SCOPE OF MODELING OF DEEP GEOTHERMAL SYSTEMS IN AN IEA CO-OPERATIVE PROGRAMME

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ABSTRACT

The large demands to exploitation of deep geothermal resources are recognized not only in Japan but also in several geothermal countries in the world, because the expansion of exploitation to deeper reservoirs would promise a greater resource base. The initiation of the IEA Task, Deep Geothermal Resources, is timely for this worldwide demands. There still remain technological and economic risks to utilize the deep geothermal resources and therefore it is worthy to forward this frontier collecting worldwide wisdom and experience. Modeling of deep geothermal systems has only recently come to be enabled when many drillholes have penetrated young plutonic bodies, that is, consolidated magma chambers as a core of geothermal systems. Modeling of magma-wall rock interactions could be one of important subjects for the better understanding of deep heat sources, deep reservoirs and deep fluids in the IEA Task, Deep Geothermal Resources.

INTRODUCTION

Current effort to establish a co-operative programme on geothermal energy research and technology under the IEA/OECD framework would provide us an opportunity to exchange worldwide aspects and experience on the field of geothermal research and development. It could be particularly timely for the field of deep geothermal resources, because recent exploitation of geothermal energy is trending toward deeper reservoirs in many countries such as Italy, United States, New Zealand, Mexico, Philippine, Japan and others. Exploitation of deep geothermal resources has still technological and economical risks at this moment such as difficulty of exploration, high cost of drilling, low probability to hit reservoirs and difficulty of high pressure-temperature drilling. However, if we could clear these obstacles, then we would obtain a large resource base, probably two or three times larger than one estimated previously at shallow depths. An approach to deep geothermal resources is at a frontier to the future magmatic energy development and the effort of research and development could be better to be promoted by an international co-operative basis collecting various case studies from the world.

As the authors are concerned with the modeling of deep geothermal systems in the Subtask A, Exploration Technology and Reservoir Engineering, this paper describes current trends of deep geothermal resources including the NEDO Deep Geothermal Resources Survey (DGRS) program and proposes subjects to be solved in the modeling of deep geothermal systems in the Subtask.

TRENDS TOWARD DEEP GEOTHERMAL SYSTEMS

Exploitation of deep geothermal resources is strongly anticipated in Japan. In the last decade, installed geothermal power capacity in Japan has been rapidly increased up to 529 MWe by the end of November, 1996 (Japan Geothermal Energy Association, 1996). At the same time, location problems for further exploitation have come to be severe, partly because more than 60 % of geothermal prospective areas in Japan are situated within the area of national parks and partly because other geothermal prospective areas in Japan

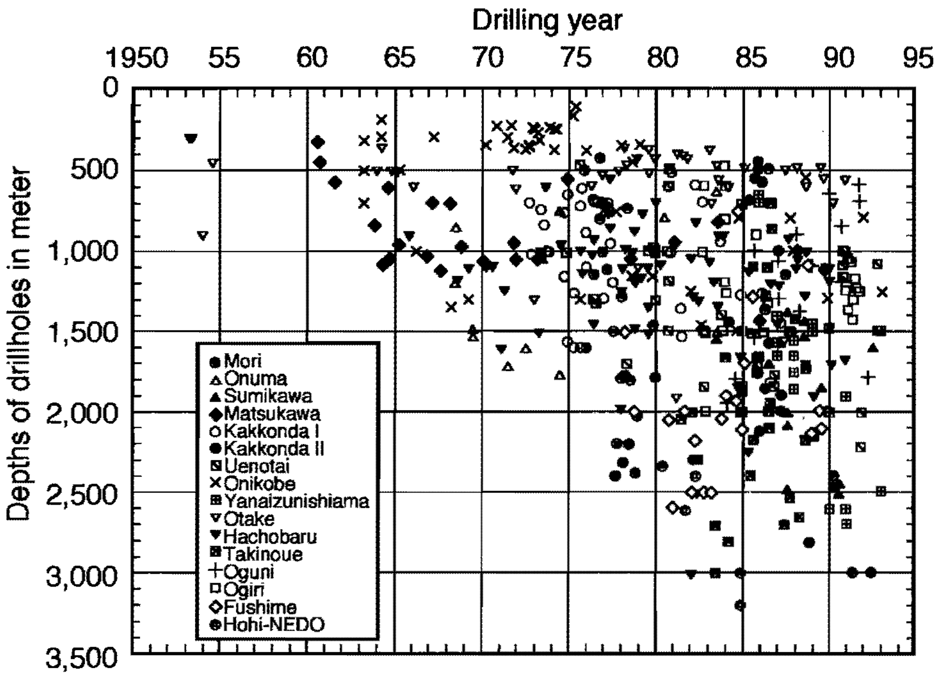

Fig. 1. Depths of geothermal drillings year by year in Japan. The data of drillings shown are those performed by the private sector except for the five NEDO's drillings in the Hohi area. Drilling year indicates the incipient time of drilling operation. The diagram was reproduced from Saito (1993).

are often situated in the developed hot spring resort conglomerates. The location problems seem the largest obstacle to forward a future geothermal exploitation in Japan. Avoiding the location problems, one practical way to forward a future geothermal exploitation is to make the existing geothermal power stations expanded to deeper reservoirs. Actually the drilling depth of Japanese geothermal wells tends to increase year by year indicating the existing large demand to deeper exploitations (Fig. 1). For response to this demand, NEDO has designed a master plan of the DGRS program in 1992 (Sasada et al., 1993).

Turning our attention to the world, attempts of drillings to deep geothermal resources are found here and there (Table 1). In Italy, the deepest geothermal drilling has attained a depth of 6,280 m at the Monte Amiata geothermal field and the highest borehole temperature is 450 °C at 4,000 m at the same field (Bertini et al., 1995). In the Unite States, a drilling for hot dry rock at the Fenton Hill experimental site has reached 4,660 m and 320 °C. At The Geysers geothermal field, some drilling has reached 3,870 m and other drilling reached

Table 1. Records of deep and high temperature geothermal drillings.

Country	Records of drilling depth		Records of borehole temperature	
Italy	Monte Amiata	6,280 m	Monte Amiata	450 °C at 4,000 m
United States	Fenton Hill	4,660 m	The Geysers	342 °C at 3,300 m
New Zealand	Ohaaki	3,500 m		
Mexico	Cerro Prieto	4,000 m	Cerro Prieto	388 °C at 4,000 m
Philippine	Mak-Ban	3,160 m		
Indonesia	Dieng	2,700 m		
Japan	Kakkonda WD-1A	3,729 m	Kakkonda WD-1A	500 °C at 3,729 m

342 °C at a depth of 3,300 m. In New Zealand, three drillings of 3,500 m class have been carried out at the Ohaaki geothermal field. In Mexico, three drillings of 4,000 m class have been carried out at Cerro Prieto geothermal field (Le-Bert, 1990) and some of them was more than 388 °C. In addition, a drilling of 6,000 m class is scheduled in 1997 (Oral communication with Dr. Victor Arellano, 1996). In Philippine, a drilling has been done to a depth of 3,160 at the Mak-Ban geothermal field.

Although 'deep geothermal resources' are tentatively defined as prevailing at a depth of 3,000 m in the Task, they might not necessarily be defined by an absolute depth in the viewpoint from geothermal geology. Geothermal heat sources of high temperature hydrothermal systems have long been ascribed to high-level magma chambers and their consolidated equivalents, because most high temperature hydrothermal systems occur in the vicinity of composite volcanoes that may mark long-lived magma chambers at shallow depths. In the last two decades, many geothermal drillholes have penetrated young intrusions in, and beneath hydrothermal reservoirs (Lovelock et al., 1982; Yock, 1982; Takeno and Noda, 1987; Thompson, 1989; Gunderson, 1989; Sternfeld, 1989; Doi et al., 1990; Reyes, 1990; Maeda, 1991; Browne et al., 1992; Kiryukhin, 1993; Kato et al., 1993; Kato and Sato, 1995; Hulen and Nielson, 1996; Muraoka, 1993). They seem to demonstrate an empirical idea on a possible role of high-level magma chambers as being essential geothermal heat sources. These drillholes that reach geothermal heat sources might also been categorized into those of deep geothermal drillholes in terms of geothermal geology, regardless to an absolute scale and depth.

IMPLICATION FROM THE NEDO DEEP GEOTHERMAL PROGRAM

As a core part of the NEDO DGRS program, a deep geothermal exploration well, named WD-1A, was drilled into the depth of 3,729 m in the Kakkonda geothermal field, Northeast Japan, from January 1994 to July 1995 using efficient borehole cooling techniques such as the top-drive system and three mud coolers. The results have been reported by numerous papers (e.g. Muraoka et al., 1995; Yasukawa et al., 1995; Yagi et al., 1995; Saito et al., 1995; Ikeuchi et al., 1996; Kasai et al., 1996; Uchida et al., 1996). The well penetrated a shallow permeable hydrothermal convection zone at depths from 981 to 2,137 m, a deeperward-impermeable contact metamorphic aureole at depths from 1,610 (biotite isograd) to 2860 m and then a neo-granodiorite pluton dated 0.19 Ma in an average of hornblende K-Ar ages, named the Kakkonda Granite (Kanisawa et al., 1994), from 2,860 to 3,729m. Unfortunately, the deep reservoir expected at the top of the Kakkonda Granite from the previous drilling experience at other portions of the Kakkonda Granite (Kato and Sato, 1995) was not encountered. However, the recovered temperature with a depth of the well indicates a boiling point-controlled profile up to 400 °C by the depth of 3,100 m and a conduction-controlled profile with a very high gradient up to 500 °C by the bottomhole of 3,729 m (Fig. 2; Fig. 3). The bottomhole temperature 500 °C may be the highest temperature record as that from geothermal wells in the world, excepting the very shallow experimental drilling into the Kilauea Iki lava lake (Hardee et al., 1981). The results are summarized as follows:

(1) WD-1A may be the first well that encountered not only the temperature higher than that of the boiling point curve but also the subsolidus temperature of the granitic magma system as has been theoretically modeled by Fournier (1987). This would provide the first logical evidence that the neo-granitic pluton found beneath geothermal fields could be actually a cooling magmatic heat source to the geothermal system.

(2) WD-1A may be the first well that completely penetrated the ductile-brittle boundary that is known to range in temperature from 350 °C to 450 °C on quartz-dominant rocks (Fournier, 1987; Nielson, 1995). An inflection point of the temperature profile of WD-1A that lies at the depth of 3,100 m and at the temperature of 400 °C may mark the ductile-brittle boundary in expectation.

(3) Those relations of the well WD-1A demonstrate that the temperature constrains the ductile-brittle

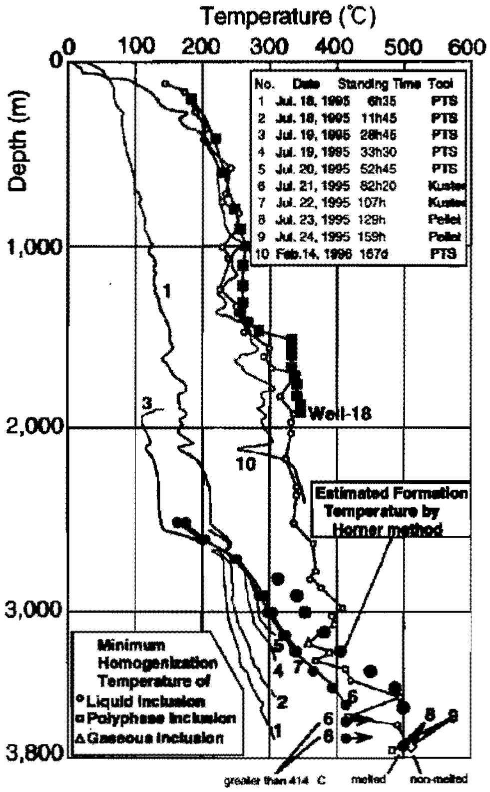

Fig. 2. Representative temperature logs of WD -1A by conventional logging tools, temperature melting tablets, minimum homogenization temperature of fluid inclusions and estimated formation temperature by the Horner method (Uchida et al., 1996).

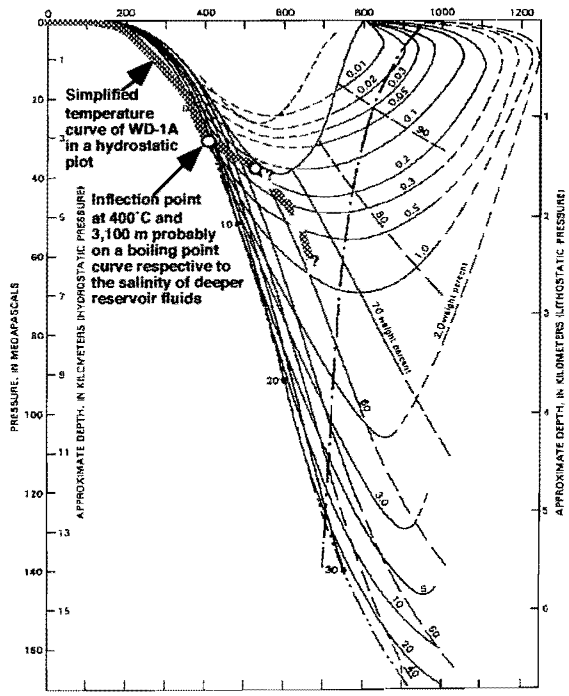

Fig. 3. Simplified recovery temperature profile of WD-1A projected to the diagram for system NaCl-H_2O by Fournier (1987).

boundary to the depth of 3,100 m, the ductile-brittle boundary constrains the deepermost of fracture distribution to the depth of 3,100 m and then the fracture distribution constrains the deepermost of hydrothermal convection to the depth of 3,100 m.

(4) WD-1A has experienced gentle ejection of uncondensible gas such as CO_2 and H_2S below 3,350 m and the borehole fluid sampling by reverse circulation has obtained metal-rich brine containing 39 wt % total dissolved solids at a depth of 3,708 m. Although the brine must have been affected by the mixing with circulated river waters and intraborehole flush, this indicates that there exists a two-phase zone of brine and uncondensible gas as intracrystalline fluids below the hydrothermal convection system.

(5) The observation of core samples and FMI logs of WD-1A detected a zone of very high concentration of low angular fractures in the contact metamorphic aureole of the Kakkonda Granite at depths from 1,850 to 2860 m (very contact). The present permeability of the zone is not necessarily high but the fracture zone could be generated by concentration of regional stress into a very thin brittle crust layer above the Kakkonda Granite and possible water weakening due to the dehydration front of the contact-metamorphic reactions such as a cordierite forming reaction.

SUBJECTS TO BE SOLVED

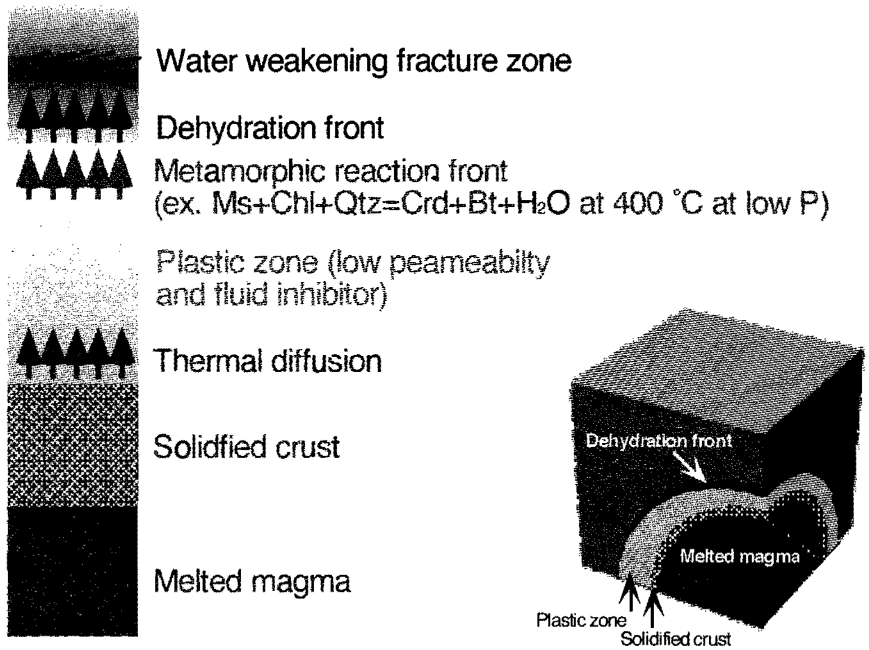

Fig. 4. A model of fracturing in the dehydration front of contact metamorphism.

The DGRS program provided us fruitful information on the deep and high-temperature geothermal systems. However, we need more comparative studies with other examples from the world. Those are as follows:

(1) What does it control the deeper limits of hydrothermal convection?

For the importance in geothermal development and resource estimation, this subject has been discussed by many researchers (e.g. Founier, 1987; Nielson, 1994). WD-1A of the DGRS program indicates that the deeper limits of hydrothermal convection is the ductile-brittle boundary, that is, a formation temperature of 400 °C. It gives us a simple criterion to predict deeper limits of hydrothermal convection, but we need more data for generalization.

(2) Are there any categories of hydrothermal reservoirs deeper than the ductile-brittle boundary?

Most of hydrothermal reservoirs are known to be composed of fractures so that they are inevitably subject to the ductile-brittle transition. However, geology told us that some type of ore deposits are found in druse like pegmatite ore deposits. Hydrothermal reservoirs derived from limestone seem also different from the fracture type.

(3) How does it cause the plutonic-rim reservoirs?

As seen in the Kakkonda Granite, a brittle crust layer at the roof of the shallow magma chamber must be very thin so that regional stress must be exclusively concentrated to the thin roof layer promoting fracturing. Dehydration reactions of contact metamorphism also play a role of water weakening at the roof of magma chamber promoting fracturing as shown in Fig. 4. Hanson (1992) pointed out that pore pressure increased in the process of metamorphic dehydration reaction. In WD-1A, the aureole has extremely high concentration of fractures, nevertheless, the aureole also forms a relatively impermeable zone at present. This paradox may be explained by a sweep process as shown in Fig. 4 that the fracturing once occurs in front of dehydration reaction but this will soon be erased by the plastic zone coming from its behind. Moreover, contraction associated with the magma consolidation will tend to form space at the top of the magma chamber.

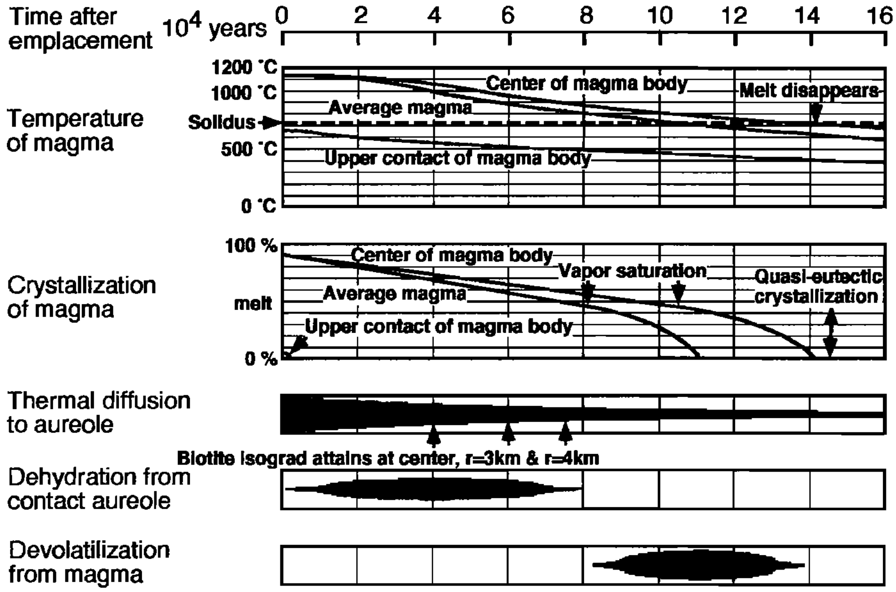

Fig. 5. A model of the chronological sequences of the various events on the magma-wall rock interactions.

(4) What is the role of a critical point or condensation-point curve?

Most of geothermal drillholes that have penetrated young intrusions indicate that the contact metamorphism has preceded hydrothermal alteration (Muraoka, 1993), even though the aureole was the place to interact with volatiles liberated from the magma chamber. A possible idea to explain this may be a supercritical behavior with no boiling or condensation below some depth at a given salinity (Founier, 1987).

(5) How does the contact metamorphism play a role in the succeeding hydrothermal convection?

As seen in the Kakkonda Granite, contact metamorphism does not go back far from the present thermal regime and may be related to the present hydrothermal regime in various ways. One of them is that the aureole forms a relatively impermeable zone, nevertheless, the aureole also has extremely high concentration of fractures. Contact metamorphic aureoles can be also used as indicators to predict the depth of the top of plutonic bodies (Muraoka and Matsubayashi, 1994; Kato and Sato, 1995).

(6) How is a general evolution drawn from melted magma stage to hydrothermal convection stage?

Interactive studies of petrology of drill core samples and theoretical modeling would provide us a general evolution of the magma-hydrothermal systems. Fig. 5 shows an example of a model of chronological sequence of various events on the magma-wall rock interactions (Muraoka, 1996).

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