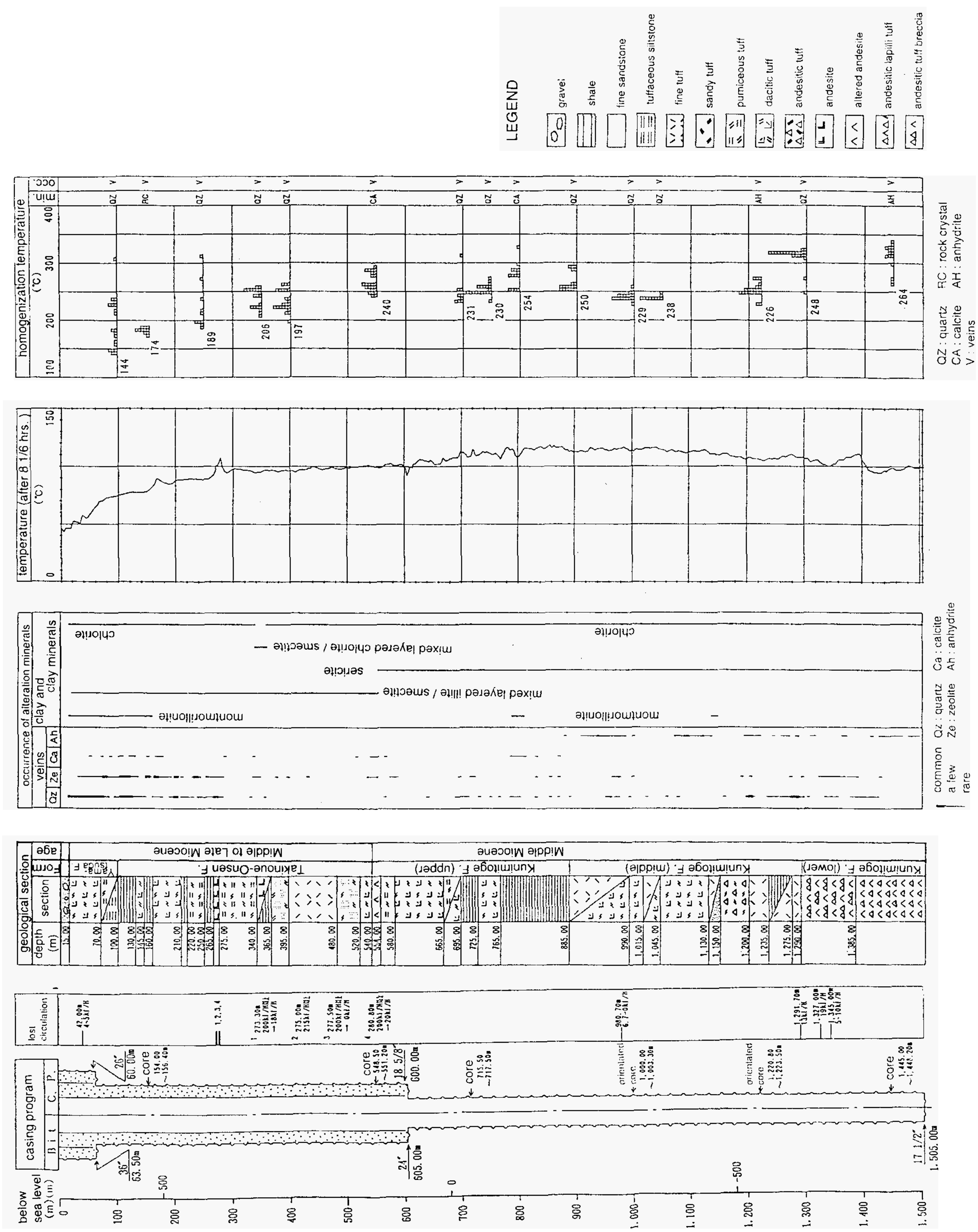
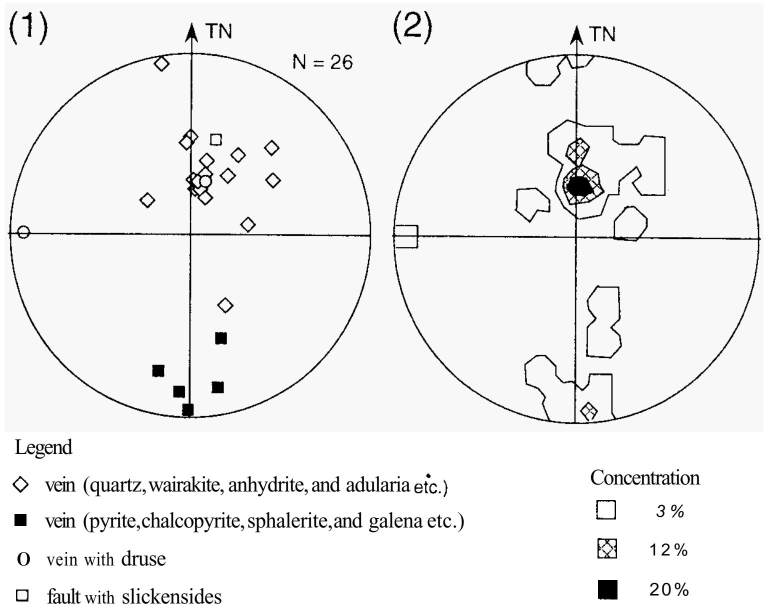


Figure 2. Geological composite log including geological section, appearance and extinction of alteration minerals, temperature (after 8 1/6 and fluid inclusion homogenization temperatures (Ths) with number of minimum Th in WD-1 to a depth of 1,505 m (right).



Figur 3. Pole plot of several kinds veins observed in No. 2 orientated core in an interval of depth 1,220.8 - 1,223.5 m in WD-1 (1), and contours of these concentration (2). Both are on Schmidt Net (lower hemispheric plot).

second power plant (30 MWe) is scheduled to begin operation in 1996. JMC recently identified a neo-granitoid pluton and its related potential reservoir by data from four drillholes as deep as 2.0 - 3.0 km in addition to various data for shallow reservoirs in Kakkonda (Kato and Doi, 1993).

Geological features of the Kakkonda geothermal field have already been described in detail by several authors, including Nakamura and Sumi (1981), Sato (1982), Doi et al. (1990), Kato et al. (1993) and Hanano and Takanohashi (1993). A petrographical description of the neo-granitoid rock has been given by Kato and Doi (1993) and the age is estimated to be 0.34 - 0.14 Ma by the K-Ar method with a mineral separation (Doi et al., 1993). A fracture analysis and a characterization of vein on the surface of the Kakkonda field have been done by Koshiya et al. (1993) and (1994), respectively. A scope of NEDO Deep-seated Geothermal Resources Survey has been primarily reported by Sasada et al. (1993) and a result of drilling of the WD-1 to 1,505 m depth has been reported by Yagi et al. (1994).

The further drilling of the WD-1 is scheduled from January 1995. Although only a few data can be added at this moment, this paper extends Yagi et al. (1994)'s report from the geological point of view and refers to the future scientific objectives.

GEOLOGICAL AND GEOTHERMAL SETTINGS

The Kakkonda geothermal field lies at the southern part of the Hachimantai clustered volcano area, which contains the installed Matsukawa, Onuma and Kakkonda geothermal power stations, and the soon-to-be-completed Sumikawa geothermal power station. The Hachimantai area is composed of pre-Tertiary basement units, Miocene tuffaceous sedimentary formations, Pliocene-Pleistocene Tamagawa Welded Tuffs and Quaternary volcanic rocks. Most of surface geothermal manifestations such as fumaroles, high temperature hot springs and alteration haloes are found along streams in the dissected flanks of several Quaternary volcanoes. Shallow-depth geothermal reservoirs in operation are within Miocene tuffaceous sedimentary formations.

A neo-granitoid pluton, aged 0.34 - 0.14 Ma, has recently been identified in the Kakkonda geothermal field by four drillholes as deep as 2.0 - 3.0 km (Kato and Doi, 1993; Doi et al., 1993). The area of the neo-granitoid pluton, which is estimated by a few tens of the shallower drillholes using mineral isograds of the contact metamorphic aureole, is more than 2.0 x 2.5 km. The extent is just comparable with that of overlying shallow reservoirs of the Kakkonda power plant. The pluton may thus be the geothermal heat source for the Kakkonda hydrothermal system, but it is still being investigated.

LATEST PROGRESS OF THE SURVEY

Core and Cuttings Investigations

A geological section drawn based on the investigation of cuttings and cores to 1,505 m depth is shown in Figure 2. The middle Miocene Kunimitoge Formation, middle to late Miocene Takinoue-Onsen and Yamatsuda Formations are observed. These formations are composed mainly of andesitic/dacitic lapilli tuffs, tuff breccias, tuffaceous sandstones, and black shales filling the Tertiary sedimentary basin. An andesite sheet which has been intensively altered exists in the top of the Kunimitoge Formation.

Alteration mineral analysis of cores and cuttings has been made to 1,505 m depth using an optical microscope and X-ray diffraction. The result is summarized in Figure 2. Laumontite appears at depths shallower than 300 m and wairakite appears sporadically in place of laumontite deeper than 300 m. Mixed layered illite/smectite changes to illite at a depth over 550 m. Anhydrite appears at a depth over 930 m. The top of the first appearance of anhydrite in the WD-1 is 500 - 900 m shallower than that in the other drillholes located in the east side of Kakkonda. The dnlling site of the WD-I is assumed to be an upflow zone for deep hydrothermal fluids by Kato et al. (1993), which is consistent with the results of the drilling of WD-1.

Fluid Inclusion Geothermometry

Fluid inclusion measurements were made on quartz, anhydrite and calcite crystals. These results are also shown on Figure 2. Most populations contain liquid-rich inclusions with uniform liquid-vapor ratio of all the crystals. The maximum homogenization temperature (Th) recorded for the No.6 core taken at a depth of 1,435 m ranges from 264 to 338°C.

Fracture Analysis Using Orientated Cores

Six cores, including two orientated cores, have already been taken to a depth of 1,505 m. Sulfide and sulfate minerals such as chalcopyrite, galena, sphalerite, pyrite, and anhydrite appear as a vein with druse in the No. 2 orientated core taken at 1,220 m in depth. Fracture analysis of cores using the orientated cores has been done (Figure 3). Its results revealed that fractures, as a vein and fault with a NE to E-W strike, are interpreted to be formed by the stress field

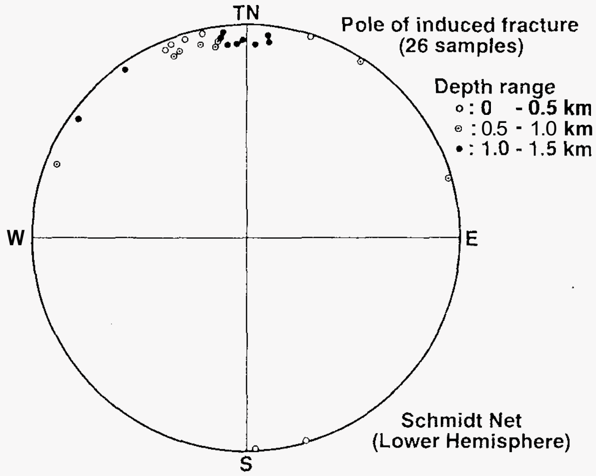


Figure 4. Pole plot of drilling-induced fractures in borehole FMI of depth 0 - 1,505 m in WD-I.

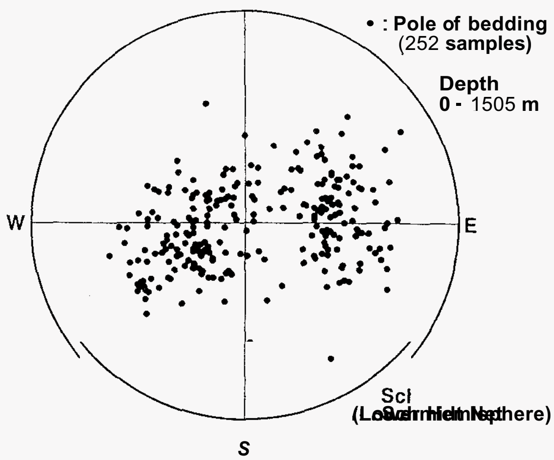


Figure 5. Pole plot of beddings observed in borehole FMI of depth 0 - 1,505 m in WD-I

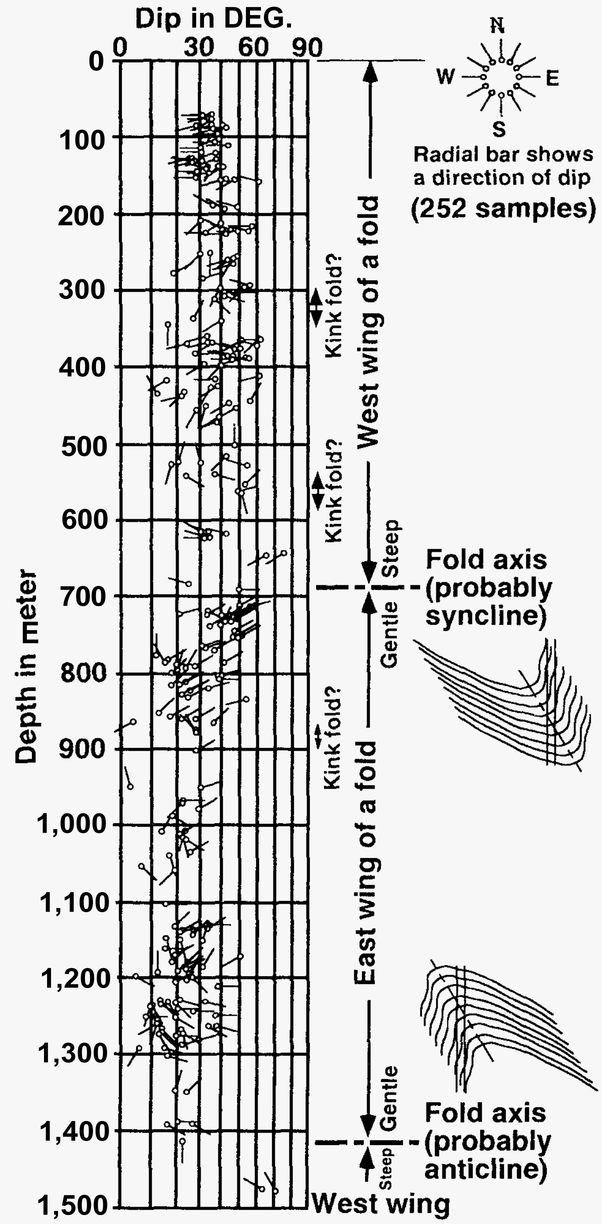


Figure 6 Variation in dip and strike of beddings with depth in borehole FMI of depth 0 - 1,505 m in WD-I

with a horizontal NNW-SSE minimum principal stress axis. This is consistent with the stress field estimated by fracture analysis on the surface (Koshiya et al., 1993, 1994) and stress analysis using micro-earthquake activities in Kakkonda (Sugihara, 1993).

Open-Hole Loggings

Two sets of borehole logs have heen collected at depth intervals from 0 to 605 m and from 605 to 1,505 m. The former includes temperature, normal, azimuthal resistivity imager **(ARI)**, phasor induction (PI), formation micro-imager (FMI), dipole share sonic imager (DSI), and litho-density log (LDL), and the latter includes temperature, normal, dual latero log (DLL), FMI, DSI, LDL, and natural gamma ray spectrometry log (NGS). The temperature profile of WD-1 after **8** 1/6 hours from the stop of the circulation is shown also in Figure 2.

The result of FMI shows that drilling induced fractures with a strike of ENE-WSW to E-W with vertical dipping are found in many intervals continuously from 0 to 1,505 m in depth (Figure 4). This shows that the horizontal minimum stress axis trends in a NNW-SSE direction, suggesting that the relative horizontal stress in Kakkonda does not change at least from the surface to 1,505 m.

Bedding has also been investigated using FMI (Figure 5). The result shows that most strata are involved in N-S trending folds of which beddings of west wings are steeper than those of east wings. This suggests that the axial planes are likely dipping eastward. Cluster patterns of beddings also indicates that those folds rather tend to plunge to the north. Furthermore, bedding data of FMI delineate the configuration of fold axes with depth (Figure 6). Major fold axes are detected at depths of 690 m and 1,410 m. They are presumably a syncline axis and anticline axis, respectively, because the dipping of the east wing is constantly more gentle than those of the upper and lower west wings.

Synthetic Fluid Inclusion Survey

To verify new methods of deep borehole temperature surveys, a borehole temperature survey using synthetic fluid inclusions will first be conducted at a depth of 1,505 m. The method of the survey is simple. Several containers filled with artificially micro-fractured mother crystals will be pulled down within a borehole. These crystals will be collected from a borehole about two weeks later. They will then be measured for homogenization temperatures (Ths) *to* estimate borehole temperatures. We will also evaluate the synthetic fluid inclusion method as a borehole fluid sampler.

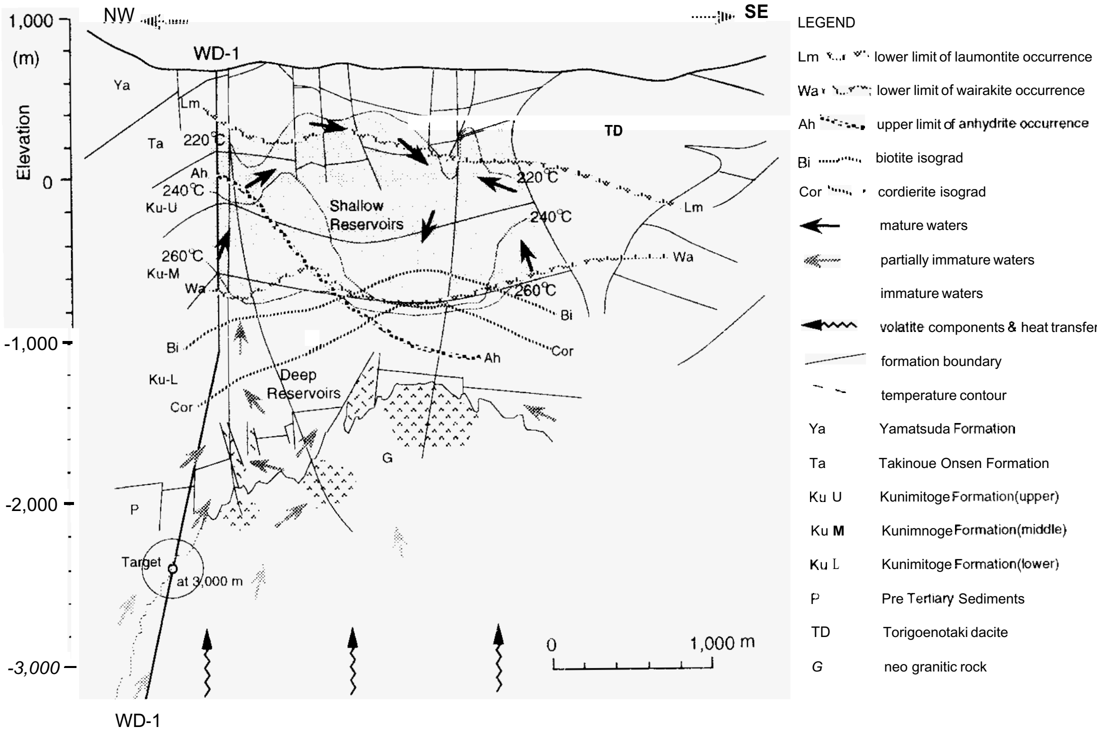


Figure 7. The first geothermal model on the geological cross section associated with the neo-granitoid pluton in the Kakkonda geothermal field.

PRELIMINARY GEOTHERMAL MODEL

Summarizing pre-existing geological and geophysical data in FY 1992, we planned the first phase of the geothermal model to predict the extension of deep geothermal reservoirs (Figure 7). The model is for deep geothermal resources associated with a deep and hot intrusion, which has been found in many geothermal exploration fields, such as the felsite body in The Geysers (e.g. Gunderson, 1992).

The present temperature of the neo-granitoid rock is greater than 350 ℃. Contact metamorphic minerals, such as cordierite and biotite, are observed over the top of the neo-granitoid rock. The upper limit of the biotite-cordierite zone exists at 600 - 700 m above the contact of the neo-granitoid rock, while that of the biotite zone is at 70G - 1000 m (Kato and Doi, 1993). Therefore, the first appearance of these metamorphic minerals must be a good indicator to predict the elevation of the top of the neo-granitoid rock during deep drilling (see Figure 7). According to the results of the cuttings investigation using a petrographic microscope to a depth of 1,505 m, biotite has not been detected yet. Probably the top of the neo-granitoid **rock** descends toward the west. We will also examine the change of the vitrinite refrectances in the borehole rocks of the WD-1 to evaluate the possibility of using them as a geothermometer.

SCOPE OF FUTURE OBJECTIVES

Deep-seated Geothermal Resources Survey is still ongoing and major results will be obtained in the coming few years. The principal objectives in the remaining course of this program are here focused from the viewpoint of geothermal geology as follows:

Nature **of** the Plutonic-Rim Reservoirs

Geothermal reservoirs that are situated on and around the boundary between the plutonic body and its wall rocks have recently been noted from various geothermal areas in the world (Muraoka, 1993), and we shall briefly refer to this type reservoir as a plutonic-rim reservoir hereinafter. The origin of the plutonic-rim reservoir is critically important for future exploration and exploitation of deep geothermal resources.

Two main hypotheses may be considered on it's origin: (a) shear and/or tensile fractures associated with intrusion of the magma body or (b) vacant space like a druse associated with contraction of the consolidating magma body. **As** for the hypothesis (a), Koide and Bhattacharji (1975) have drawn a picture of shear or tensile fracture zone caused by magmatic intrusions, but this type fracture zone is not necessarily restricted to the plutonic boundary. Taking account of the magmatic temperature, the plutonic rim may be subject to a ductile condition at the time of intrusion. This idea is also supported even by the present micro-earthquake distribution which almost disappears inside the plutonic body at the Kakkonda geothermal field (Sugihara, 1993). For this reason, the hypothesis (b) seems rather reasonable at this moment (Muraoka, 1993). This may encourage the future development of deep geothermal reservoirs even to further deeper levels, because the depth of plutonic-rim reservoir is not limited by the ductile-brittle boundary. Further drilling of the WD-1 would provide some results on the occurrence of plutonic-rim reservoir at the Kakkonda geothennal field.

Role **of** the Granitoid Pluton in Magmatic, Metamorphic and Hydrothermal History

The neo-granitoid pluton at the Kakkonda geothermal field ranges in age from 0.34 Ma on hornblende to 0.14 Ma on K-feldspar (Doi et al., 1993). This may be one of the youngest plutons among the known granitoid plutons (Harayama, 1992), nevertheless it is still being evaluated for its role as a geothermal heat source to the present geothermal activity at the Kakkonda geothermal field. Overall thermal history of the granitoid pluton through the magmatic, contact-metamorphic and hydrothermal processes will be obtained by the cores and cuttings analyses, thermal analyses and fluid geochemistry in the deeper part of the WD-1.

Nature **of** Deep Fluids

Chemical and isotopical investigations of borehole fluids in conjunction with fluid inclusions in core and cutting samples will provide information on the nature of deep fluids, contribution of magmatic water, brine development and water-rock interaction at the plutonic-rim environment.

Physical Properties of the Rocks around the Granitoid Pluton

Systematic variation in physical properties of the rocks with depth has been observed at The Geysers geothermal field, probably due to contact metamorphism (Gunderson, 1990). Determination of the physical properties such as density, porosity, permeability, resistivity and seismic wave velocity by core sample measurements and open-hole loggings in this survey would assist in the interpretaiion of physical changes after intrusion and the modeling of deep reservoirs.

Relation between Shallow and Deep Reservoirs

Shallow and deep reservoirs are separated to each other by a relatively impermeable zone of contact metamorphic rocks at the Kakkonda geothermal field. Cross-well tests of pressure interference and tracers between the two reservoirs would provide information on the pressure and fluid responses between the two reservoirs.

CONCLUSIONS

Three factors essential for deep geothermal resources, namely, heat supply from a heat source, hydrothermal fluid convection system and formation of fracture systems, which make up a geothermal system, will be investigated in this program. Fracture system, the alteration pattern of the rocks and the structure of seismic wave velocity, etc. from the surface to the shallow reservoir in the Kakkonda area are being revealed from the results of the WD-1 to 1,505 m depth through the survey program.

However, most important information will be obtained in the near future through the plutonic-rim depths from 3,000 m to 4,000 m. The plutonic-rim reservoir environment is subject to the volcanic, plutonic, contact-metamorphic and hydrothermal processes and its understanding would require the integration of those processes.

REFERENCES

Doi, N., Kato, O., and Muramatsu, Y. (1990): On the neo-granite and geothermal reservoir in the pre-Tertiary rocks at the Kakkonda geothermal field, Iwate Prefecture. Abstract, 1990 Annual meeting of Geotherm. Res. Soc. Japan, p.6 (in Japanese).

Doi, N., Kato, O., and Kanisawa, S. (1993): K-Ar age of neo-granite and formation age of the Kakkonda geothermal system. Abstract, 1993 Annual Meeting Geotherm. Res. Soc. Japan, p.2 (in Japanese).

Gunderson, R.P. (1992): Distribution of oxygen isotopes and noncondensible gas in steam at The Geysers. In *C.* Stone, ed., Monograph on The Geysers geothermal field: Geothermal Resources Council, Special Report No. 17, p.133-138.

Hanano, M. and Takanohashi, M. (1993): Review of recent development of the Kakkonda deep reservoir, Japan. 18th Workshop on Geothermal Reservoir Engineering, Stanford University (in press).

Harayama, S. (1992): Youngest exposed granitoid pluton on Earth: Cooling and rapid uprift of the Pliocene-Quaternary Takidani Granodiorite in the Japan Alps, central Japan. Geology, 20, p.657-660.

Kato, O. and Doi, N. (1993): Neo-granitic pluton and later hydrothermal alteration at the Kakkonda geothermal field, Japan. Proc. 15th NZ Geothermal Workshop, p. 155-161.

Kato, O., Doi, N., and Muramatsu, T. (1993): Neo-granitoid pluton and geothermal reservoir at the Kakkonda geothermal field, Iwate Prefecture, Japan. lour. Geotherm. Res. Soc. Japan, Vol. 15, No. 1, p.41-57 (in Japanese with English abstract).

Koide, H. and Bhattacharji, S. (1975): Formation of fractures around magmatic intrusions and their role in ore localization. Economic Geology, 70, p.781-799.

Koshiya, S., Okami, K., Kikuchi, Y., Hirayama, T., Hayasaka, Y., Uzawa, M., Honma, K., and Doi. N. (1993): Fracture system developed in the Takinoue geothermal area. Jour. Geotherm. Res. Soci. Japan., Vol. 15. No. 2, p.109-139 (in Japanese with English abstract).

Koshiya, S., Okami, K., Hayasaka, Y., Uzawa, M., Kikuchi, Y., Hirayama, T., and Doi. N. (1994) : On the hydrothermal mineral veins developed in the Takinoue geothermal area, Northeast Honshu, Japan. Jour. Geotherm. Res. Soc. Japan., Vol. 16. No. 1, p.1-24 (in Japanese with English abstract).

Muraoka, H. (1993): Scope of the future geothermal resources from the viewpoint of magma. Chinetsu (Journal of Japan Geothermal Energy Association), Vol. 30, p. 100-126 (in Japanese).

Nakamura, H. and Sumi, K. (1981): Exploration and development at Takinoue, Japan. In Geothermal System (Edited by Rybach, L. and Muffler, L. J. P.), p. 247-272, John Willey & Sons.

Sasada, M. Miyazaki, S. and Saito, S. (1993): NEDOs deep-seated geothermal resources survey at the Kakkonda system, Northeast Japan. Geothermal Resources Council, Transactions, Vol.17, p. 181-185.

Sato, K. (1982): Analysis of geological structure in the Takinoue geothermal area. Jour. Geotherm. Res. Soc. Japan, Vol. 3, No. 3, p. 135-148.

Sugihara, M. (1993): Geothermal exploration using micro-earthquake surveys -"Chinetu" Energy for the 21st Century. Jour. Geotherm. Res. Soc. Vol. 15, No. 4, p. 72-75 (in Japanese).

Yagi, M., Yasukawa, K., Muraoka, H., Doi, N. and Miyazaki, S. (1994): Geothermal Resources Council, Transactions, Vol. 18 (in press).