NEO-GRANITIC PLUTON AND LATER HYDROTHERMAL ALTERATION AT THE KAKKONDA GEOTHERMAL FIELD, JAPAN

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SUMMARY - A neo-granitic pluton ranging from adamellite to quartz diorite exists at 1,950-2,770m depth at the Kakkonda geothermal field. The intrusion of the pluton is younger than 4.9±1.0Ma. The metamorphosed area covers over 2.0×2.5km. The pluton underlies about 700-1,000m below the biotite isograd and about 600-700m below the cordierite isograd. There are productive fractures in the pluton, on surface of the pluton and in the metamorphosed rocks. contraction caused by cooling of the magma is one of the main reasons of the formation of the fractures. The pluton is fresh, however there is a little hydrothermal alteration along the fractures. The hydrothermal minerals distribute in the metamorphic rocks. Wairakite distributes extensively in the 230-260°C zone, and is characteristic in that zone. It distributes below the biotite isograd. These facts tell that the pluton is a part of the heat source and that the pluton has started cooling by hydrothermal convection.

1. INTRODUCTION

The Kakkonda (Takinoue) geothermal field is located about 600km northeast of Tokyo and is one of the most active liquid-dominated geothermal systems belong to the Sengan geothermal area in Japan (Fig.1). The first power plant, Kakkonda Unitl, 50MW, has been in operation since 1978 by Tohoku Electric Power Inc., where Japan Metals and Chemicals Co., Ltd. (JMC) is a steam supplier. Currently, development of the Kakkonda Unit2, 30MW, is being continued by the same method. The depths of the most recent wells for the Kakkonda Unit2 are more than 2,000m. Consequently, the Kakkonda hydrothermal system was found to consist of two reservoirs with different characteristics, shallow reservoir and deep reservoir. A boundary of the twe reservoirs was indicated by rapid increase in bore-hole temperature around the 1,500m depth (Doi et al.; 1988, 1990). The shallow reservoir, which is characterized by slightly alkaline fluid whose pH is around 8 in the reservoir, is very permeable and 230-260°C. On the other hand, the deep reservoir, which is characterized by acid fluid whose pH range from about 3 to 5 at the well heads, is less permeable and 300 - 350°C and over. This acid fluid was inferred to be meteoric origin which dissolves volcanic gas which contains HCl and SO_2 (Yanagiya, 1990).

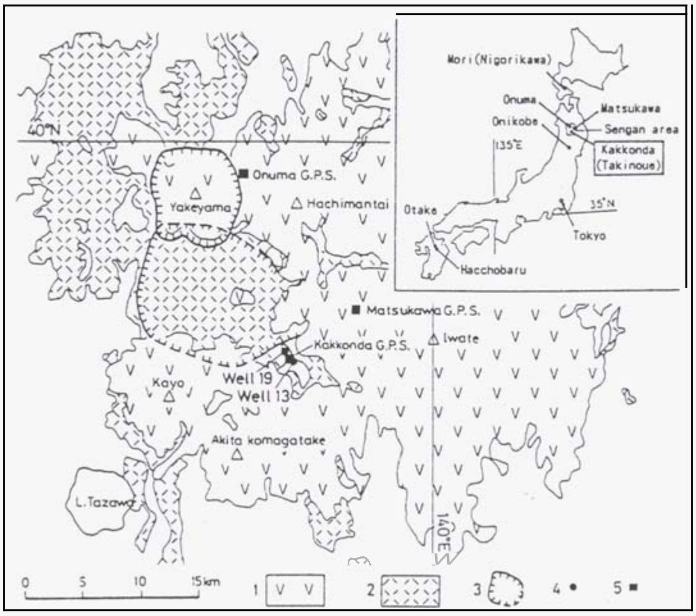

Figure 1- Geological map of the Sengan geothermal area (modified from Kato et al., 1993). 1:Quarternary volcanic rocks, 2:Tamagawa Welded Tuffs (Late Pliocene- Early Pleistocene), 3:Calderas associated with Tamagawa Welded Tuffs, 4:Geothermal wells, 5:Geothermal power plants.

Despite the difference in permeability of the shallow and the deep reservoirs, reservoir pressure of the deep reservoir is responding to exploitation in the shallow reservoir of the Kakkonda Unitl. Thus, these two reservoirs are connected with each other, and are included in a single hydrothermal system (Hanano and Takanohashi, 1993). Kakkonda Unit2 development has made great progress in fracture exploration in this field, because of confirmation of the thermal metamorphic minerals and the pluton which is a heat source of the metamorphism, and the confirmation of productive fractures which are associated with the pluton. Fractures associated with deep intrusion in geothermal fields have been studied recently (e.g. Lovelock et al., 1982; Thompson, 1989; Thompson and Gunderson, 1989).

The geology of the Kakkonda geothermal field is composed of Tamagawa Welded Tuffs, Miocene formations, Pre-Tertiary . formations, old intrusive rocks and the neo-granitic pluton (Nakamura and Sumi, 1981; Sato, 1982; Doi et al, 1988; Kato et al, 1993; Koshiya et al, 1993). The Miocene is divided into Yamatsuda F., Takinoue-onsen F., Kunimitouge F., in descending order. The Kakkonda reservoir consists of formations below Yamatsuda F. (Fig.2). Many old intrusive rocks such as Torigoeno-taki dacite, Matsuzawa dacite and porphylite distribute in this field, and they intrude into the Miocene series (Sato, 1982). Torigoeno-taki dacite has K-Ar age, 4.9±1.0Ma (Tamanyu, 1980), and Tamagawa Welded Tuffs has age ranging from about 2.0Ma to 1.0Ma (e.g. Suto, 1982). Therefore the recent activities of acidic magma observed in the field were the dacite intrusion of Pliocene and Tamagawa Welded Tuffs of Pleistocene.

Koshiya et al. (1993) show that the present paths of geothermalwater are controlled by the fractures belonging to the northeast to east-west surface fracture systemwhose K-Ar age of K-feldspar is 0.2±0.1Ma.

2. NEO-GRANITIC PLUTON

The neo-granitic pluton which is petrographically composed of biotite hornblende adamellite, hornblende biotite cummingtonite tonalite and pyroxene hornblende biotite guartz diorite has been encountered in Well-13, Well-19, Well-20 and Well-21 at 1,950-2,770m depth. It suggests that the pluton is a heat source of thermal metamorphism described below, because the pluton has absolutely or almost no thermal metamorphism. The pluton at Well-21 is composed of tonalite and adamellite. Adamellite has undergone thermal metamorphism slightly, and has small amount of biotite in some hornblende. Therefore the pluton is a composite intrusion, and have many dikes which were encountered by Well-13 and other three wells (Fig.3).

The pluton is younger than 4.9±1.0Ma because deeper part of the Torigoeno-taki dacite has undergone metamorphism by the pluton. The pluton is possibly a plutonic rock associated with the Tamagawa Welded Tuffs (2.0-1.0Ma) and calderas around the Kakkonda geothermal field (Fig.1).

3. THERMAL METAMORPHIC MINERALS

The thermal metamorphic rocks were confirmed by appearance of biotite, that were found in depth deeper than 1,006m (-309m at S.L.). The metamorphic minerals are biotite, muscovite, cordierite, anthophyllite, cummingtonite, hornblende, hastingsite, actinolite, andalusite, orthopyroxene, clinopyroxene, garnet, tourmaline, magnetite pyrrhotite, spinel, ilmenite, rutile and so on. Fig.3 show the distribution of the major metamorphic minerals at the deep wells. The metamorphosed formations by the pluton are Pre-Tertiary formations, Miocene formation (Kunimitouge F.) and Pliocene dikes. The metamorphic minerals are biotite, cordierite, anthophyllite, cummingtonite, andalusite and orthopyroxene in descending order. However the orthopyroxene distribution was different at each wells. This probably depends on chemical composition of original rocks. Biotite was detected at 21

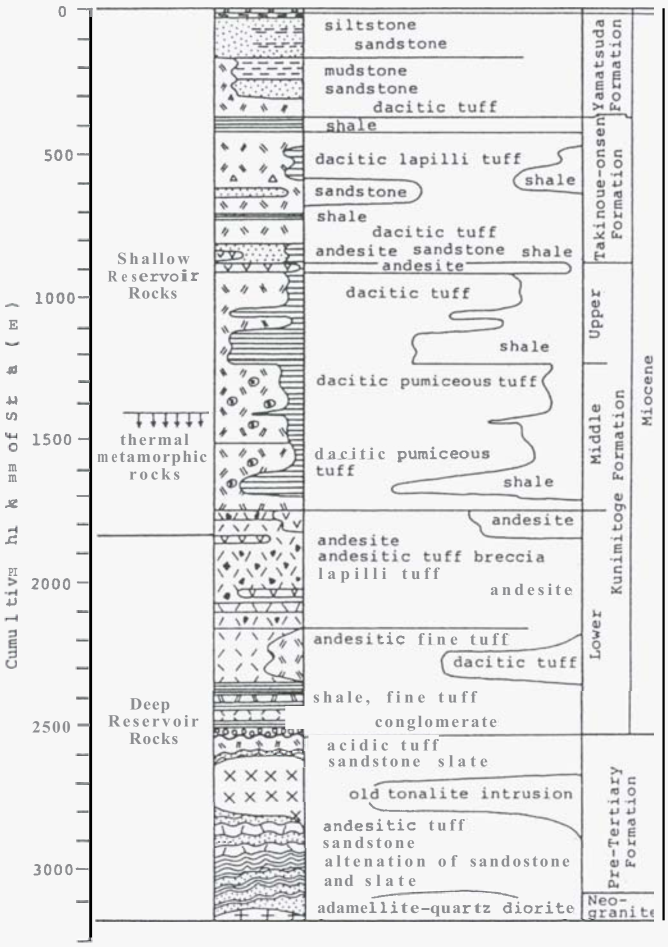

Figure 2- Schematic geologic sequence at the Kakkonda geothermal field (modified from Kato et al., 1993).

wells and cordierite was detected at 11 wells. We drew the biotite and cordierite isograd based on these data (Figs.4, 5). The biotite was detected by a microscope, and the cordierite was detected by X-ray diffraction. Bulk chemical composition is important to make mineral isograd, but it is not considered in this paper. The metamorphosed area covers over 2.0×2.5km. The biotite isograd is shallow from the western-westsouthern to northeastern part of the field as a whole, but it waves up in the center (Fig.4). The cordierite isograd is shallow from the western-westsouthern to center, and the shallow part has spread relatively horizontally to the northeast.

The distribution of the pluton inferred from drilling results and isograds is deep (about -2,000m S.L.) in the western part of the field and shallow (about -1,300m S.L.) in the center. The pluton underlies 1,100m deeper than the biotite isograd, 700m deeper than the cordierite isograd in the western part, at Well-19 and 20. On the other hand, the pluton is 700m deeper than the biotite, 600m deeper than the cordierite in the center, at Well-21. The top of the pluton which is located at deeper part has thick metamorphic zone, but that located at shallower depth has thin metamorphic zone (Fig.3).

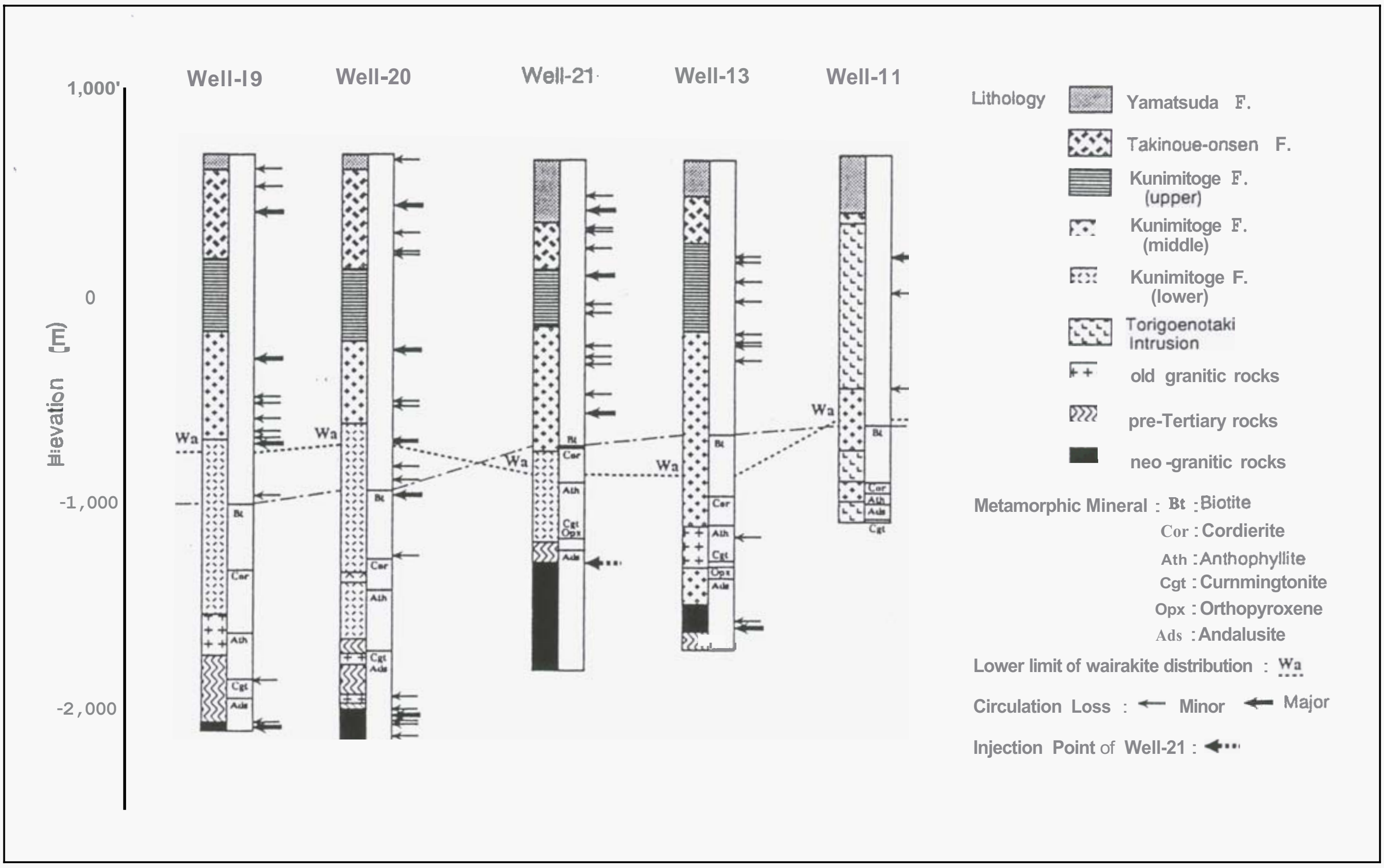

Figure 3– Lithology, major metamorphic minerals, Wairakite and lost circulations of the deep wells. Dash-dotted line show the biotite isograd.

The thicknesses of metamorphic zone indicate the difference of thermal gradient from the pluton to the ground surface after the emplacement of the pluton.

Hence the pluton underlies about 1,000-700m below the biotite isograd and about 700-600m below the cordierite isograd. The top of the pluton is deep in the western part of the field, and shallow in the center, and is uneven as small dikes indicate.

4. HYDROTHERMAL ALTERATION

The pluton is fresh, however, there is a little hydrothermal alteration along fractures around the top of the pluton. Quartz and anhydrite veins are formed in the fractures. Quartz diorite which is located close to a feed point of Well-13 has undergone hydrothermal alteration, so that the rim of the primary biotite has been changing to clay minerals and tremolite. Moreover chlorite, sericite, tremolite, cummingtonite, anhydrite, epidote and garnet veins are formed within the quartz diorite (Fig.7). Therefore the productive fracture in the deep reservoir has been formed after emplacement of the pluton. Anhydrite, tremolite, magnetite and pyrrhotite are the major metamorphic minerals in closer part of the thermal metamorphic rocks around the pluton. On the other hand, clay mineral, K-feldspar, zeolite, calcite, epidote and tremolite are the major minerals formed in the shallow part of the metamorphic rocks and above formations. The shallow reservoir, characterized by slightly alkaline reservoir fluid, is very permeable and 230-260°C as described above. Wairakite distributes extensively in the 230-260°C zone, and is characteristic in that zone. It distributes below the biotite isograd. The lower limit of the wairakite is 1,480m at Well-13 (Fig.3). The area of the biotite has started cooling by hydrothermal convection, and has undergone the present hydrothermal alteration.

These facts indicate that the hydrothermal fluid in the shallow and deep reservoirs has flowed in the fractures formed by some events after the emplacement of the pluton, and the pluton is a part of the heat source and has started cooling.

5. FRACTURES *AROUND* THE NEO-GRANITIC PLUTON

The pluton was encountered at four deep wells. Well-13,19 and 20 had some lost circulations (LC) at the surface and inside of the pluton which are good production zone (Fig 3). Moreover Well-19 have some feed points in the Pre-Tertiary rocks (Fig 8), and Well-20 have a LC in the old granitic rocks which underwent the thermal metamorphism (Fig 3). The permeable fractures are abundant in the depth shallower than 1200-1700m (-500 to -1000m S.L.), but are poor in the deeper depth. However, the permeable fractures are formed in the pluton ,

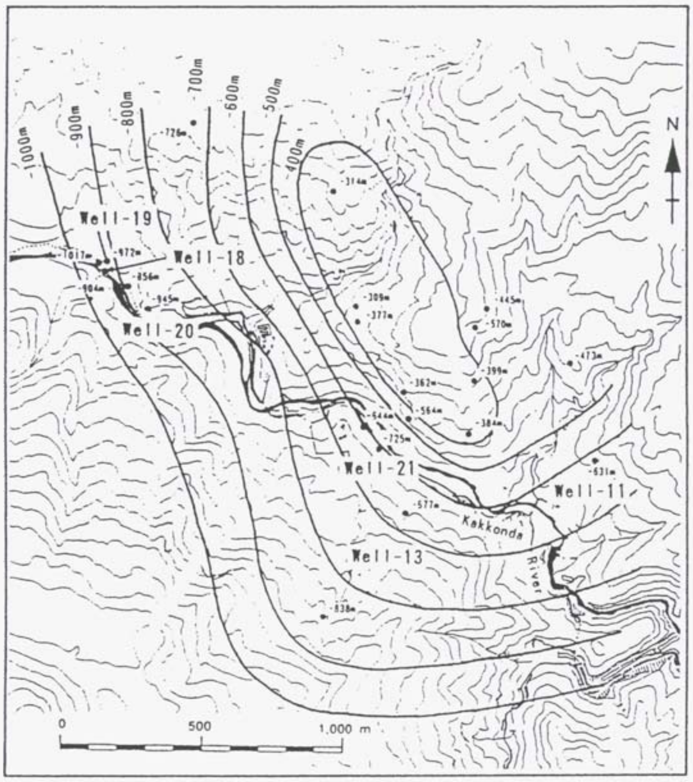

Figure 4- Map showing generalized biotite isograd (modified from Kato et al., 1993). Contours in meters below sea level.

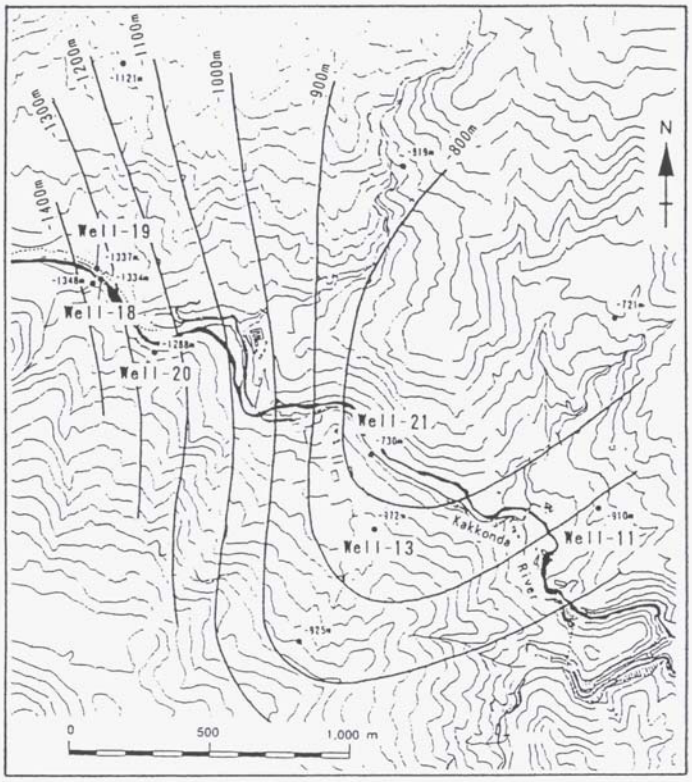

Figure 5- Map showing generalized cordierite isograd (modified from Kato et al., 1993). Contours in meters below sea level.

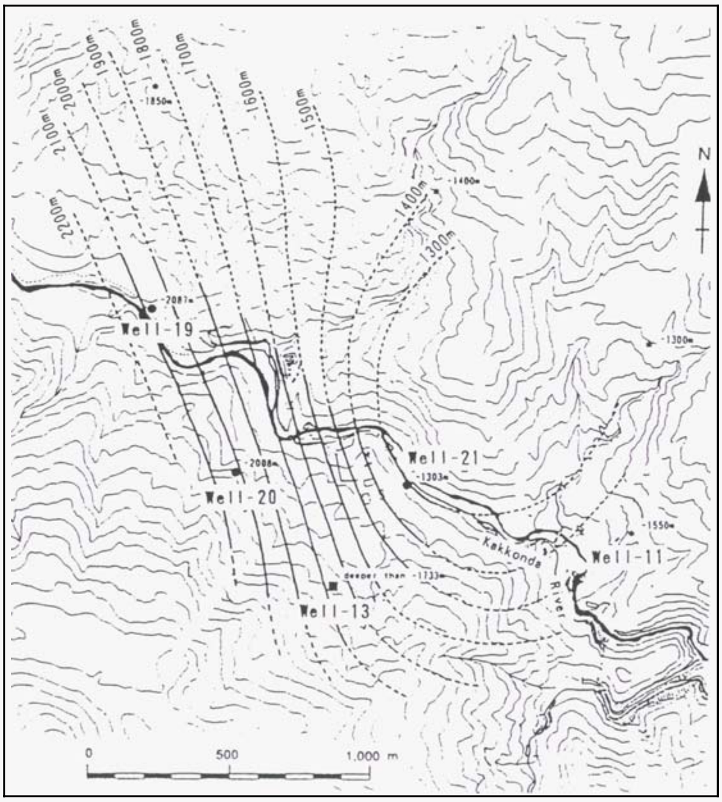

Figure 6- Map showing generalized top of the neo-granitic pluton. Contours in meters below sea level. Symbols show the depth, 1:the pluton encountered at deep wells, 2:bottom of Well-13, 3:the pluton estimated by cordierite isograd. Dotted line is probable top of the pluton.

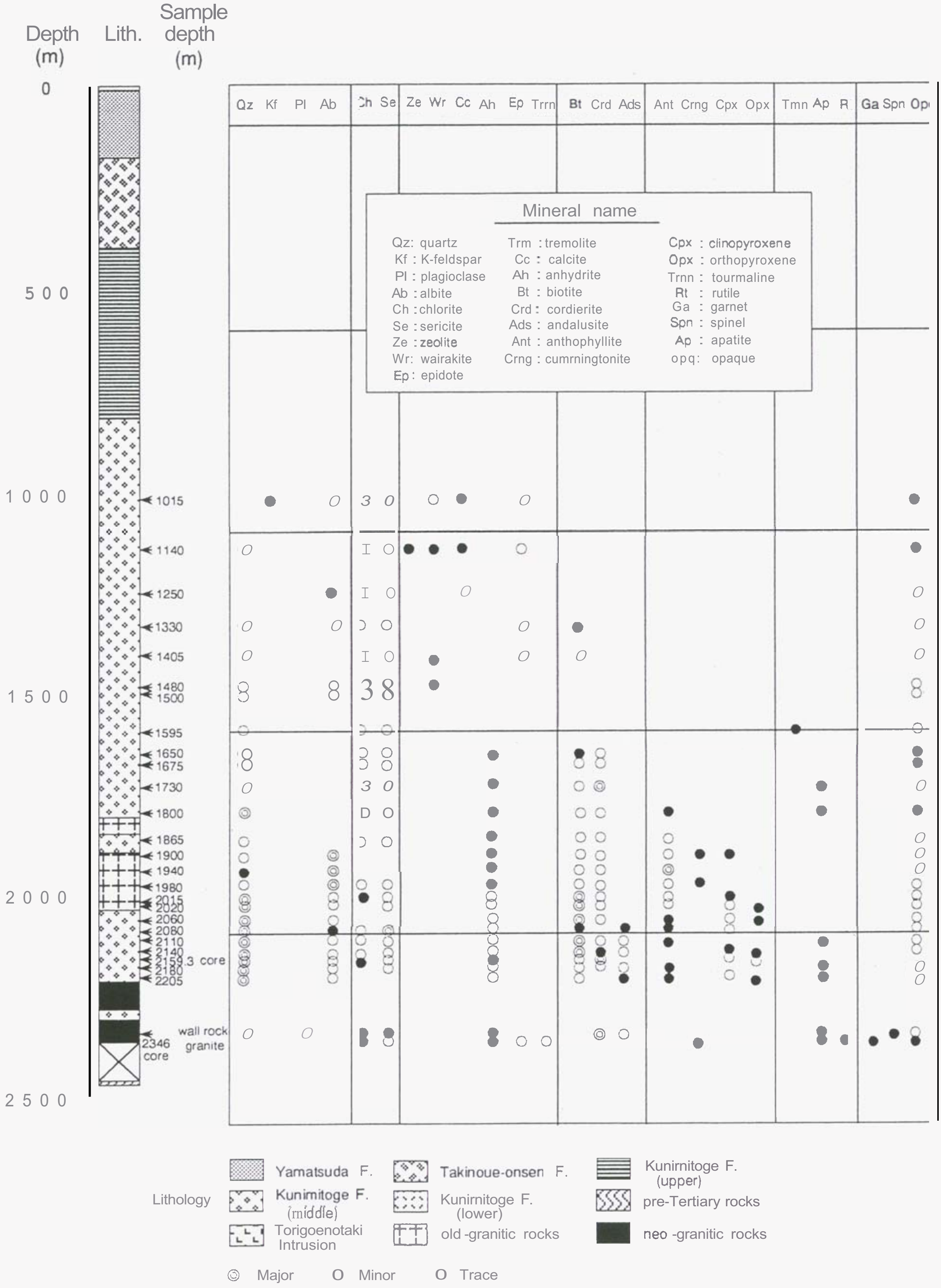

Figure 7- Hydrothermal and metamorphic minerals detected under a microscope in Well-13.

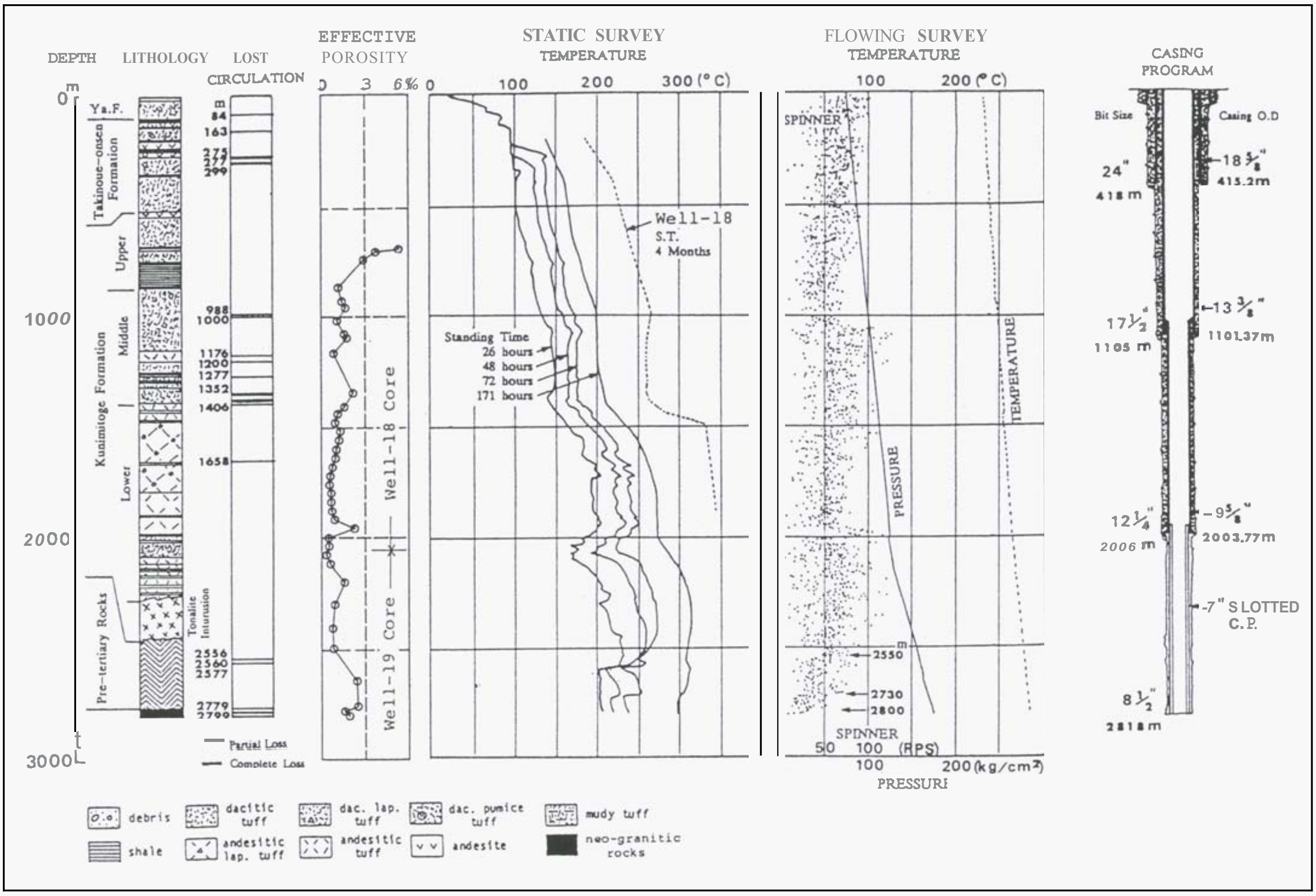

Figure 8- Lithology, porosity and logging data of Well-19 (modified from Takanohashi, 1991).

on the surface of the pluton and in the hornfels. These are main productive zone in the deep reservoir.

The effective porosity of core samples decreases with depth, but is relatively large in the pluton and the Pre-Tertiary rocks (Fig 8). Although the data is few (4 data), its trend is similar to the fracture distribution.

Well-21 did not encounter LC around the pluton, but the water of a hydraulic fracturing job flowed into a section of 200m thickness from top of the pluton (Fig.3). These evidences suggest that the fractures present in the pluton at least for the depth of 200m from its surface, though the permeabilities are different. The fractures were formed after emplacement of the pluton and were formed by contraction of the pluton induced by cooling of the magmas. On the other hand, the fractures in Pre-Tertiary rocks and old granitic rocks were probably formed by regional tectonic stress and/or movements after emplacement of the pluton and by stress generated during intrusion.

Sugihara (1991) shows that microearthquakes distribute above the pluton, and its distribution infers the reservoir structure. Thompson and Gunderson (1989) show existence of high angle fractures which are associated with recent strike slip tectonics in the felsite in The Geysers area. We continue to examine the origin of fractures in Pre-Tertiary rocks and old granitic rocks and the difference of permeability in the pluton.

6. CONCLUSIONS

(1) A neo-granitic pluton ranging from adamellite to quartz diorite has been at 1,950-2,770m depth, and the age is younger than 4.9 ± 1.0Ma. The metamorphosed area covers over 2.0×2.5km. The distribution of the pluton is estimated by the isograd. That is the pluton underlies about 1,000-700m below the biotite isograd and about 700-600m below the cordierite isograd. The pluton situated in the shallow area has thin metamorphic zone. The pluton is a heat source of the metamorphism.
(2) The pluton is fresh as a whole, however there is a little hydrothermal alteration along the fractures. wairakite is a characteristic mineral in the shallow reservoir, and distributes below the biotite isograd. The pluton is a part of the heat source and has started cooling.
(3) The permeable fractures decrease with depth. However there are fractures in the pluton for the depth of 200m from its top and in the hornfels, though the permeabilities are different. These fractures form productive zones in the deep reservoir.
(4) The fractures in the pluton for the depth of 200m from its top were formed after emplacement of the pluton and were formed by contraction of the pluton induced by cooling of the magmas.

7. ACKNOWLEDGMENT

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8. REFERENCES

Doi, N., Muramatsu, Y., Chiba, Y. and Tateno, M. (1988) Geological Analysis of the Kakkonda Geothermal Reservoir. *Proc. Int. Symp. Geotherm. Energy, 1988, Xumamoto and Beppu, Japan*, 522-525.

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 the Geotherm. Res. Soc. Japan*, P6.*

Hanano, M. and Takanohashi, M. (1993) Review of Recent Development of the Kakkonda Deep Reservoir, Japan. *Proc. 18th Workshop on Geothermal Reservoir Engineering, Stanford University*, in press.

Kasai, K., Kotanaka, K. and Chiba, F. (1990) Operation and Reservoir Management of the Kakkonda Geothermal Power Station. *Chinetsu* (J. *Japan Geotherm. Energy Assoc.)* Vo1.27, 1-22.**

Kato, O., Doi, N. and Muramatsu, Y. (1993) Neo-Granitic Pluton and Geothermal Reservoir at the Kakkonda Geothermal Field, Iwate Prefecture, Japan. J. *Geotherm. Res. Soc. Japan*, Vol.15, 41-57.**

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. J. *Geotherm. Res. Soc. Japan*, Vol.15, 109-139.**

Lovelock, B.G., Cope, D.M. and Balstar, A.J. (1982) A Hydrothermal Model of the Tongonan Geothermal Field. *Proc. Pacific Geothermal Conf., Auckland, New Zealand*, 259-264.

Nakamura, H. and Sumi, K. (1981) Exploration and Development at Takinoue, Japan. In: *Geothermal Systems ; Principles and Case Histories*, ed. Rybach, L. and Muffer, L.J.P., John Wiley & Sons, 247-272.

Sato, K. (1982) Analysis of Geological Structure in The Takinoue Geothermal Area. J. *Geotherm. Res. Soc. Japan*, Vol.3, 135-148.**

Sugihara, M. (1991) Geophysical Model of Sengan -Microearthquake Study of the Kakkonda Geothermal Area-. In: *Extended Abstract Geothermal Symposium of Deep Geothermal Systems with Special Reference to Neo Felsic Intrusive Bodies*, Nov. 1991, Geol. Surv. of Japan, 18-22.

Suto, S. (1982) K-Ar age of the Tamagawa Welded Tuffs and Related Rocks from Hachimantai Geothermal Field, Northeast Japan. *J. Geotherm. Res. Soc. Japan*, Vol.4, 159-170.**

Takanohashi, M. (1991) Geothermal Energy Extraction from Deep-seated Reservoir System in the Kakkonda Field, Northeast Japan. *Proc.* 1991 *fall meeting of Mining and Mater. Process Inst. Japan*, [J2], 5-8.*

Tamanyu, S. (1980) Radiometric Dating of Igneous Rocks in the Sengan Area. In: *Research on Hydrothermal System*, Interim Rpt. Japan's Sun-Shine Project, FY1978-1979, Geol.surv. Japan, 15-23.*

Thompson, R.C. (1989) Structural Stratigraphy and Intrusive Rocks at The Geysers Geothermal Field. *Trans.. Geotherm. Resour. Counc.*, Vol.13, 481-485.

Thompson, R.C. and Gunderson, R.P. (1989) The Orientation of Steam-Bearing Fractures at The Geysers Geothermal Field. *Trans. Geotherm. Resour. Counc.*, Vol.13, 487-490.

Yanagiya, S. (1990) chemistry of Deep Geothermal Fluid at the Kakkonda. *Abstract*, 43rd *Annual Meeting of the Balneological Society of Japan*, 20.*

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** in Japanese with English abstract