The Geyser

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FIRST-EVER FOREIGN PARTICIPATION INVITED!

JAPAN'S FUJITA REVEALS TOP-SECRET TOWER OF POWER

By James P. Miner

Surrounded by ancient Shinto shrines and the fertile agricultural acreage of Kyushu, Japan's towering Mount Aso — one of the world's largest volcanic craters — stands guard over what may be this island nation's richest natural resource. Beneath this majestic mountain's inscrutable mass exists an estimated 1000 MWe of geothermal power — a nonpolluting energy source that is about to thrust Japan into the world of the future.

Located on a remote volcanic plateau, a spider web of power lines and interconnections emanates from two drilling rigs. This fragile network is mute evidence of the first stages of a massive project expected to produce enough geothermal fuel to provide the Kyushu Electric Power Company with as much as 10% of the electricity required to satisfy the needs of the island's 10,000,000 resident customers.

Once the plant is operational, Kyushu Island will be home to the world's first self-sufficient geothermally-powered community. Nurtured with an infusion of over one billion dollars (provided by Japan's Ministry of International Trade and Industry to finance extensive initial resource investigation and exploration), the dream has become reality under the direction of the giant Fujita Corporation.

So far, the project has far exceeded Fujita's expectations. The developers hit a 20 MWe bullseye at their first discovery well on the Hohi Geothermal Area on the flank of Mount Aso. As a result of their work, this site is now the single largest such well ever discovered anywhere in the world. Two other well-known Kyushu producing fields — Otake and Hatchobaro — are located in the same general area. Interestingly, steam is being obtained from fractures in the basement

Fujita Corporation is harnessing Japan's geothermal genie on Kyusho Island.

INTERNATIONAL GEOTHERMAL ENERGY NEWSLETTER

rock — an area where it hasn't been found before.

Keeping an effort of this magnitude under wraps (in order to protect proprietary data) prior to its official international unveiling was one of the challenges faced by Fujita. To minimize the chances of premature intranational exposure, Fujita hired a foreign company, Canada's Westbourne Drilling, to do the initial work. Crews made up of Canadian, American and Philippino workers were brought in and rotated on a monthly basis. Temporary housing and other material needs were provided by other North American vendors.

As a result, the site — nestled among the traditional terraced farms of rural Japan — has had all the hallmarks of an international community right from the start. Even now that local labor is being employed, English remains the official language of this operation. And the stirring sight of four countries' flags flying over the housing units dramatically underscores what is clearly the most impressive aspect of this entire undertaking: Fujita and Uchida have always intended to involve the international community in this multi-phased geothermal project.

As Kazuaki Fujita, Fujita Corporation Chairman of the Board explains, "To date this project has had only one money supply — Fujita. We are now inviting the most talented people in the geothermal world and the international investment banking

FUJITA & UCHIDA — THE POWERS BEHIND JAPAN'S MOST AMBITIOUS GEOTHERMAL PROJECT

KAZUAKI FUJITA
Chairman/President
Fujita Corporation

GENKO UCHIDA
First proposed
Kyushu Project

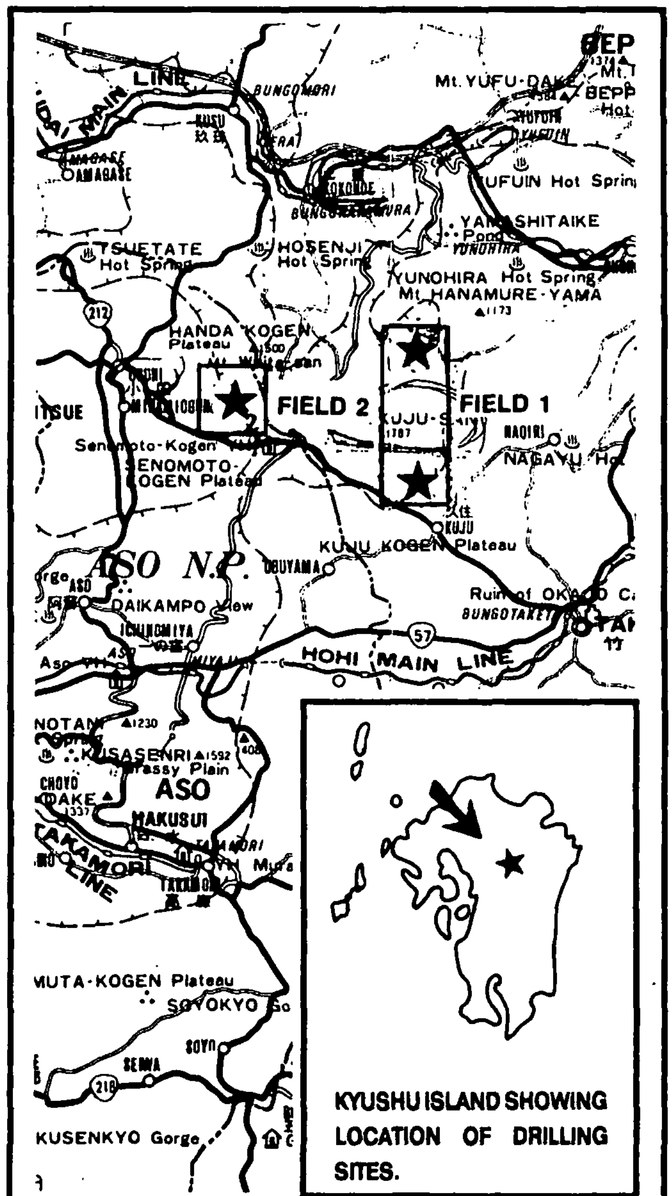
It is appropriate that Japan's giant Fujita Corporation would be called upon to develop the unprecedented geothermal power project described in our feature article.

Founded in 1910 by Ichiro and Sadaichi Fujita, this company is one of its country's most prestigious property development and general contracting firms. Under the direction of the current Chairman of the Board, Kazuaki Fujita, the Fujita Corporation prides itself on its involvement in all aspects of property and human resouce development. In addition to being in the forefront of construction in its own land, Fujita owns and has developed properties in several Southern California locations.

It may surprise readers to learn that this immense undertaking originated as the brainstorm of just one man — Genko Uchida. The plant now being constructed on Kyushu is the literal realization of Mr. Uchida's desire to provide his power-dependent homeland with a source of inexpensive geothermal energy.

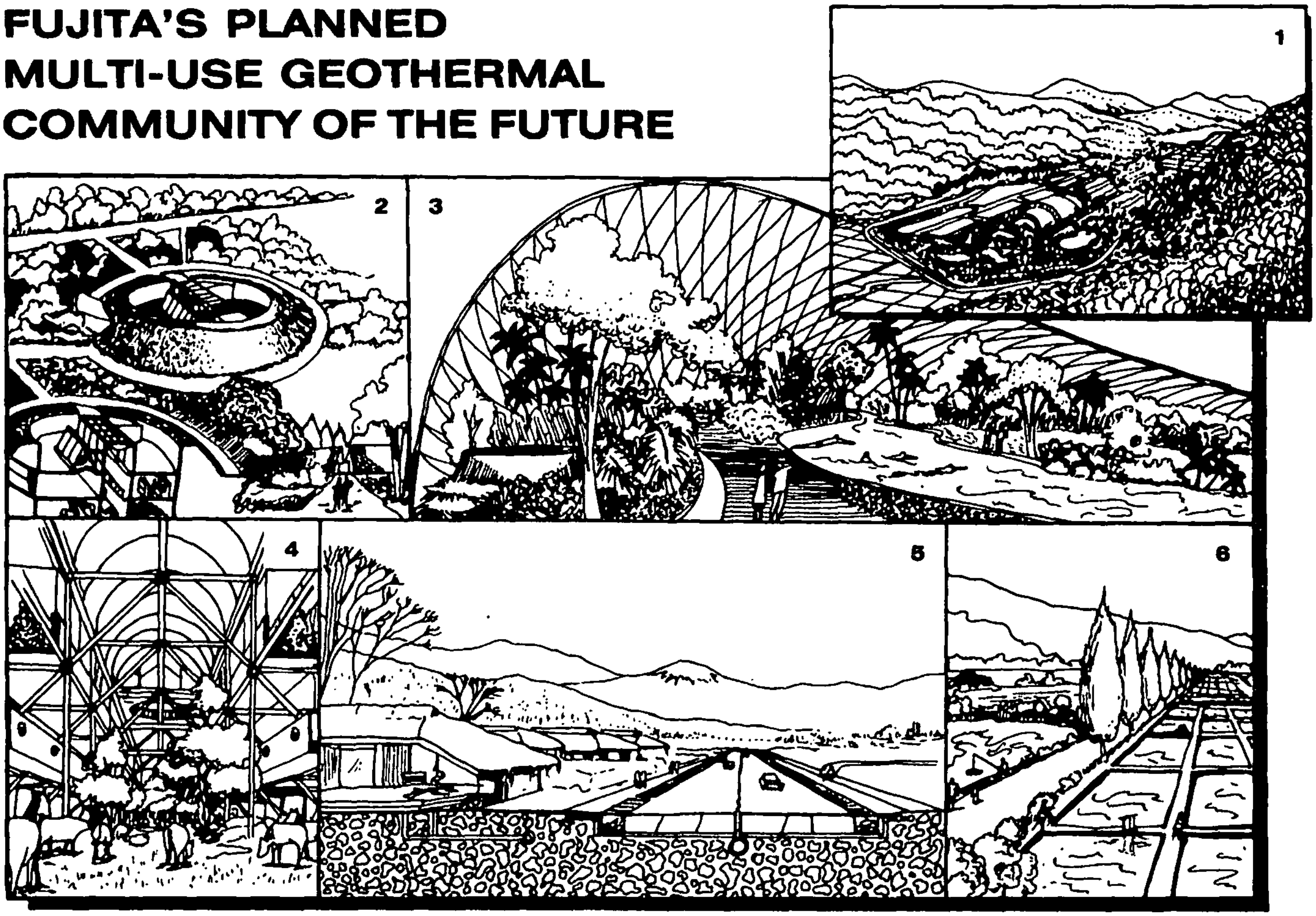
This is not, by any means, Mr. Uchida's first significant contribution to the people of Japan or the formidable "Japanese Economic Miracle." As a planning member of Japan's Ministry of International Trade and Industry (MITI), he was among the first to propose exporting Japanese automobiles to global customers, using the ocean's thermal gradient as a source of energy and installing the advanced fiber optics systems that make this country's telephone communications clear as a bell.

It was at Uchida's suggestion that MITI lay the groundwork for the Kyushu project by spending over one billion dollars to investigate and explore the most favorable location to exploit Japan's considerable geothermal potential.



KYUSHU ISLAND SHOWING LOCATION OF DRILLING SITES.

FUJITA'S PLANNED MULTI-USE GEOTHERMAL COMMUNITY OF THE FUTURE



1. Aerial overview of the completed Kyushu Project
2. Ground-level steam vents for underground power plant
3. Luxurious spa featuring constant controlled tropical environment.
4. Enclosed hydroponic farming operation
5. Constant residential temperature maintenance and road de-icing
6. Aquaculture and geothermally-heated outdoor farming area

community to participate with us in our venture." Genko Uchida, one of Japan's foremost industrial visionaries (this project was first conceived by Uchida), adds, "We want to give foreign companies an opportunity to invest in Japan and its geothermal energy future."

With electric contracts presently wholesaling at 10¢/KwHr in Japan — more than twice the rate of North American Standard Offers — that future may be very bright indeed.

Noting that conservative estimates project that over 3,000 MWe of geothermal energy will be put to use in Japan during the next decade, Mr. Fujita goes on to say, "We will need many kinds of people to engineer our projects and we believe that international participation will only add to our knowledge."

The Mount Aso sites — like the Comstock and Klondike lode areas where riches were found in days gone by — were nearly inaccessible at first. Roads, reminiscent of those in The Geysers Field in Northern California, are steeply-graded, gravelly and snaked with sidewinds and switchbacks.

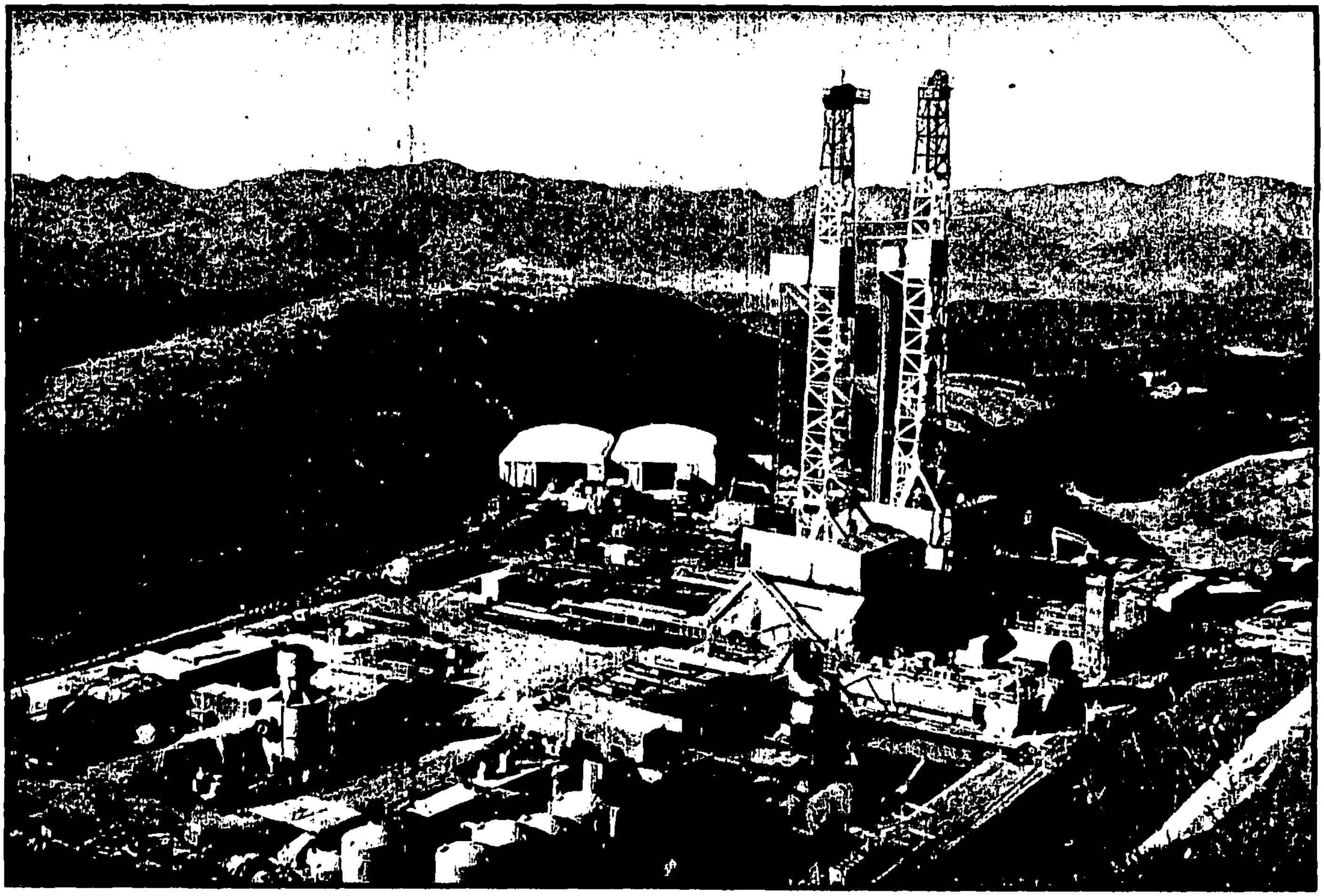
To reach the first drilling site (Field 1), engineers have developed a modern-day tramway that travels 300 meters up a 43% grade. Using an oversized bucket, workers winch heavy equipment and tools up the hill.

The second drilling site (Field 2) has two state-of-the-art rigs working side by side, 24 hours per day. The equipment, which was purchased from suppliers in Dubai and Western Canada, is specially adapted for geothermal exploration. In keeping with the intentionally international direction of the project, Fujita has enlisted the services of Bechtel Corporation as a plant design consultant. Reservoir estimates are in the 250 MWe range for the 250-acre plot.

Together, Fujita Corporation and Uchida have expended more than 125 million dollars on the project to date — an amount they feel confident of recouping in sales of electricity alone. But electric power generation is only one aspect of this multiphase project.

Fujita's first power plant will produce 250 MWe, making it the largest geothermal generating facility in the world.

Under the auspices of the Agricultural Resources and Energy Foundation (AREF), waste heat from the three sites will also be put to work. A hardwood drying plant, using new technology to produce geothermally-cured wood with the strength of steel, is planned. Acres of subterranean PVC piping will enable farmers to raise crops the whole year



State-of-the-art drilling rigs tower over one of Fujita Corporation's Kyushu geothermal project sites.

round — without interfering with the aesthetics of the rural countryside. Geothermal energy will also provide both home heating in winter and air conditioning during the summer months.

Local residents are eagerly looking forward to enjoying a planned geothermal recreational facility that will include mineral water baths and swimming areas. Those same geothermal waters may eventually be mined for their mineral content since silica, lithium and other rare elements used in fusion have been detected.

While all of this may sound a bit Utopian, Fujita insists it is not creating some sort of geothermal Disneyland. After all, why would the company waste its time on a futuristic fantasy park when the world's first totally-planned, self-sufficient, multiple-use geothermal community is there for the building?

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THE JAPAN INDUSTRIAL JOURNAL

Outline of Research & Development of Geothermal Energy Technologies

Nobuaki Mori,
*Director for Development Program,
New Sunshine Project Office,
Agency of Industrial Science and Technology*

Nobuaki Mori was born on Aug. 12, 1946. He graduated from a postgraduate course of Kyushu University in 1971 and joined the Ministry of International Trade and Industry (MITI) in the same year.

He went to the United States to study nuclear power in October, 1977. He was appointed general coordination section chief for the nuclear power safety administration Division, Agency of Natural Resources & Energy in 1982, director of the division in 1984 & director of General Coordination Division, Nagoya bureau of MITI in 1985. He is director of Development Program, New Sunshine Project Office, Agency of Industrial Science and Technology.

THE Sunshine Project started in 1974 to develop technologies for securing clean and petroleum-substitute energies. As Japan is one of the most volcanic countries and is abundant in geothermal resources, technological development for geothermal energy is promoted as one of the main subjects in the Sunshine Project.

Technological development is about exploration and drilling/recovering of geothermal reservoirs, and utilization of unused geothermal resources. Basic research is carried out by national research institutes and technological development for practical use by the New Energy and Industrial Technology Development Organization (NEDO). The main R&D has aimed at technologies for development of shallower geothermal resources, but will center of deeper resources. Developed technologies in the Sunshine Project are mainly used for and expected to support development of geothermal power generation by the Agency of Natural Resources and Energy.

Furthermore, in order to consistently develop technologies for energies and the global environment, the New Sunshine Project will begin in FY1993 integrating the Sunshine, the Moonlight (energy-saving technology R&D) and the Global Environmental Technology Projects.

Basic research studied in national research institutes are as follows:

1) "Research on Exploration Technology of Deep Geothermal Resources" to obtain useful data for exploration of deep-seated resources in "Technology for Exploration of Geothermal Energy".
2) "Studies on Drilling Methods for Geothermal Well and Downhole Coaxial Exchanger System" to develop a directional bit applied to a downhole motor, and downhole coaxial exchanger system used for heat extraction from high-temperature magmatic zones in "Techniques for Exploration of Geothermal Energy."
3) "Studies on Geothermal Material Development" to search for materials to be used in the geothermal environment of high temperature and corrosion/errosion.
4) "Research on Fracturing and Heat Extraction from Hot Dry Rock" to study techniques for fracturing and acoustic-emission exploration in "Technology for Hot Dry Rock Power Generation System".

Developing technologies for practical use by NEDO are as follows;

1) "Development of Comprehensive Analysis System" using information-processing highly advanced computer technology, to systematically understand the conditions of geothermal resources in Japan, and to extract promising areas by analyzing ground surface survey data.
2) "Investigation of Exploration Methods for the New Type Geothermal Resources" using ground surface survey data of geology and alteration zones, and airborne magnetic and electromagnetic surveys utilizing resource-satellites and aircraft, to build effective exploration techniques for various types of geothermal resources,
3) "Development of Exploration Techniques for Fracture-type reservoirs" consisting of techniques for seismic exploration (seismic reflection, vertical seismic profiling and seismic tomography methods), electromagnetic wave exploration (new and more efficient array-type controlled source magnetotelluric survey system) and microearthquake exploration, to make accurate exploration methods for fracture-type geothermal reservoirs, the main reservoir type in Japan.
4) "Development of the Binary Cycle Generation (10 MW-class) Plant" furnishing a downhole pump, to search for effective utilization of unused medium to high temperature thermal water.
5) "Development of Technology for Increasing Geothermal Energy Recovery" to establish basic technologies of effective fracturing and accurate prediction for a volume of energy recovery.
6) "Development of MWD (Measurement While Drilling) System for Geothermal Wells" to get various types of well-bottom information on a real time basis while well drilling, and to make possible improvement of efficiency and precision for geothermal well drilling.
7) "Development of Hot Dry Rock Power Generation Technology" consisting of the heat extraction experiments using an artificial reservoir, to utilize heat of high-temperature rocks, one of the unused geothermal resources, effectively.

Furthermore, "Deep Geothermal Resources Survey" program has started to understand conditions of deep-seated geothermal resources (4000m-class), useful to increase geothermal power generation, and to develop effective exploration methods for deeper reservoirs.

"Development of Deep Geothermal Resources Recovering Technology" program consisting of development of drilling and recovery technologies used in high-temperature environments for effective and economic recovery from deep resources, as development of a downhole motor.

For development of the technologies, a budget of ¥4.6 billion is requested for FY1993. The New Sunshine Project Office intends to promote technological development on the basis of advanced domestic and foreign technologies, and to consider joint R&D with overseas enterprises. □

Present Status and Future Prospects of Geothermal Power Generation

Yukio Arai was born in March 1949. After graduating from the Atomic Power Engineering Dept., Faculty of Engineering, University of Tokyo, he joined the Ministry of International Trade and Industry (MITI) in May 1972. He became the technical official in charge of industrial technology at the Sunshine Project Promotion Headquarters, the Agency of Industrial Science and Technology, MITI, in June 1976. He became Head of the No. 2 Nuclear Fuel Section, the Nuclear Energy Industry Division, Director-General's Secretariat, the Agency of Natural Resources and Energy (ANRE), in March 1978; Head of the Survey Technology Section, Nuclear Power Generation Dept., Electricity Power Generation Division, ANRE, in January 1980; and Director of the Technology Dept. of the same division in April 1982. After October 1986 he was engaged in the development and planning of advanced reactors in the Nuclear Power Generation Dept., Electricity Power Generation Division. In May 1988 he went to China as Director of the Electric and Nuclear Power Dept., Beijing Office of the Japan-China Economic Association. He was appointed Director in charge of safety management of nuclear power generation, Electricity Power Generation Division, ANRE, in July 1991. Since June 1992 he has been Director, Electricity Power Generation Division.

Yukio Arai,
Director,
Electricity Power Generation Division,
Agency of Natural Resources and Energy, MITI

1. Introduction

JAPAN has endeavored positively for the introduction of alternative energy resources to petroleum after going through two oil crises. But its energy structure is still very flimsy, depending on import from abroad for the supply of practically all energy resources. The energy demand in Japan is tending to increase steeply along with vigorous economic activities and the nation's aspiration for affluent living.

On the other hand, the rising interest of people in global environment problems, represented by global warming and acid rain, has given rise to lively discussions on the use of energy derived from fossil fuels.

The Advisory Committee for Energy, an advisory organ of the Minister of International Trade and Industry, compiled a report with a long-term projection of energy demand in June 1990 in response to these contemporary trends. The projection predicts that national energy demand will rise 1.24 times by 2000 and 1.38 times by 2010 from the level of 1988, even assuming that the nation will make maximum efforts to save energy. The energy to meet this huge demand must be procured somehow. The report points out the need for promoting comprehensive development of all sorts of alternative energy resources to petroleum, including solar energy, nuclear power, geothermal energy and hydroelectric power.

2. Position of Geothermal Power Generation in Japan

The Supply and Demand Committee of the Electricity Utility Industry Council (June 1990) recommended the energetic development of geothermal power generation as a basic power source, which, like hydroelectric power generation, is free from the environmental load of CO_2 and features a very stabilized supply as domestic energy. The following features also rank geothermal energy as a clean energy resource matching the demand of the times because of its stabilized supply and compatibility with the environment.

(1) Geothermal power is purely domestic, inexhaustible and renewable energy. As a volcanic country, it is one of the very few energy resources abundantly available in Japan.
(2) The technology for practically utilizing geothermal power has already been established and its utilization is expected to expand further along with the reduction of development risks and costs.
(3) It is accompanied by little emission of smoke, dust or CO_2.
(4) Besides power generation, hot geothermal water can be utilized for agriculture, fisheries and forestry, and multiple utilization is expected to stimulate local economies.

3. Present Situation of Geothermal Power Generation and National Policy

(1) Present Situation of Geothermal Power Generation

The development of geothermal power generation in Japan dates back to 1925 when Dr. H. Tachikawa carried out the first experimental geothermal power generation of 1.3kW using natural steam in Beppu, Oita Prefecture. Large-scale geothermal power generation started with the putting into commission of the Matsukawa Geothermal Power Plant for private power generation by Japan Metals & Chemicals Co., Ltd. The geothermal power plants operating in Japan at present number 10: five for electric utilities and five for private power generation with a total generating capacity of 270MW.

Seven geothermal power plants are in development at present with definite construction plans. These new power plants with total capacity of about 260MW are slated to start operation by 1996. However, there are only two other locations where geothermal power generation are eventually planned. Private-sector companies have no plans to carry out development surveys in other locations for the time being.

On the international scene, the overall plant generating capacity stood at 6,010MW as of December 1990. Japan boasts the sixth geothermal power generating capacity in the world.

(2) Development Form of Geothermal Power Generation

The development of geothermal power plants in operation or under planning at present can be classified into two forms. The components of the geothermal power plant consist of underground facilities for steam production and the power generation facilities for using the steam.

The first form is characterized by a single company undertaking the development of all components from steam production to power generation. The tasks are performed either by electric power companies, including power distribution, or companies engaged in only the development of power resources.

The second form is characterized by different companies performing the steam production and power generation. It constitutes the mainstream of development including the power plants now in the process of development. The power plant is naturally entrusted to electric power companies, but steam production is frequently performed by firms specializing in the development of geothermal resources, which are often mining companies or their affiliated firms.

(3) National Policy in Japan

The Japanese government is implementing various supporting measures for the survey, development and introduction of geothermal power generation.

1) Budget measures
   * The government takes the initiative in comprehensive surveys regarding geothermal resources.
   * The government conducts surveys on environmental countermeasures.
   * Cost and interest subsidies are granted to drilling enterprises for prospecting wells.
   * Subsidies for the construction of geothermal power plants.
2) Treasury investment and loans
   * Treasury investment and loans for steam production and power generation
3) Taxation
   * Partial exemption of national and local taxes for private power generation facilities

4. Future Prospect of Geothermal Power Generation

The Supply and Demand Committee of the Electricity Utility Industry Council announced the supply target of geothermal power generation according to which the present geothermal power generation capacity of 270MW is to be raised to 1.000MW by 2000 and 3,500MW by 2010.

The solution of various problems inherent in geothermal power generation is indispensable for achieving this target. Principal pending problems are enumerated as follows: (1) various development risks such as those attending survey and industrialization; (2) economic problems related to long lead time and interest load for development; (3) difficulty in harmonizing development with natural parks and hotsprings.

The regulations of national budget and treasury investment and loans are being expanded to deal with these problems. In addition, the three rules to facilitate joint geothermal development by electric power companies and geothermal developers are being worked out. The basic concept regarding pricing for steam purchases was established in April 1992. The rules for cooperation between electric power companies and geothermal developers from the initial stage of development and the standardization of methods for evaluating geothermal resources are being worked out.

The expansion of existing regulations and the improvement of rules related to geothermal development are expected to gradually raise the importance of geothermal power generation for Japan's entire energy supply. For instance, the output capacity and the output of geothermal energy, which now occupies 0.1% and 0.2%, respectively, of the total electricity supply, are projected to account for 0.4% and 1% in 2000, and 1% and 2% in 2010. ◘

Developing Hot Water Power Generation Plants

Kunio Ishibashi,
Director General,
Geothermal Energy Technology Dept.,
New Energy and Industrial Technology Development Organization (NEDO)

Kunio Ishibashi was born in September 1941. He graduated from Mechanical Engineering Department, Faculty of Engineering, Kinki University, in March 1966 and joined Kyushu Electric Power Co., Inc. in April of the same year. He was engaged in operation, maintenance and management of thermal power plants from 1967 to 1976. He was assigned the tasks related to environmental assessment and monitoring of thermal and nuclear power plants from 1976 to 1982. He was transferred to The Federation of Electric Power Companies from 1982 to 1984 and was engaged in tasks related to environmental assessment and monitoring. He took part in the management of thermal power plants from 1984 to 1988. He was assigned tasks related to environmental assessment and monitoring of thermal and nuclear power plants from 1988 to 1992. Since July 1992 he belongs to Geothermal Energy Technology Department, New Energy and Industrial Technology Development Organization (NEDO).

1. Foreword

GEOTHERMAL energy is a subterranean power source. The technologies for prospecting, drilling and exploitation are indispensable for its development and utilization. The precision and efficiency of these technologies must be improved for development promotion.

The vast volume of geothermal water of medium to high temperature and hot dry rock is left untapped underground and the technology to utilize them for electric power generation has not been established yet. It is an urgent task to develop the methods for the development and utilization of these resources.

NEDO is promoting the "Development of Power Generation Plant Utilizing Geothermal Fluid, etc." as an auxitiary project for the "Sunshine Project." Specifically, it is aimed at

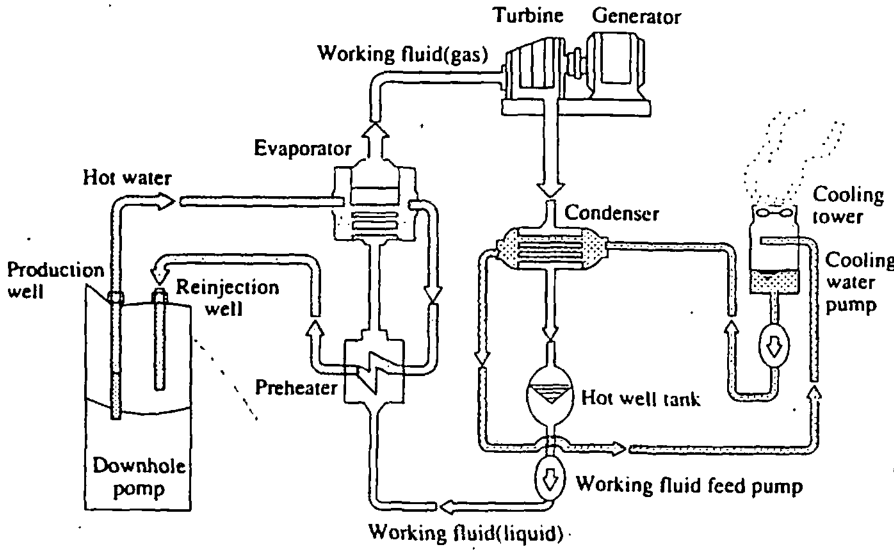


Fig. 1-a Flow Diagram of a Binary Cycle Power Plant

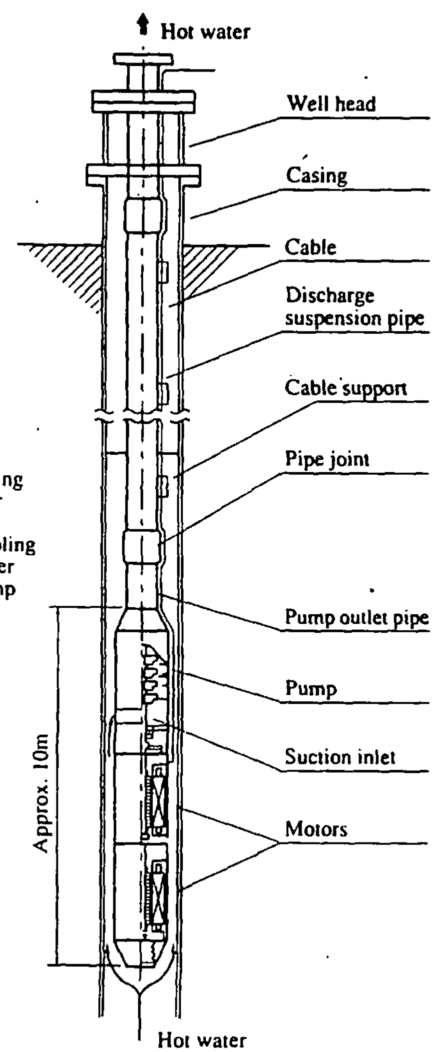


Fig. 1-b General Configuration of a Downhole Pump

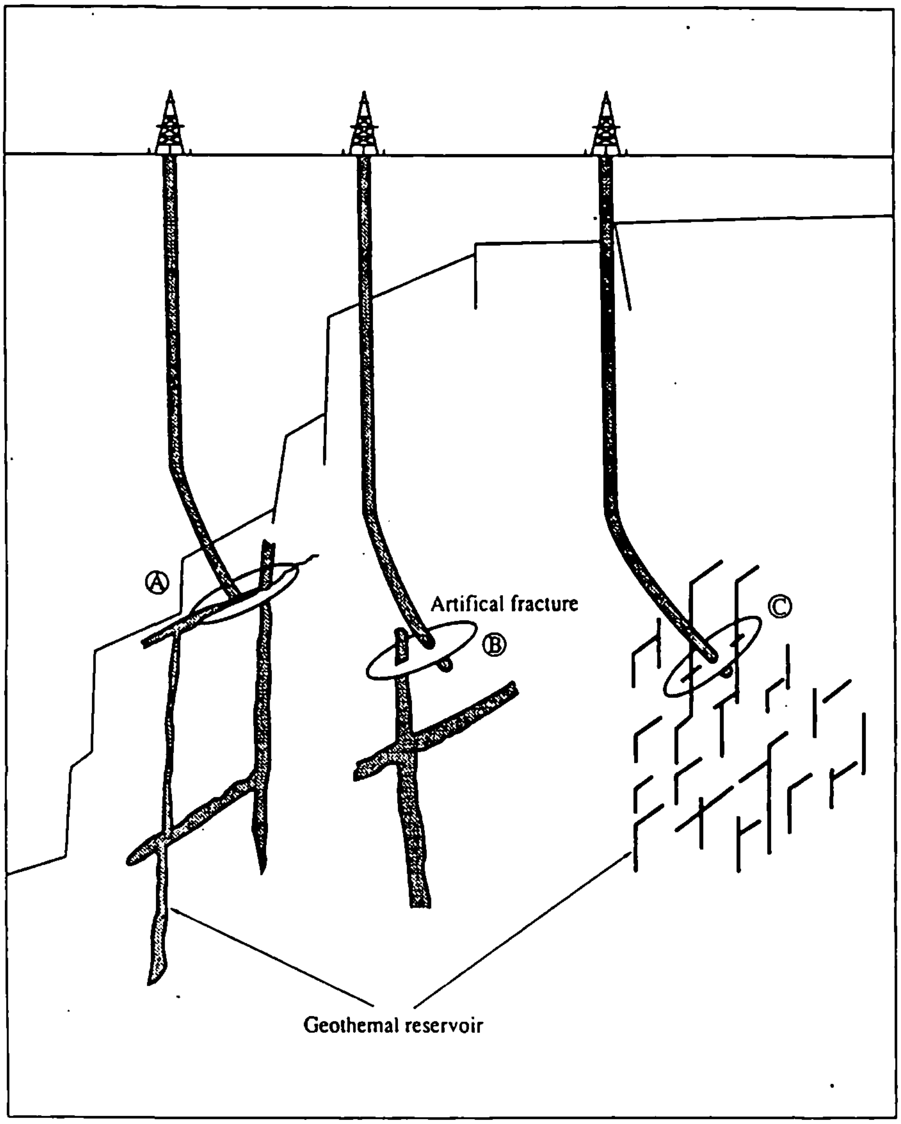


Fig. 2-a Development for Increasing Geothermal Energy Recovery

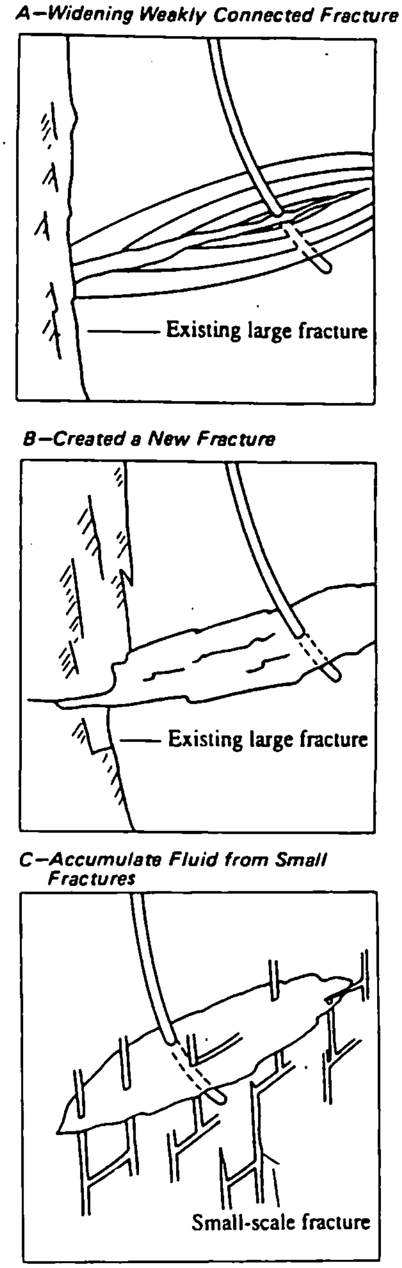


Fig. 2-b Concept of Hydraulic Stimulation for Different Types of Reservoir

the development of technology for expanded utilization of still untapped geothermal resources (hot water and hot dry rock); development of technology for cost reduction of geothermal resources development; and development of technology for exploiting deep-seated geothermal fluid such as drilling and production methods indispensable for increased geothermal power generation capacity and the development of deep-seated geothermal resources:

2. Development of Binary Cycle Power Generation Technology

NEDO is endeavoring to establish technology for binary cycle power generation permitting the utilization of geothermal fluid resources of medium to high temperature which are known to exist in vast quantities in Japan. According to this method, the downhole pump driven by a submerged motor is installed in the geothermal well to pump above ground the geothermal hot water which lacks the power to flow out by itself. Energy contained in hot water is then transferred to a working fluid of low boiling point so as to generate the vapor of the fluid, raising its pressure high enough to drive the turbine for power generation.

At the same time, NEDO is developing the technology for increasing geothermal energy recovery and of a MWD (measurement while drilling) system for geothermal wells as technologies for supporting binary cycle power generation and also for reducing the development cost of geothermal power generation.

(1) Development of a 10MW Demonstration Binary Cycle Plant

As regards the utilization of geothermal water of medium and hot temperature, NEDO is carrying out the "Development of a 10MW Demonstration Plant" based on the above-mentioned binary cycle power generation and the "Development of a

Downhole Pump" (specifications: discharge, 200t/h; lift, 380m; water temperature, 200°C). (Fig. 1).

If these technologies are established, the effective utilization of the latent-type geothermal resources at present (geothermal fluid resources of medium and high temperature of 150 - 200°C) will become possible, laying the foundation for tremendous expansion of geothermal power generation capacity in Japan.

(2) Development of Technology for Increasing Geothermal Energy Recovery

Many geothermal production wells developed so far produce steam and hot water through fractures. Their performance will not be as good as expected if drilled wells do not connect to fractures, or if connections between wells and fractures are poor.

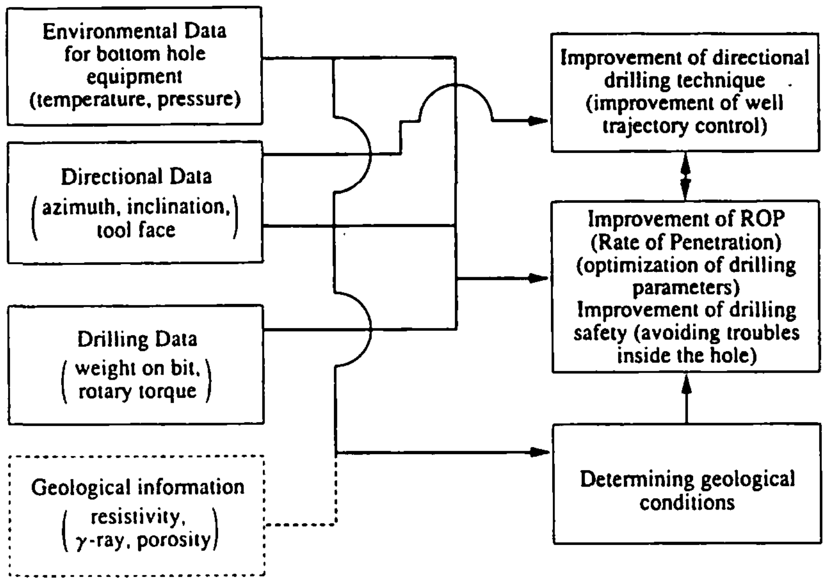
The technology for increasing energy recovery is intended to create artificial fractures by injecting pressurized water into such wells. (Fig. 2). This technology, when perfected, will revive and regenerate existing wells with low productivity, increase the power generating capacity per field unit, reduce the number of wells needed for power generation, reduce the time needed for development and thereby contribute to cost reduction of geothermal power generation.

(3) Development of a MWD (Measurement While Drilling) System for Geothermal Wells

Geothermal wells must be drilled under high temperature conditions. Furthermore, wells are located in complex formations with numerous fissures and water leakage, especially in Japan. Geothermal development areas are subject to environmental conservation regulations and therefore the technique (directional drilling technique) of many wells in many directions from one spot in high precision is increasingly required.

Hence, we started the development

Fig. 3-b Bottom hole measurements and expected effects



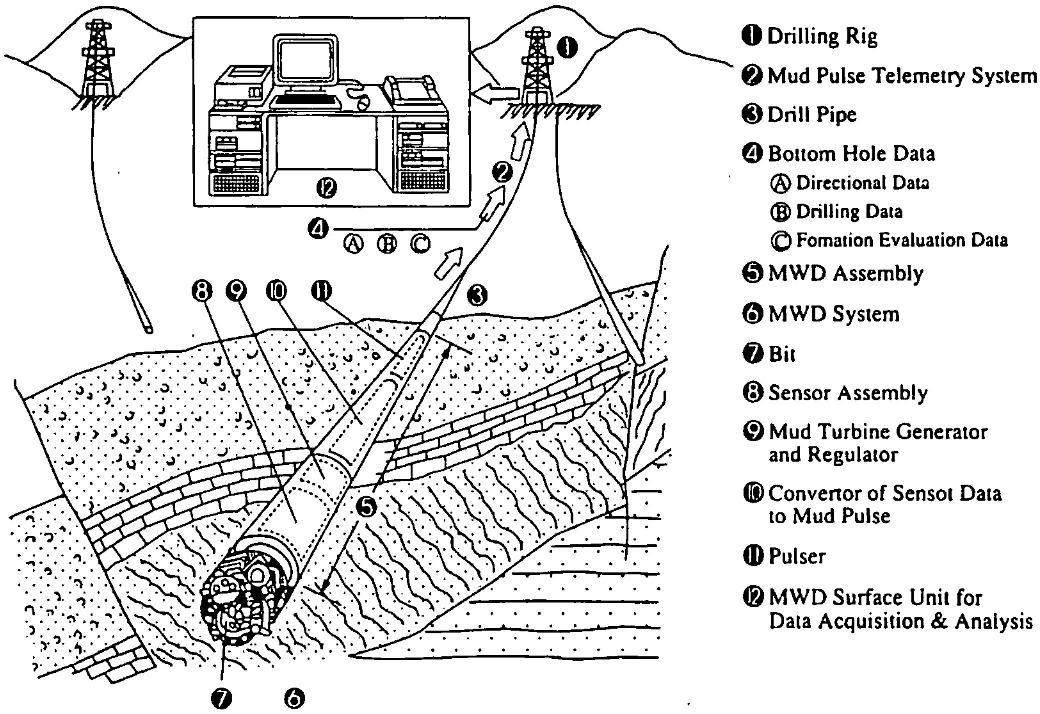


Fig. 3-a Concept of MWD system

of a MWD (Measurement While Drilling) system for geothermal wells which allows the surface personnel to acquire in real time the bottom hole measurement data (direction, inclination, temperature, pressure, etc.) for analysis. (Fig. 3).

This technology, when established, will permit early grasping of changing conditions in the bottom hole, adequate countermeasures based on that data, the improvement of drilling efficiency and precision, and further reduction of drilling cost.

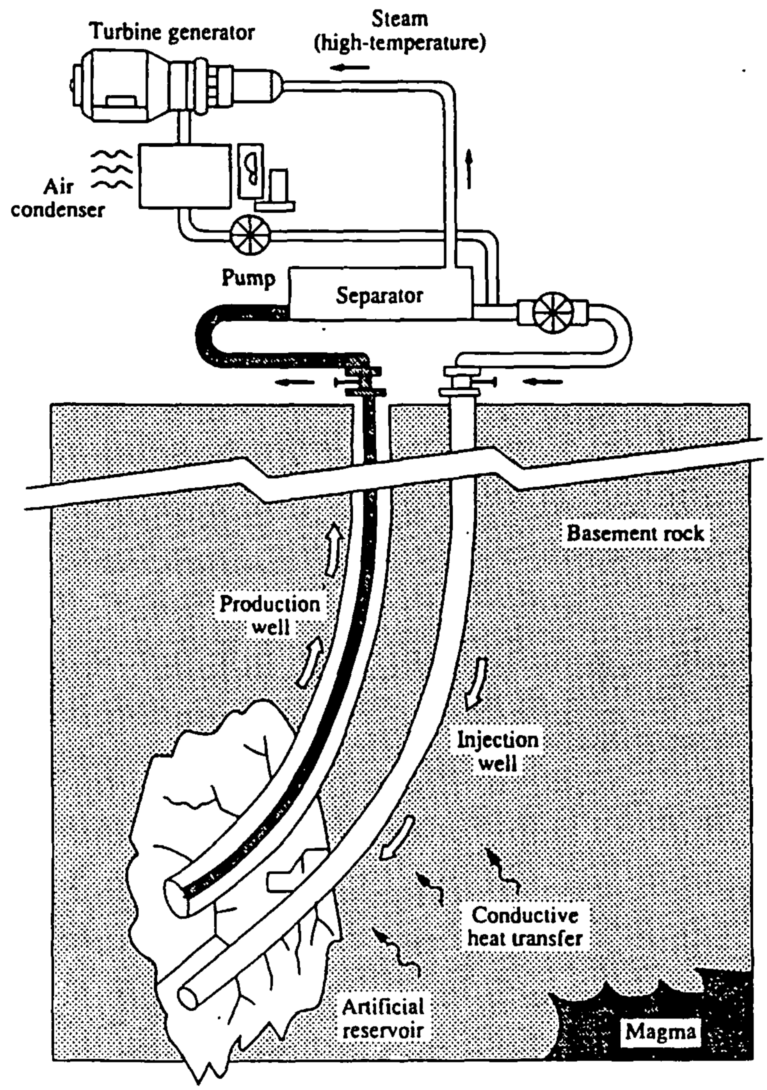
3. Development of a Hot Dry Rock Power Generation System (Elementary Technologies)

NEDO is pursuing the development of a hot dry rock power generation system, namely, the system for developing and utilizing geothermal energy in the so-called hot dry rock or natural high-temperature geothermal reservoir with little water content. Artificial fractures are made in the hot dry rock, water is injected into this artificial geothermal fracture system via a number of wells and steam or hot water is recovered on the ground as in the case of geothermal fluid reservoirs.

Feasibility studies of geothermal power generation from hot dry rock are continuing by injecting pressurized water to make fractures for the artificial geothermal reservoir, the fracture mapping technology and down-hole measurement technology for estimating the extent of the artificial reservoir and the heat extracting system of the artificial geothermal fluid reservoir. (Fig. 4).

Japan as a volcanic country is endowed with abundant hot dry resources which contain an inexhaustible quantity of thermal energy. If we can establish hot dry rock utilization technology that suits Japan's geological conditions, our reserves of recoverable geothermal energy will increase dramatically.

Fig. 4 Concept of a Hot Dry Rock Power Generating Plant



4. Development of Utilization Technology for Deep-Seated Geothermal Reservoirs

The deep-seated geothermal resources that are believed to exist beneath the geothermal reservoir (shallow geothermal resources) developed so far are regarded as very promising geothermal energy resources that lend themselves relatively easily to prospecting and production. They will undoubtedly contribute to increased geothermal power generation capacity at an early date.

NEDO has launched the "Development of Utilization Technology for Deep-Seated Geothermal Resources" as a project to develop drilling, production design technologies and other elementary technologies indispensable to prospecting for deep-seated geothermal resources.

When these technologies have been established, they can be applied to shallow geothermal areas now in operation or development and will contribute to the prevention of the depletion of steam production through adequate production control covering both shallow and deep-seated geothermal resources.

The applications of these technologies to new geothermal areas will pave the way to efficient exploitation of geothermal energy in these areas through planning and execution of a consistent development program comprising the disposition of wells, and production and management of geothermal reservoirs for optimum production modes, taking into account both shallow and deep-seated resources.

The perfection of elementary technologies for drilling, production and management of deep-seated high-temperature resources is expected to exert a stimulating effect on the development of other deep-seated high-temperature resources such as hot dry rock and magma. □

Geothermal Resource Surveys and the Development of Exploration Technology

Keiji Kimbara,
Director General,
Geothermal Energy Development Department,
New Energy and Industrial Technology Development Organization (NEDO)

Keiji Kimbara was born on July 4, 1944. He graduated from the Geological and Mineralogical Institute, Faculty of Science, Niigata University, in March 1967 and obtained his Ph. D from the Physics Dept., Tokyo University of Education, in March 1973. He joined the Geological Survey of Japan, the Agency of Industrial Science and Technology, in April 1974 and was engaged in survey and research of geothermal resources. He was appointed Director General, Geothermal Energy Development Department, NEDO, in June 1992, and is in charge of the survey and development of exploration technology of geothermal resources.

1. Foreword

NEDO is carrying out the geothermal resources survey and technology development as a part of the state's new energy development project (Fig. 1). I would like to explain the outlines of the geothermal resources survey, exploration technology development, development of geothermal reservoir evaluation technology and the diffusion and promotion of expertise.

2. Geothermal Resources Survey

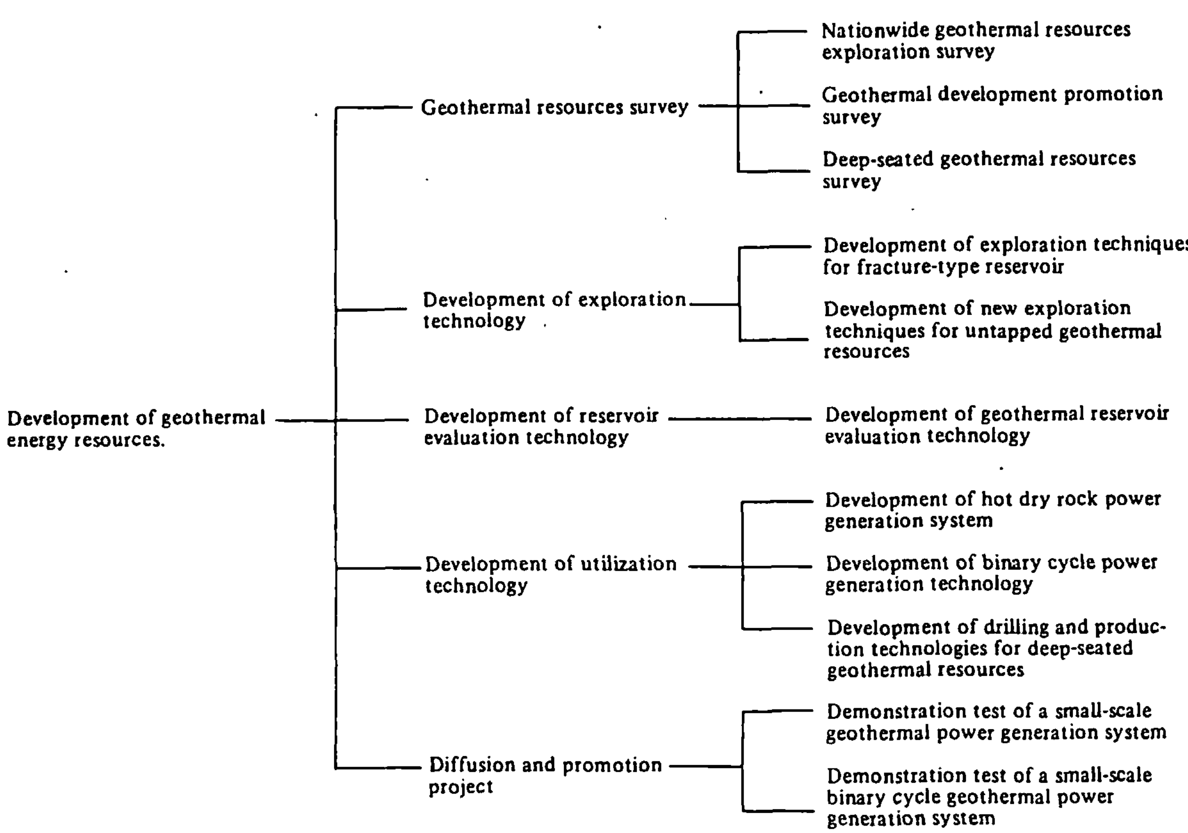
Since its establishment in 1979, NEDO has been conducting the geothermal resources survey of the country based on the flow chart in Fig. 2.

2.1 Nationwide Geothermal Resources Exploration Survey (FY1980 - 1992)

The first phase survey (FY1980-1983) comprised the advanced remote sensing surveys, including a radar (SAR) imagery survey, a curie point survey and a gravity survey covering Japan's entire territory (about 370,000km²). The data, collected and analyzed on a nationwide basis, revealed several prospective geothermal types such as volcano-related hydrothermal convention systems, possible high temperature areas and hot water in deep sedimentary basin system areas. The Geological Survey of Japan evaluated from this data that shallow geothermal resources of over 150°C, enabling flash power generation, amounted to 20,540MWe/30 years.

The second and third phases (FY 1984 - 1992) were devoted to the surface survey of 10 prospective geo-

Fig. 1. Development of Geothermal Energy Resources in NEDO



thermal areas on wide-area scale (500 - 1,000km^2/area) and the analysis of their geothermal structure. The geothermal potential was evaluated and the heat source evaluation system was studied in the second phase, while various surface survey data was efficiently analyzed and a comprehensive analysis system was developed by applying advanced data processing technology in the third phase.

The third phase was also the period of research on survey methods of still untapped geothermal resources including hot dry rock, magma, deep-seated geothermal resources and medium-high temperature geothermal resources.

2.2 Geothermal Development Promotion Survey (FY1980-)

NEDO takes the initiative in this survey in prospective geothermal areas where the investigation is hampered by survey risks, thereby expediting the development of geothermal power generation by private-sector companies. The survey consists of the confirmation of the geothermal reservoir by drilling six to eight wells with depths of 1,000 - 1,800m per area (50 - 70km^2) for three years, in addition to various surface surveys. Surveys were finished in 32 areas since the start of project in 1980, and they are still continuing in six other areas (Fig. 3).

As a result, subterranean temperatures of over 200°C, enabling steam power generation, were confirmed in 21 areas. Development surveys are progressing based on preliminary results in Uenotai (Akita Prefecture, 27.5MW), Yanaizu-Nishiyama (Fukushima Pref., 65MW), Ogiri (Kagoshima Pref., 30MW) and Hachijo Island (Tokyo Metropolis).

However, it would be extremely difficult to achieve the development target of 1 million kW by 2000 and 3.5 million kW by by 2010 if development is to proceed at the present slow pace. Hence, a new geothermal development promotion survey was inaugurated in FY1992. The new project classifies the surveys in Survey A (district survey), survey B (same as previous surveys) and survey C (detailed survey) according to area characteristics and the state of existing data as shown in Fig. 2. This arrangement is aimed at a further reduction of survey risks and development lead time. If, in particular, the results of survey C, including geothermal reservoir evaluation using large-bore production wells (period of four years), are assessed as promising, the development project is to be handed over directly to private-sector companies.

2.3 Deep-seated Geothermal Resources Survey

The development of new areas or the premises expansion of existing power plants is not easy in Japan owing to limitations due to topography and the presence of hotsprings and national parks. Under these circumstances, it appears most efficient to develop deep-seated resources lying beneath the already available shallow resources at a depth of 1-2km as a step to expand the geothermal power generation capacity. NEDO inaugurated in FY1992 the project to ascertain the existence of deep-seated resources at a depth of 3-4km by drilling deep wells in areas where shallow resources have already been developed.

2.4 Other Geothermal Resources Surveys

NEDO conducted wide-area surveys including well drilling of the 3,000m class in Hohi (Oita and Kumamoto Pref.) in central Kyushu in FY1978 - 1985 and Sengan (Akita and Iwate Pref.) and Kurikoma (Miyagi Pref.) in northeastern Japan in FY1980 - 1988. The results of these surveys led to the development at Sumikawa (Akita Pref., 50MW) and Oguni (Kumamoto Pref., 25 - 30MW) by private-sector corporations.

3. Development of Exploration Technology (FY1988-)

In the initial stage of geothermal development the geothermal fluid was thought to be stored in a simple porous-type reservoir. However, further progress of the development led to the finding that the fluid is stored in complex subterranean fractures which are difficult to explore from the ground surface. NEDO, therefore, has been conducting since 1988 technical development of prospecting methods using seismic waves, electromagnetic waves and microearthquakes as methods to ex-

Fig. 2. Flow of exploration survey for geothermal resources

Survey	Nationwide survey → 370,000km²	Area survey → (500 ~ 1000 km²)	District survey ↔ Detailed survey Survey A 100~300km²	Survey B 50~70km²	Survey C 5~10km²	→ Exploitation survey (3 ~ 4 km²)	→ Construction of power generation plant (1 ~ 2 km²)
Purpose	Rough survey of the nationwide distribution of geothermal resources; selection and classification of prospective areas	Elucidation of wide-area geothermal structures and selection of prospective areas for district survey	Confirmation of high-temperature abnormal areas	Confirmation of geothermal reservoirs	Evaluation of geothermal reservoirs	Detailed evaluation of geothermal reservoirs and detailed design	Construction of geothermal power generation plants
Project	Nationwide geothermal resources exploration survey (Phase I)	Nationwide geothermal resources exploration survey (Phase II and III)	Previous geothermal development promotion survey New geothermal development promotion survey			Private-sector companies	
Executing organization	NEDO	NEDO	NEDO			Geothermal development enterprises	Power utilities companies

plore fracture-type reservoirs.

NEDO has already completed basic experiments using seismic wave prospecting method such as VSP (vertical seismic profiling), seismic tomography, high-resolution seismic survey, etc. by means of three wells of 500 - 600m in the basic experimental field using the Tanna fault (Izu Peninsula, Shizuoka Pref.) as a fracture model. It has been conducting tests of prospecting methods in the application experimental field of Yutsubo near Otake Geothermal Power Plant (12.5MW) in Oita Prefecture since 1990.

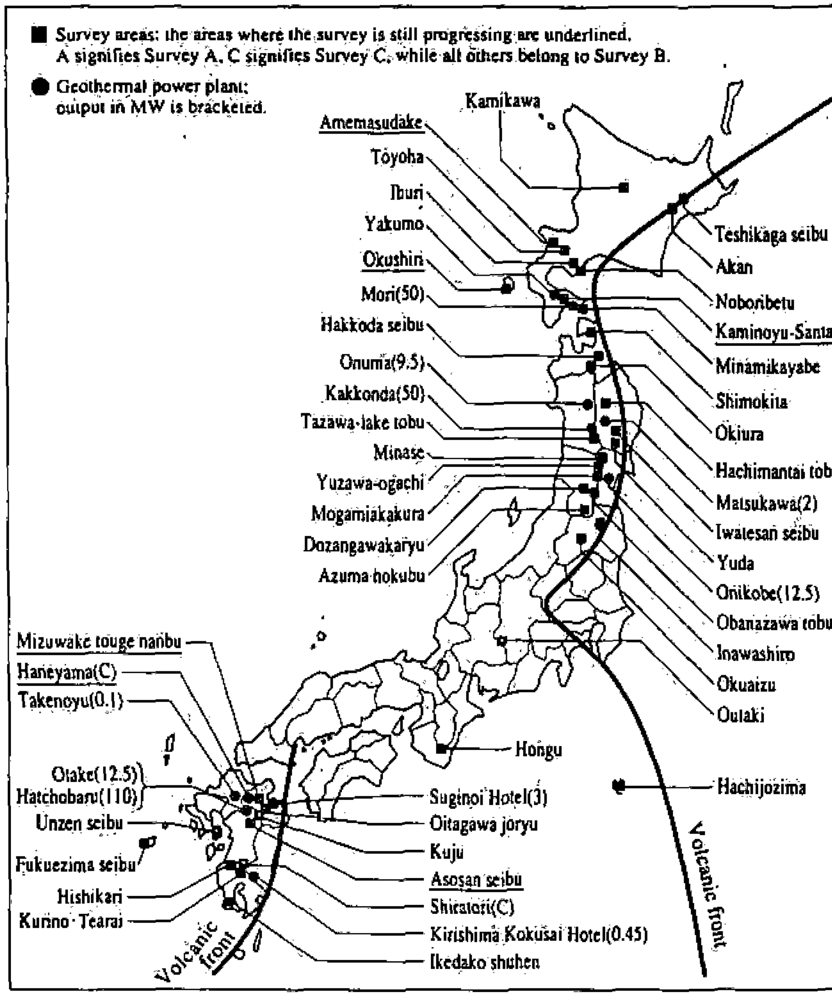
As regards the development of prospecting methods using electromagnetic waves, the array MT (magnetotelluric) method is being developed. This method, using linear arrangement of observation points, features data acquisition of higher accuracy than the previous MT method for prospecting the subterranean resistivity structure using discretely arranged observation points. The development of practical systems is underway for prospecting methods using microearthquakes by exploring geothermal reservoirs with microearthquakes generated by the movement of geothermal fluid.

4. Development of Geothermal Reservoir Evaluation Technology (FY1984 - 1992)

Accurate evaluation of the potential in a geothermal reservoir and the preliminary assessment of the generation capacity based on the potential is extremely important for reducing development risks. NEDO is conducting the development of a simulator for this purpose and application research on simulation methods in the model field.

It developed in Phase I (FY1984 - 1987) the reservoir simulator "SING I" assuming a reservoir made of porous media and the fluid consisting of pure water in gaseous and liquid phases, as well as the in-well dual phase flow simulator "WENG." This was followed by Phase II (FY1988-1992) in which SING II was being developed. This new simulator assumes a fracture-type reservoir and can handle multi-component fluid including CO_2 gas and chlorine. In parallel with the development of simulators, two or three observation wells of about 1,500m in depth have been drilled in four geothermal exploration model fields with different subterranean geological conditions for application research. The in-well test data and the continuous pressure observation data prepare the ground for natural condition simulation in these model fields, history matching simulation and the improvement of the reservoir model.

Fig. 3. Location of Geothermal Development Promotion Survey



5. Diffusion and Promotion Project

NEDO is conducting the following projects for the diffusion and promotion of geothermal energy resources development.

5.1 Demonstration Test of a Small-Scale Geothermal Power Generation System (FY1986 - 1992)

This project was aimed at the development of a small-scale geothermal power generation system that enables efficient operation even under adverse geothermal conditions, such as hot-springs wells with low steam pressure which are not utilized for power generation at present. Specifically, a condensing-type small-scale power generation system of 200kW (turbine entrance pressure of $0.6kg/cm^2$) and a back pressure-type system of 300kW ($3.0kg/cm^2$) have been designed and constructed. A long-term demonstration test is being carried out at Kirishima International Hotel of Kagoshima Pref. using hotsprings wells.

5.2 Demonstration Test of a Small-Scale Binary Cycle Geothermal Power Generation System (FY 1991-)

This project concerns the development of a small-scale binary cycle geothermal power generation system applying medium-high temperature hot water resources of below 200°C which cannot be utilized for direct steam power generation. Specifically, a medium with a low boiling point is heated as a heat source and the obtained steam is then used for power generation. The project calls for the development and demonstration test of a small-scale power generation system (100kW) provided with a screw expander and a medium-class system (500kW) provided with a radial turbine for promoting their applications. ◻

Advancing the Utilization of Geothermal Energy & the Effective Use of Geothermal Water

Masahiko Hayakawa,
Executive Managing Director
New Energy Foundation

Masahiko Hayakawa was born in 1930. He graduated from the Mechanical Engineering Department, Nagoya Institute of Technology, in 1957, and joined MITI in the same year. He later studied in the graduate school of Nuclear Engineering at Iowa State University of Agriculture & Engineering. He has been primarily engaged in the promotion and development of thermal and nuclear power. He became Managing Director of the New Energy Foundation in 1986 and currently serves as its Executive Managing Director.

1. Geothermal Resources and Their Utilization in Japan

1) Estimated Geothermal Resources

JAPAN with its numerous volcanos has abundant geothermal resources with magma continuously discharging a tremendous amount of heat. Since the dawn of history, hot springs have existed at about 2,300 places throughout the country. Some 2,700 geothermal wells were in actual operation as of the end of March 1991, producing about 2,200 kl/min or 132,000 kl/h of hot water.

Assuming the temperature of hot water to be 50°C and that heat exchanges down to 15°C are possible, it can produce 4,600 x 10^3 Mcal/h or 5,350 MWt of thermal energy. The estimation of geothermal resources at 204 locations throughout the country in 1989 showed that the potential of high temperature geothermal fluid of over 150°C existing in depths less than 3km totaled 69,000 MWe (volumetric method, 30 years). Estimated amount of geothermal resources based on prospecting well surveys totaled 25,000 MWe.

Assuming that the steam/water ratio of the geothermal fluid is 1 : 2 in the development of the power generation of 25,000 MWe, directly utilizable thermal energy would amount to 170,000 MWt, or 30 times greater than the total heat energy of existing hot springs.

2) Actual Situation of Utilization

a. Utilization for power generation
The capacity of geothermal power generation, as of the end of March 1992, totaled 270 MWe. Resources in the process of development or development surveys come to roughly the same amount. Hence, total geothermal power generation capacity is estimated to increase to 540 MWe by 1996.

b. Direct utilization
* Assuming that the water in the temperature range between 50°C and 35°C can be utilized for bathing in hot springs, 2,289 MWt is actually being utilized at present.
* If waste water from existing hot springs in the range between 35°C and 15°C can be utilized in the future, 3,051 MWt will become available, markedly expanding the volume of waste heat utilization.
* Some 180~200 MWt produced by hot springs equipment and systems is utilized for various purposes, not including private bathing.

c. Geothermal co-generation
* 500 kl/h of hot water produced during geothermal power generation, average temperature being 75°C, is utilized. Most of the hot-temperature geothermal fluid is re-injected underground without being utilized.
* 35 MWt would become available if the geothermal fluid in the temperature range of 60deg. can be utilized.

2. Present Situation of Diffusion Promotion Policy

1) Promotion of District Energy Development and Utilization

The Ministry of International Trade and Industry (MITI) has formulated the following steps aimed at diversification of utilization forms and stages of natural energy, including geothermal energy, energy derived from waste heat, and products and improvement of the conventional energy supply system within the framework of the policy for promotion of district energy development and utilization.

a. Promotion of commercialization
* Surveys on feasibility and plans for commercialization
* Execution of model project
* Subsidy to general project
b. Promotion of enlightenment and diffusion.
c. Perfection of promoting organization.

The subsidies to geothermal utilization enterprises include the interest subsidy of 3~3.5% for the installation cost of systems for hot water receiving, water intake, heat exchange and transport (not including the cost for drilling geothermal wells), for the enterprise of direct utilization of geothermal energy less than ¥500 million. A geothermal power generation enterprise of less than ¥300 million will be entitled to the same interest subsidy.

The subsidy for geothermal energy utilization totaling ¥6,400 million was granted to 74 projects in the period from 1982 to 1992 and is used for the facilities of district hot water supply, space heating and hot water dispensing, eel culture, horticulture and snow melting. ¥150 million per power generation project of 200KW was granted.

2) Demonstration Studies on Hot Water Supply Projects at Geothermal Power Plants

MITI has been conducting the demonstration survey on hot water supply project at Shizukuishi-cho, Iwate Prefecture, and Kazuno City, Akita Prefecture, since 1980. Geothermal wells for power generation are over 1,000m deep. As the geothermal water contains harmful substances such as arsenic and silicon in high concentration, heat exchange must take place with clean water. Two types of hot water production systems are adopted: the type to evaporate the geothermal fluid (unit capacity: 400 t/h) and the tank and tube type (unit capacity: 11 t/h x 14 units).

3. Promotion of Effective Utilization of Hot Water and Related Tasks

1) Suitable Geothermal Resources and Multi-Stage Utilization

As geothermal resources are a natural occurrence, one should build the utilizing system conforming to the heat quantity, temperature and components of the heat transfer medium.

Geothermal resources are clean, domestically available and renewable energy sources. In order to achieve effective utilization to the maximum extent, heat extraction must be stepped up from surplus water and waste water of hot springs to deep-seated geothermal fluid and underground water. Multiple utilization forms should be considered corresponding to the temperature level of the heat medium, including multi-stage or cascade systems, the application of heat pumps to low temperature fluid and combined utilization of different heat sources according to varying load.

2) Location

Matching the locations of geothermal resources development and heat consumption areas is indispensable. The securing of clean water for heat exchange and adequate reinjecting capacity of original geothermal fluid are also essential tasks.

3) Economical Factor

The heat supply enterprises require heavy investment cost just like other public utility enterprises. The condition for the successful enterprise is rather stringent since supplied hot water must compete with kerosene and other fuels in cost.

The following factors must be considered as essential requirements of the enterprise:
a. High heat demand density;
b. Little fluctuation of heat load;
c. Performance and reliability of systems including the heat exchanger should be maintained; simplified systems are needed ("Keep it simple."),
d. The development of the heat demand market should be possible;
e. Possibility and condition for subsidies.

4) Harmonization with Nature and Society

A larger part of prospective geothermal areas in Japan overlaps with national parks. Harmonization with natural scenery is an essential condition. Present strict administrative control measures for the construction of geothermal power plants are an important factor limiting geothermal power generation and heat supply.

Co-existence with hot spring enterprises, together with the prevention of effect on hot springs, is important from the social standpoint.

5) Development and Demonstration of Technology

We cannot as yet regard as fully established the system engineering for simplifying and ensuring the reliability of design, construction and maintenance of systems and equipment for direct utilization. The pH control method for preventing the deposition of silica scale in the system is being tested. A system for the direct elimination of harmful ingredients from geothermal fluid, besides hot water production using a heat exchanger, should be demonstrated at an early date, from the standpoint of utilizing hot spring resources.

6) Heat Supply Enterprise Setup

Enterprises related to direct utilization are demanded to fulfill several tasks, including the stabilized supply of geothermal fluid, maintenance of equipment reliability not depending on the property of the fluid and the management of survey and development costs. For this purpose, securing of able and dedicated personnel as well as stabilized management organization are indispensable. Local public organizations are awaited to play their role positively in a project to improve the living conditions of regional communities.

7) Preparation of Circumstances for Participation of New Geothermal Enterprises

Enterprise risk should be reduced in order to facilitate the participation of new enterprises in the geothermal project. We need to establish information services, suitable circumstances for the investment related to society and living, and the preparation subsidies and other aids.

Heat supply enterprise needs large funds at the initial stage. Large capital cost should be supported by construction subsidy and other aids.

The information service should take following points into account:
a. Expansion of an organization with functions to collect and analyze the information on direct utilization;
b. The information furnishing service and introduction manuals should be improved;
c. Service and guidance related to feasibility studies should be improved. □

Japan Metals and Chemicals Co., Ltd. Working to Develop Geothermal Resources

Hitoshi Kojima,
Director,
Geothermal Division,
Japan Metals & Chemicals Co., Ltd.

Hitoshi Kojima was born in 1932. He graduated from No. 1 Faculty of Science & Engineering, Waseda University, in 1955, and joined Japan Metals and Chemicals Co., Ltd. in 1956. Since 1981 he has been engaged in the development of geothermal resources. He is now Director and General Manager, Geothermal Division, JMC.

The Company's Outlook

JAPAN Metals & Chemicals Co., Ltd. (JMC) was established in 1917 as a manufacturer of ferro alloys which are indispensable as auxiliary materials for steel making. JMC's advance into geothermal power generation was motivated by the need to secure the electric power needed for operating submerged are furnaces, the equipment for making ferro alloys. The company's business scope has been gradually expanded since its establishment, ranging over chemical fertilizers, electronic materials and computer software. JMC's activities are making substantial contributions to many sectors of society.

Matsukawa Area (Iwate Pref.)

Geothermal development by JMC was touched off in 1952 when a prospecting well drilled in quest of a hot spring here caused an abnormal eruption of a large quantity of steam. The first geothermal power station in Japan was built on this site in 1966 to supply electricity to a ferro alloy plant. As the eruption of steam alone is a rate phenomenon, Matsukawa is often compared to Geysers in the U.S. The capacity of this power plant was gradually expanded and at present it is providing a stabilized output of 22MW.

The natural ventilation type cooling tower, with a height of about 40 meters rearing up in the valley, harmonizes well with the surrounding scenery and has become a notable sightseeing spot.

Kakkonda Area (Iwate Pref.)

The success in Matsukawa became a great stimulus for the development of geothermal resources in other regions. JMC conducted joint development with an electric power company in the Kakkonda Area which is located across a mountain from Matsukawa. As this locality is a so-called water dominated area, several problems had to be solved such as the separation of steam and hot water, the reinjection of hot water into underground layers and the interference of reinjected water with production wells. A geothermal power station was built here in 1978 with a rated output of 50MW. This project was characterized by the division of labor with JMC undertaking the production of steam and an electricity utility company undertaking power generation. JMC thus became the first sales company of geothermal steam in Japan. Kakkonda plant started its operation in the midst of the oil crisis and geothermal energy came into the focus of general attention as a "domestically produced, clean and recoverable energy" in Japan. The success of this plant exerted a favorable effect on the state's energy policy.

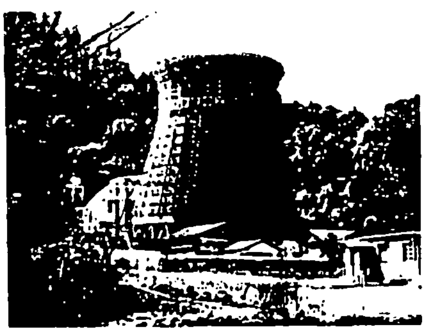
The "Geothermal Hot Water Reinjection System" developed in this area by JMC was commended by the state and the electric power company as an outstanding technology.

The government is at present conducting demonstration tests for utilizing hot water produced through heat exchange between the river water and the geothermal water after the separation of steam for power generation. The results are being looked forward to with much expectation by the local community.

The Kakkonda II Project is progressing in parallel and is scheduled to start operation in 1996 with a capacity of 30MW.

Mori Area (Hokkaido)

Mori Geothermal Power Station, built in a joint project of JMC and an electric power company, started operation in 1982 with an output of 50MW. The geothermal reservoir in this area is characterized by a caldera structure. As the wells tend to be clogged by scales of calcium carbonate, we have established a technology for injecting a scale inhibitor into wells through tubing pipe in order to prevent the growth of scales and thereby to ensure stable steam production.



Cooling Tower of Matsukawa

GRC Pioneer Award

As mentioned above, JMC has been promoting geothermal development projects in three areas with entirely different geological features. Our company received the GRC Pioneer Award from Geothermal Resources Council in 1990 for its success in Matsukawa and persistent activities in the development of geothermal resources.

Japan ranks 6th in the world in total power generation capacity of geothermal equipment. The JMC Group boasts a share of 45% in the total domestic geothermal power generation capacity of 270MW, and we believe that our efforts in the past have won high appreciation from the electric power industry.

R&D and International Cooperation

JMC with its numerous able engineers is in a position to offer wide expertise related to prospecting, drilling and plant design. Besides the maintenance work of already existing facilities, these engineers are pursuing their own research and development, including participation in the state R&D projects promoted mainly by NEDO (New Energy and Industrial Technology Development Organization) as well as overseas cooperation with JICA (Japan International Cooperation Agency).

JMC Geothermal Research & Development Co., Ltd. (JMCD), a company of the JMC Group, has been offering diversified exploration and drilling technology incorporating its rich experience and technical knowhow accumulated over the past 20 years as a torch-bearer of geothermal development. ◘

The Energy Development Programs of Geothermal Energy Research and Development Co., Ltd.

Masao Tsuge,
President
Geothermal Energy Research and Development Co., Ltd. (GERD)

Masao Tsuge was born on May 23, 1936. After graduating from the Department of Mineral Industry at Waseda University, he entered the Ministry of International Trade and Industry (MITI) in 1961 and became director of the Mexico Center of the Japan External Trade Organization (JETRO) in 1985. In 1988, he transferred from MITI to GERD and was promoted to president in 1990.

Foreword

DUE to the Middle East War in 1974, we were faced with a so-called energy crisis, such as shortage of oil for industry, a steep rise in energy prices, etc. This triggered the Agency of Industrial Science and Technology (AIST), MITI to begin a new R&D project – the Sunshine Project for the development of alternative energy sources, namely solar power, geothermal, coal, and hydrogen.

GERD was established to carry out part of the Sunshine Project in November 1975 with investment from 25 private companies (now 32, refer to Table 1). Our company aims are to develop technologies related to geothermal exploration, production of geothermal resources, environmental maintenance and so on, then to promote geothermal energy development in Japan.

So far under the Sunshine Project, we have conducted some 30 projects and four R&D projects are active now. On the tenth anniversary of the project, in September 1984, GERD was commended by AIST, MITI.

GERD also has a consulting business for geothermal energy development. We have applied technologies developed by our R&D and have introduced many excellent foreign technologies, in cooperation with about 40 foreign organizations.

Research & Development

Over the last 10 years the Sunshine Project has been concerned with seven major subjects, with cooperation from other companies.

We are currently involved with the following four subjects:

(a) Development of hot dry rock power generation technology;
(b) Development of technology for increasing geothermal energy recovery;
(c) Development of measurement while drilling system;
(d) Development of exploration technology for fracture-type geothermal reservoir exploration (Array CSMT method).

In this paper, I will outline the development of hot dry rock power generation technology, which, since 1985, has been field-tested in Hijiori, Yamagata Prefecture.

Hot dry rock (HDR) power generation harnesses the heat kept in high-temperature rocks deep in the earth. Since the thermal power available is tremendous, it should be harnessed worldwide, and will probably be a major energy resource for the next generation.

As shown in Fig. 1, a fracture zone is situated between two wells. Water injected through one well is heated in the fracture zone, and heated water in extracted through the other well and used for power generation.

In Japan, basic research has been conducted since fiscal year 1974 as part of the Sunshine Project. Experiments have been carried out with an artificial reservoir constructed in a granite layer 1,800m deep (at approximately 260°C) in Hijiori, Yamagata Prefecture. A plan is underway to construct an artificial reservoir on a larger scale at a depth of 2,300m, and to conduct experiments to evaluate it as a power generation system.

Consulting Business

Our consulting business consists of the following three streams:

(a) Geophysics; magnetotelluric method, the only method for deep resistivity sounding, and EM methods;
(b) Reservoir engineering; PTS (pressure, temperature, spinner) logging, pressure monitoring, and its analysis;
(c) Drilling service; steering tool service, downhole motor service and so on for mainly directional drilling service.

In addition, we try to introduce very common and valuable technologies used overseas to Japanese geothermal developers. When we introduce new technologies, we not only make a technical tie-up with the organization, but also develop software for analyses by employing the technology ourselves. Because we are

Table 1 GERD stockholders

Akita Geothermal Energy Co., Ltd.	Niigata Engineering Co., Ltd.
Chuo Kaihatsu Corporation	Nippon Mining & Metals Co., Ltd.
Furukawa Co., Ltd.	Nippon Steel Corporation
Hokuriku Electric Power Company	Nittetsu Mining Co., Ltd.
Idemitsu Geothermal Co., Ltd.	NKK Corporation
Ishikawajima Harima Heavy Industries Co., Ltd.	Sanki Engineering Co., Ltd.
Japan Metals & Chemicals Co., Ltd.	Sekisaku Co., Ltd.
Japan Petroleum Exploration Co., Ltd.	Sumitomo Metal Mining Co., Ltd.
Kawasaki Heavy Industries, Ltd.	Teikoku Oil Co., Ltd.
Kyushu Electric Power Co., Ltd.	The Dai-Ichi Kangyo Bank, Ltd.
Mitsubishi Heavy Industries, Ltd.	The Industrial Bank of Japan, Limited
Mitsubishi Materials Corporation	The Long-Term Bank of Japan, Ltd.
Mitsui Mining & Smelting Co., Ltd.	TIX Corporation
NEC Corporation	Tohoku Electric Power Co., Ltd.
Nichiboh Co., Ltd.	Toho Zinc Co., Ltd.
Nihon Cement Co., Ltd.	Toshiba Corporation

(32 companies in all, listed in alphabetical order)

well aware of the importance to the client of interpreting the data acquired by new technologies, we of course regard measurement of new technologies as vital.

Development of Technologies Adapted to Japanese Geothermal Fields

We introduced the MT (magnetotelluric) method from the US in 1981, and also started to develop modeling techniques.

Then, we were entrusted with the "Development of high-accuracy MT method", which adapted exploration to Japanese geothermal fields, which was one of the New Energy and Industrial Technology Development Organization (NEDO) R&D projects for 1984 through 1988. Through this R&D, we became the world's top level supplier of equipment, data processing, and analysis. There were three critical features employed in designing the MT method:

(a) complex geologic structures;
(b) abrupt topographic relief; and
(c) high cultural noise.

These are all commonplace problems faced by exploration in Japan, and have played an important role in the successful interpretation of MT data. As a result of this project, we have shown the MT method is useful for geothermal exploration. The following is a list of highlights of the high-accuracy MT system (refer to Fig. 2):

(a) Triple-reference and real time processing;
(b) Simultaneous 4-point measurement capability;
(c) Wide frequency band measurements (0.001Hz-20kHz);
(d) Parallel and serial measurement capability;
(e) Digital data communication via an optical fiber link.

In Future

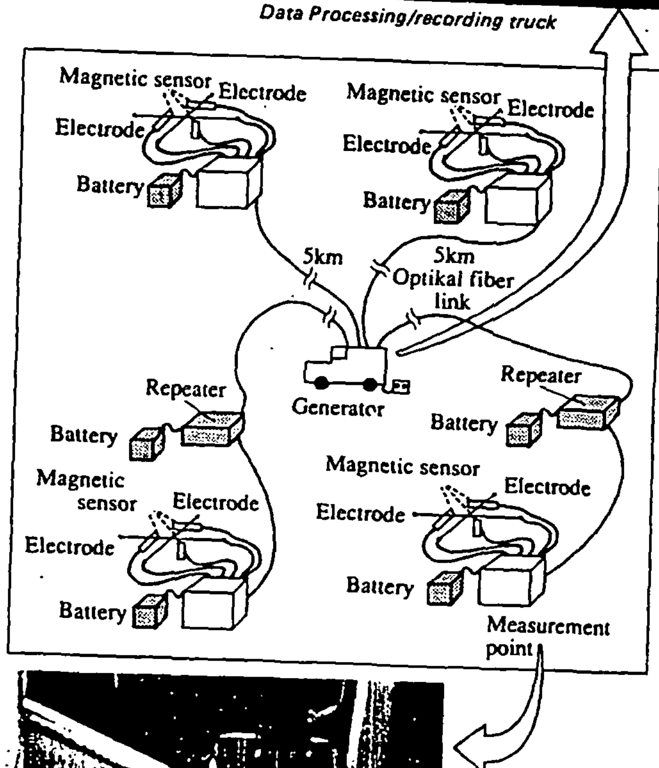
We are determined to continue R&D into new technology developments and for our consulting business to introduce new foreign technologies and hope our activities will contribute to future development of Japan's geothermal resources.

We would also like to contribute to the New Sunshine Project, a new policy for MITI. This may enable us to apply technologies we have developed and improved through R&D and our consulting business to foreign geothermal development.

We are sure our activities can be of help both inside and outside Japan, from both geothermal development and global environmental standpoints. ◻

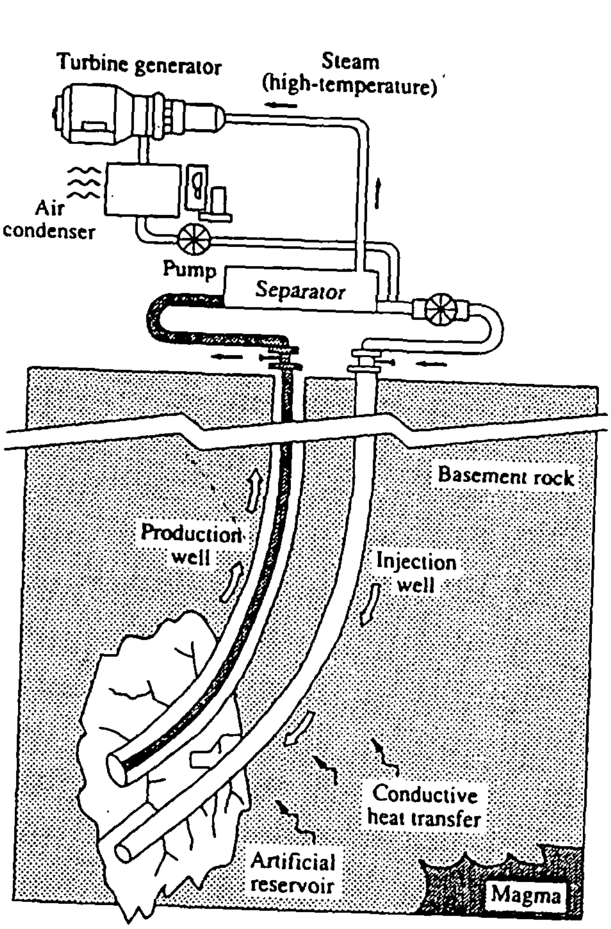
Fig. 2. The high-accuracy MT system, which has the capability of simultaneous measurements at 4 MT sounding stations with real time triple-reference data processing.

Data Processing/recording truck



Equipment at measurement point

Fig. 1 Concept for hot dry rock power generation



Kyushu Electric Power Company Promotes the Development of Geothermal Energy

Kuniyoshi Ishii graduated from the Electric Engineering Department, Faculty of Engineering, Kyushu University, in March 1957 and joined Kyushu Electric Power Co., Inc. in April of the same year. He was appointed General Manager of the Thermal Power Department in June 1987 and Director of the company in June 1991.

Kuniyoshi Ishii,
Director,
Thermal Power Department,
Kyushu Electric Power Co., Inc.

1. Foreword

JAPAN as one of the leading volcanic countries of the world has been known to have geothermal resources since ancient days. Geothermal energy was familiar to all people in Japan mainly for bathing in hot springs. But it was only about 20 years ago that geothermal energy was conceived of as a source of electric power. Since then 12 geothermal power plants have started operation with a total output of 270,000kW.

The development of geothermal resources faces numerous difficulties. However, geothermal energy, as one of the few types of clean and domestically available energy, should be promoted by all means from the standpoint of the national energy situation and the global environment.

I would like to explain briefly the history of geothermal development by Kyushu Electric Power Co., (hereafter abbreviated KEPCO), its present situation and problems, and the future outlook.

2. The History of Geothermal Energy Development by KEPCO

KEPCO started the survey on geothermal resources as early as 1945-50 and constructed Japan's first geo-

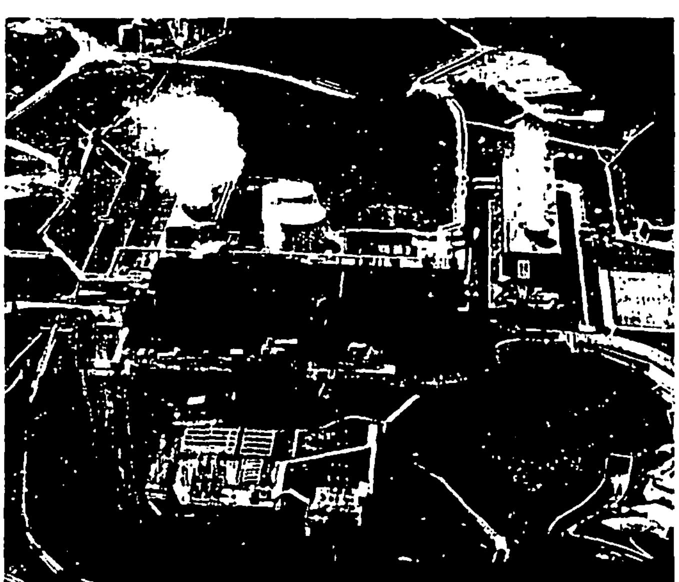
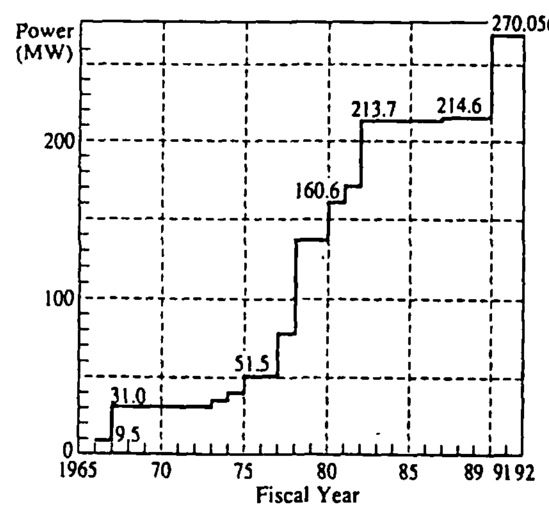
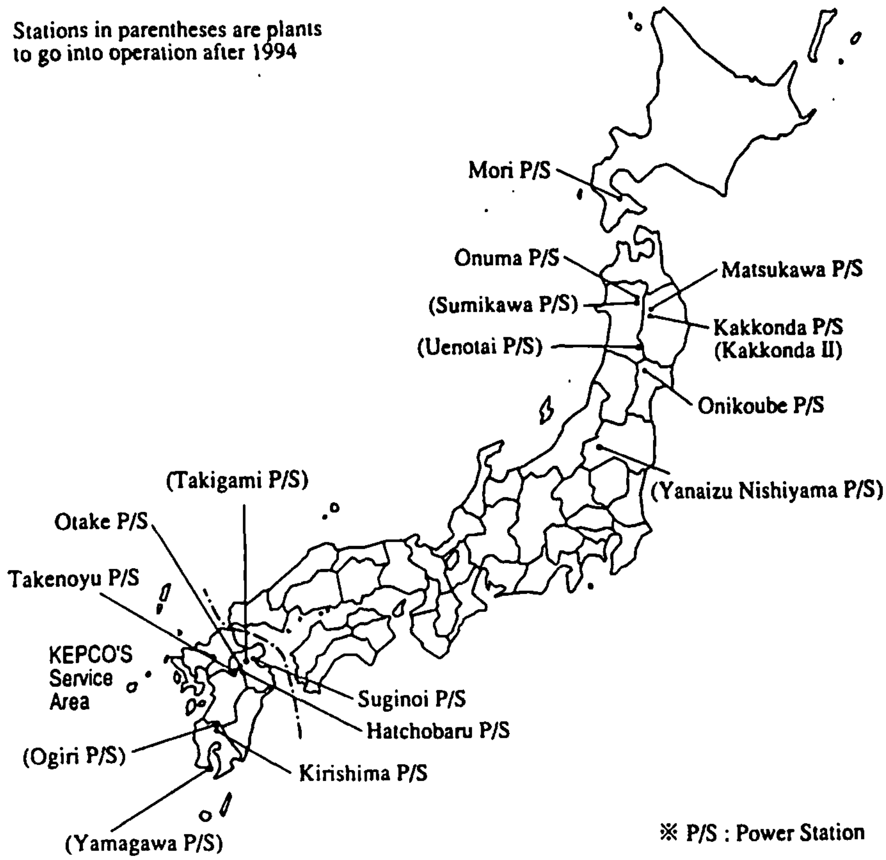


Fig. 1 Power Generating Capacity of Japan's Geothermal Power Plants



thermal power station for commercial use in 1967 with a capacity of 12,500kW in Otake, Oita Prefecture. Based on this success, the company built in 1977 the No. 1 Hatchobara Geothermal Power Station, a full-scale commercial geothermal power station, in Hatchobara, Oita Pref. adjacent to the Otake plant, and attained a rated output of 55,000kW in 1980. It was followed by the putting into commission of the No. 2 plant in June 1990 with an output of 55,000kW. KEPCO is probably the only company in the world that carries out an integrated development of geothermal resources covering survey, development, construction of the power plant and its management. We are positively promoting geothermal development, being aware that it contributes to effective utilization of domestic energy resources and to the preservation of the global environment.



3. Problems Related to Geothermal Power Development

The development of geothermal resources is currently being carried out at seven localities in Japan in the form of joint projects by electric power utility companies and developers. But the total power generating capacity of all these plants far falls short of the target of 1 million kW by the year 2000, as set by the Electricity Utility Industry Council.

(1) Economic feasibility

Electricity is the only product resulting from geothermal development, with no by-products such as mineral resources that may bring profit to the industry. Geothermal power development is demanded to possess an economic feasibility comparable to that of other energy types such as petroleum, coal, atomic energy and LPG. However, the technology related to prospecting and drilling still has numerous gaps and a geothermal development project is always attended with more risks than conventional energy. In particular, a long period of time is needed from the survey to development and power generation and is very unfavorable to economic feasibility.

(2) Problems related to legal controls

Prospective geothermal areas are often located in or near sightseeing spots and hot springs. Development should not interfere with the existing landscape. Furthermore, many geothermal resources are located in national parks where development is forbidden.

Since a law directly controlling geothermal power development is absent at present, the developer must follow complicated legal procedures under several jurisdictions including laws regarding forestry, hot springs and parks.

(3) Social environment

As stated in the previous section, prospective geothermal areas frequently overlap with old hot springs. Development is impossible without prior understanding and adjustment with local communities, which is very time-consuming. Adequate steps should be taken to protect the environment and to ensure co-existence with local communities.

4. Future Prospect

The solution of the above-mentioned problems is a prerequisite for successful geothermal power development. Establishment and improvement of prospecting technology are indispensable for enhancing economic performance. Development risks may be reduced and the evaluation of resources may be expedited by conducting sufficient surveys and adequate analysis utilizing advanced technology.

The economic performance is expected to be improved further through the currently enforced subsidy system and low interest loan system of the state to support development projects and the New Geothermal Power Development Promotion Surveys introduced in 1922. We hope for further expansion and improvement of these institutions.

The problems related to national park law and local communities may be solved by strict observance of harmony with the environment, contributions to the local community through effective utilization of hot water and the construction of power stations that tend to enhance the local image. The creation of a law pertaining to geothermal development is also desirable from this standpoint.

The development of geothermal resources thus seems to be indicated from the standpoint of effectively utilizing domestic energy sources and protecting the global environment. KEPCO is resolved to work for the solution of these problems and to promote the development of technology for exploiting precious domestic geothermal resources. ◘

Geothermal Energy Resource Development by the Electric Power Development Co., Ltd.

Terumi Ushijima,
Director,
Geothermal Engineering,
R&D Department,
Electric Power Development Co., Ltd.

Terumi Ushijima was born in November, 1935. He graduated from the Civil Engineering Department of Kumamoto University in 1959, joining Electric Power Development Co. Ltd. (EPDC) the same year and was engaged in hydro and coal thermal power development projects. Since July 1991, he has been the Director of Geothermal Engineering Division of Research & Development Department.

1. Foreword

ELECTRIC Power Development Co., Ltd. (EPDC) was established as a state policy corporation for carrying out large-scale development of electric power resources in the country's reconstruction after World War II. It developed gigantic hydroelectric power resources, including the Sakuma Dam, and built thermal power plants burning domestically produced coal, large pumping-up power plants and thermal power plants using imported coal. The power generation facilities developed by EPDC are comprised of 55 hydroelectric power plants with a total capacity of 7,630,000kW and seven thermal power plants with a total capacity of 4,650,000kW, totaling 12,280,000kW. The power transmission lines for them have a cumulative length of about 2,271km. EPDC is also engaged in wide-area projects linking electricity utility companies in each district. It has extended overseas assistance to 39 countries of the world.

EPDC started the collection and analysis of data in 1960 as a preparatory step for the development of geothermal resources. It selected six prospective areas in Japan in 1961, which were regarded as promising in view of geological structure and freedom from hot springs and other impediments. They were Kussharo, Noboribetsu (Hokkaido), Onikobe (Miyagi Pref.,), Oshirakawa (Gifu Pref.), Tsukahara (Oita Pref.) and Shijuku (Kagoshima Pref.). After working out the basic survey plan, EPDC commenced on-the-spot surveys in these areas in 1962. The surveys led to the conclusion in 1964 that Oshirakawa Area and Onikobe Area were the most promising sites. Prospecting wells were drilled accordingly. However, Oshirakawa Area was later dropped because it was located within the special conservation area of a national park at the foot of Mt. Hakusan (Gifu Pref.). Onikobe Area was judged as more suitable in 1965 and after that the surveys were concentrated in that district.

2. Development of Onikobe Geothermal Power Station

Onikobe Area is located at about 50 minutes by car from Naruko Hot Springs of Miyagi Prefecture. It finds itself in a ring-shaped area called "Onikobe Caldera" where three geothermal manifestation called Arayu Jigoku (Hell), In Jigoku and Katayama Jigoku still constitute an active geothermal phenomenon.

Onikobe Geothermal Power Station is located in Katayama District. Prospective wells from GO-1 TO GO-12 were drilled and several surveys were conducted using electric prospecting (Schramberger method of C.G.G. Co.), refractive method and reflective method. We confirmed that high-quality and high-temperature steam is available at a relatively shallow stratum of 300m deep. On the other hand, two deep wells (1,350m and 1,300m. respectively) produced a steam jet of 30-40 t/h. However, this geothermal fluid was found unsuitable for power generation as it contains hydrochloric acid with pH of 2.6-3.2 and corrodes the strainer in a short period of time. The drilling of deep wells was discontinued afterwards.

Onikobe Geothermal Power Station began to operate with an output of 9,000kW on March 19, 1975, and the power was stepped up to 12,500kW after April 1976. The plant has already been operating for 17 years.

3. Commissioned Execution of Survey of Large-Scale Deep Geothermal Development with regard to Environmental Conservation

The oil crisis in 1973 was the direct motive for the planning and development of new energy resources after 1975. "Geothermal energy" came to the fore as the most fruitful energy source alternative to petroleum.

EPDC has carried out the "Environmental Protection Demonstration Survey for Large-Scale Deep-Seated Geothermal Power Generation" since FY1978 as a commissioned task of the Agency of Natural Resources and Energy within the framework of the Sunshine Project.

The purpose of this survey is to expand geothermal power generation by utilizing hitherto untapped deep-seated geothermal fluid of high temperature and pressure as a part of the state policy to expand the utilization of domestically available energy resources and to diversify energy supply. Surveys were mainly conducted in the Hohi District of Northern Kyushu in order to grasp deep-seated geothermal reservoir in wide area, to ascertain the feasibility of large-scale power generation and to assess the effect of collection and re-injection of geothermal fluid on the environment. EPDC accepted the survey project from New Energy and Industrial Technology Development Organization (NEDO) which was established in October 1980, and completed the survey in 1985 after establishing the R&D Department and Geothermal Development Office within the latter.

The surveyed site, called Hohi District, is located at about 40km to the southwest of Beppu City and covers an area of about 200km^2 (15km from west to east and 14km from north to south) stretching over Oita and Kumamoto prefectures.

This survey took place in close cooperation with the government, universities and the private sector. The latest high-precision methods were employed for surveying and analysis of data. The geothermal reservoir of Hohi District was investigated by means of five prospecting wells of the 3,000m class, 10 holes of the 1,500m class for surveying the geological structure, seven 500m geothermal wells and 82 80m test wells.

Modern equipment and methods were mobilized in the ground survey including gravity methods, analysis of terrestrial magnetism and electricity and aerial magnetism. These methods are going to exert a tremendous influence on future geothermal surveys. In particular, new methods of prospecting and analysis were taken over by the subsequent geothermal development promotion surveys.

4. Commissioned Execution of Survey and Development Tasks Related to Binary Cycle Power Generation

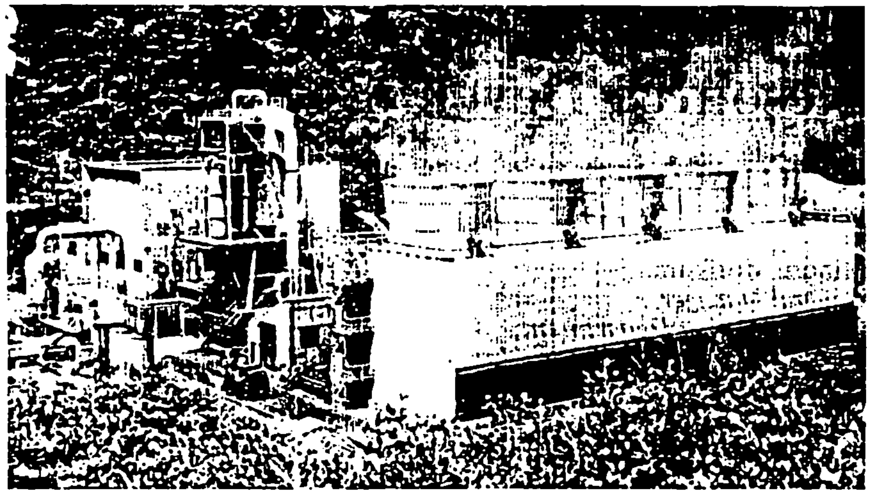
The research and development of binary cycle geothermal power generation in Japan was started simultaneously with the Sunshine Project in 1974. Operating tests were conducted until 1978 for evaluating technical feasibility at a pilot plant of 1,000kW. EPDC accepted the commissioned task of comprehensive equipment control and evaluation of the 1,000kW plant from the Agency of Industrial Science and Technology from FY1977 to 1979. Test operation and analysis were carried out in FY1978 and 1979 to evaluate technical feasibility.

It was followed by research on a demonstration plant of the 10,000kW class after FY1979. EPDC took charge of the overall coordination and the setting of field and economic conditions as a part of the plant concept design. The development of the downhole pump and the evaluation of the underground geothermal fluid resources were further research themes. We surveyed Sugawara District of Oita Pref. and obtained hot water corresponding to 20,000kW using three production wells. The presence of geothermal fluid resources sufficient for power generation of 10,000kW has been thereby confirmed.

Although the development of the downhole pump was hampered by several troubles, we successfully concluded in November 1992 the operating test for 1,000 hours under the condition of 200°C. On-location tests were started at Sugawara in February of this year, and the consecutive construction of a 10,000kW demonstration plant is planned if all goes well.

5. Development Survey of Oguni Area

Whereas Survey of Large-Scale Deep Geothermal Development with regard to Environmental Conservation is progressing, Oguni Area was found to be suitable for conventional geothermal power generation and its development survey was entrusted to EPDC in autumn of 1983. This site is located in the northeastern part of Kumamoto Pref. adjacent to and partially overlapping Oita Pref., covering an area of about 20km^2. The reservoir simulation evaluation is being conducted at present incorporating the results of long-term steam production tests conducted since autumn of last year. The expertise will serve for mapping out the power generation program.



Onikobe Geothermal Power Station

6. Overseas Technical Assistance

Our company is carrying out international technical assistance, endowed as it is with outstanding technical expertise on geothermal development and the ability to conduct development surveys in wide ranges.

For instance, EPDC conducted geothermal development surveys in Argentina from 1988 to 1992 at the request of JICA (Japan International Cooperation Agency). The survey took place in the Andes close to the border to Chile. The slim hole of NQ size was drilled and reached a steam reservoir at a depth of 1,065m, with successful production of 10t/h of steam.

The present development program calls for the power generation of 30,000kW as the first phase, taking into account the estimated energy demand of the region and hitherto available information.

7. Conclusion

The actual task of geothermal power generation in EPDC is mainly carried out at its Geothermal Engineering Office, R&D Department. The accumulation of diversified techniques and expertise is indispensable for the promotion of geothermal development. Our company is pursuing the development in close liaison with related firms in each business sector. It should be remarked in this connection that the concentration of total technology power in one group is very advantageous for the progress of development.

Geothermal energy is the most realistic, clean and domestically available type of energy alternative to petroleum. The demand for its development is destined to grow in the future. On the other hand, geothermal development faces several difficulties because most of the prospective sites are located within national and quasi-national parks or else the resources are of low quality and are attended with high risks. Moreover, the present development projects entail huge costs for surveys and well drilling, so that geothermal power is more expensive than other energy resources.

Further effort for winning understanding and support for geothermal development is essential for steady development of underground energy in the optimal composition of electric power sources in coming days. Enterprises engaged in the development of geothermal resources should demonstrate the safety and usefulness of this new energy source with actual results in order to obtain general support. Under these circumstances, Electric Power Development Co. as a state policy corporation intends to pursue the development of geothermal resources with new determination. □

Tohoku Electric's Geothermal Resource Development Projects

Minoru Morikuni,
General Manager,
Thermal Power Department,
Tohoku Electric Power Co., Inc.

Minoru Morikuni was born in 1936. He graduated from the Electric Engineering Department, Faculty of Engineering, Hokkaido University, in 1959, and joined Tohoku Electric Power Co., Inc. in the same year. He was mainly engaged in the planning of thermal power stations. He became general manager of Thermal Power Department in 1990 and concurrently one of the senior officers of the company in 1991.

Abundant Geothermal Resources in Tohoku

GEOTHERMAL power is one of the relatively abundant energy resources available in Japan proper. The Tohoku District of northeastern Japan is believed to account for about 30% of geothermal power resources existing in our country. There are four geothermal power stations, including private plants, in this area with a total approved generating capacity of 94,000kW, or 35% of Japan's total geothermal power generating capacity.

The development of geothermal resources by Tohoku Electric Power Co., Inc. started in 1978 with the putting into commission of the Kakkonda Geothermal Power Station in Shizukuishi-cho, Iwate Prefecture, with an output capacity of 50,000kW.

Based on the experience accumulated in the course of this project, Tohoku Electric Power is carrying out the development of three additional geothermal power stations at Uenotai, (Yuzawa City, Akita Pref.), Sumikawa, (Kazuno City, Akita Pref.). Yanaizu Nishiyama, (Yanaizu-cho, Fukushima Pref.), and an expansion of the Kakkonda Geothermal Power Station in Shizukuishi (Fig. 1).

Development of the Kakkonda Geothermal Power Station

The development of this plant was originally planned by Japan Metals & Chemicals Co., Ltd. (JMC) in 1969, and Tohoku Electric Power joined the project in 1970. It is a joint project between these two companies with JMC undertaking the steam production and Tohoku Electric undertaking the power generation.

This power station has the following distinctive features:

(1) The closed system for re-injection of high-temperature geothermal fluid is adopted.

(2) As this power plant is located within a national park, care is taken to preserve and maintain harmony with the natural landscape. Specifically, the main equipment is housed in a building, and the area of the premises is reduced with the adoption of a geothermal well base.

(3) Anti-corrosive material is employed inside the turbine. The cable coating material is sulfur-resistant.

(4) The operation is controlled with a remote monitoring system located in Shizukuishi at a distance of 23 kilometers.

This power station has operated for 13 years without major accident. The availability comes to 90%.

Development and Expansion of Plants

The geothermal development method of Tohoku Electric Power is characterized by the joint project with the geothermal field developer taking charge of steam production. Development is accomplished in the three steps cited below, while evaluating geothermal reserves and economical feasibility.

1. Establishment of a joint survey and study committee;
2. Signing of a contract for promoting the project;
3. Signing of the final agreement.

The development plan for four sites is summarized in Table 1.

(1) Uenotai Site

Dowa Mining Co., Ltd., the parent company of Akita Geothermal Energy Co. which is conducting actual development, started the survey in 1971. The two firms have been carrying out survey and study for joint development since 1981. A steam production volume of 270t/h has been confirmed using simultaneous continuous steam production tests using prospecting wells.

The capacity has been set at 27,500kW on the basis of the evaluated geothermal reserves including the production forecast for the next 30 years. The final agreement was concluded in 1989 and the application for site approval was submitted to local authorities in 1990.

An environment survey was simultaneously conducted by developers for one year and the development plan was approved by the Electric Power Development Coordination Council of the state in the spring of 1991, after due procedures for environmental assessment.

Construction commenced in spring of 1992 after the procedures required by the Electricity Utility Industry Law and the regulation regarding the termination of protective forests were met. Construction work is progressing smoothly for the scheduled start of commercial operation in 1994.

(2) Sumikawa Site

Mitsubishi Material, Corp. (formerly Mitsubishi Metal Corp.) started the basic survey of Sumikawa together with Onuma Geothermal Power Station in 1965. The survey at Sumikawa was stepped up in 1974. Tohoku Electric Power joined the survey in 1985. Steam production of 420t/h was confirmed using the simultaneous continuous steam production test with prospecting wells. The evaluation of steam production volume and estimated geothermal reserves showed that power generation of about 50,000kW is possible. The basic contract was concluded and the application for the site of a geothermal power station was submitted to local authorities in 1990.

The development plan was approved by the Electric Power Development Coordination Council in spring of 1992 after the due procedures of environmental assessment. Construction is to start in spring of this year with the scheduled start of operation in 1995.

Fig. 1. Geothermal Power Stations and Geothermal Development Sites in Tohoku District

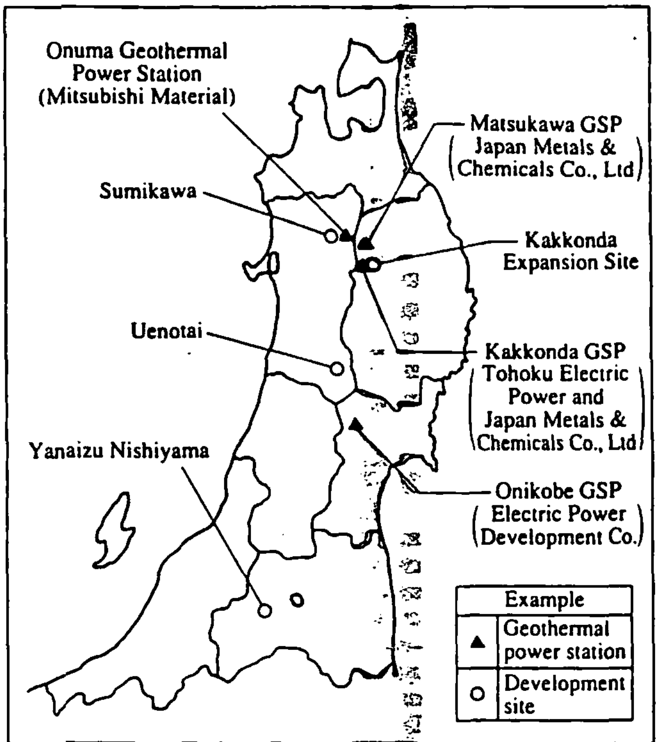
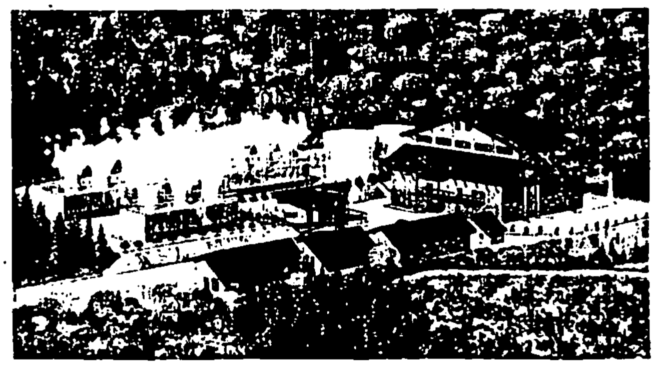


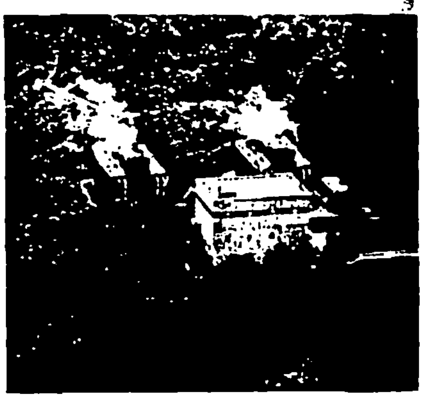
Table 1. Geothermal Development Schedule

Name (site)	Output capacity (kW)	Schedule (year, month)	Developers of steam production plant
Uenotai GSP (Yuzawa, Akita Pref.)	27,500	EPDCC 1991 - 3 Construction start 1992 - 4 Operation start 1994 - 3	Akita Geothermal Energy
Sumikawa GSP (Kazuno, Akita Pref.)	50,000	EPDCC 1992 - 3 Construction start 1993 - 4 Operation start 1995 - 3	Mitsubishi Material
Yanaizu Nishiyama GSP (Yanaizu, Fukushima Pref.)	65,000	EPDCC 1992 - 12 Construction start 1993 - 6 Operation start 1995 - 5	Oku Aizu Geothermal
Kakkonda No. 2 GSP (Shizukuishi, Iwate Pref.)	30,000	EPDCC 1993 - 3 Construction start 1994 - 4 Operation start 1996 - 3	Tohoku Geothermal Energy

Note: According to Facility Plan FY1992



Artist's Conception of Uenotai Geothermal Power Station (Operation scheduled to start in 1994; capacity 27,500kW)



Kakkonda Geothermal Power Station (Operation started in 1978; capacity 50,000kW)

(3) Yanaizu Nishiyama Site

Oku Aizu Geothermal Co. and its parent company, Mitsui Mining Co., Ltd. started a basic survey of this area in 1974. A basic survey by the state took place in FY1976 and 1977, and the geothermal energy development promotion survey in FY1982 and 1983. Oku Aizu Geothermal took over the survey and development in FY 1984 based on previous results.

Tohoku Electric Power and Oku Aizu Geothermal inaugurated a joint survey in 1986. Steam production volume of 470t/h was confirmed with tests using prospecting wells. Additional wells confirmed steam production capacity of 170t/h, so that total steam production capacity comes to 640t/h. This confirmed steam volume and the evaluation of geothermal reserve led to the decision to set the unit capacity at 65,000kW, the greatest in Japan.

The final agreement was signed in 1991 and was submitted to local authorities. The plan was approved by the Electric Power Development Coordination Council in autumn of 1992 and the power plant is slated to start operation in 1995.

(4) Expansion Project at Kakkonda

The site is adjacent to the existing power station. Survey and study for expansion are being conducted by Tohoku Geothermal Energy Co., which undertakes actual development work, and its parent company, JMC. Steam production of 170t/h was confirmed using prospecting wells. The evaluation of the deep-seated geothermal reserves at a depth of 3,000m was conducted for the entire area.

They next drilled deep prospecting wells for evaluation of deep-seated reservoirs. Steam production of 150t/h was confirmed using these deep wells, adding up to 320t/h.

This confirmed steam production capacity and the evaluation of geothermal reserves led to the decision to expand the power generation facilities by 30,000kW. The final agreement was signed in 1992 and submitted to local authorities for approval. Preparations are underway for deliberations at the Electric Power Development Coordination Council in spring of 1993. The construction of the power station is to start in 1994 and to be completed in 1996.

For Improvement of the Global Environment and the Revitalization of Local Economies

The development of renewable energy is coming into focus in connection with the global environment. Geothermal power generation is such energy. As stated above, our company is energetically promoting geothermal development at four sites with a total output capacity of 172,500kW. This project is expected to make a contribution, however slight, to improvement of the global environment. We also hope that the construction and operation of geothermal power stations will be a great stimulus to the revitalization of the local economies. ◘

GEOTHERMAL DEVEROPMENT
in
FUSHIME FIELD

1. Introduction

Since 1977, Japan Petroleum Exploration Co., Ltd. (JAPEX) has carried out an active drilling and well testing in the Fushime field. In addition JAPEX has completed geological, geophysical and geochemical surveys using various tech niques.

As a resurt, the 30Mw power generating potential during relatively long term in this field has been recognized based on the above surveys including a comp uter simulation.

After the recognition, JAPEX Geothermal Kyushu Ltd. wholly sponsored by JAPE X(100% share holder) has been established as the actual operating company at Dec. 1988.

Investigation, exploration historys and future development schedule in this field as follows.

2. Investigation, exploration historys and future development schedule

(1) Investigation, exploration historys

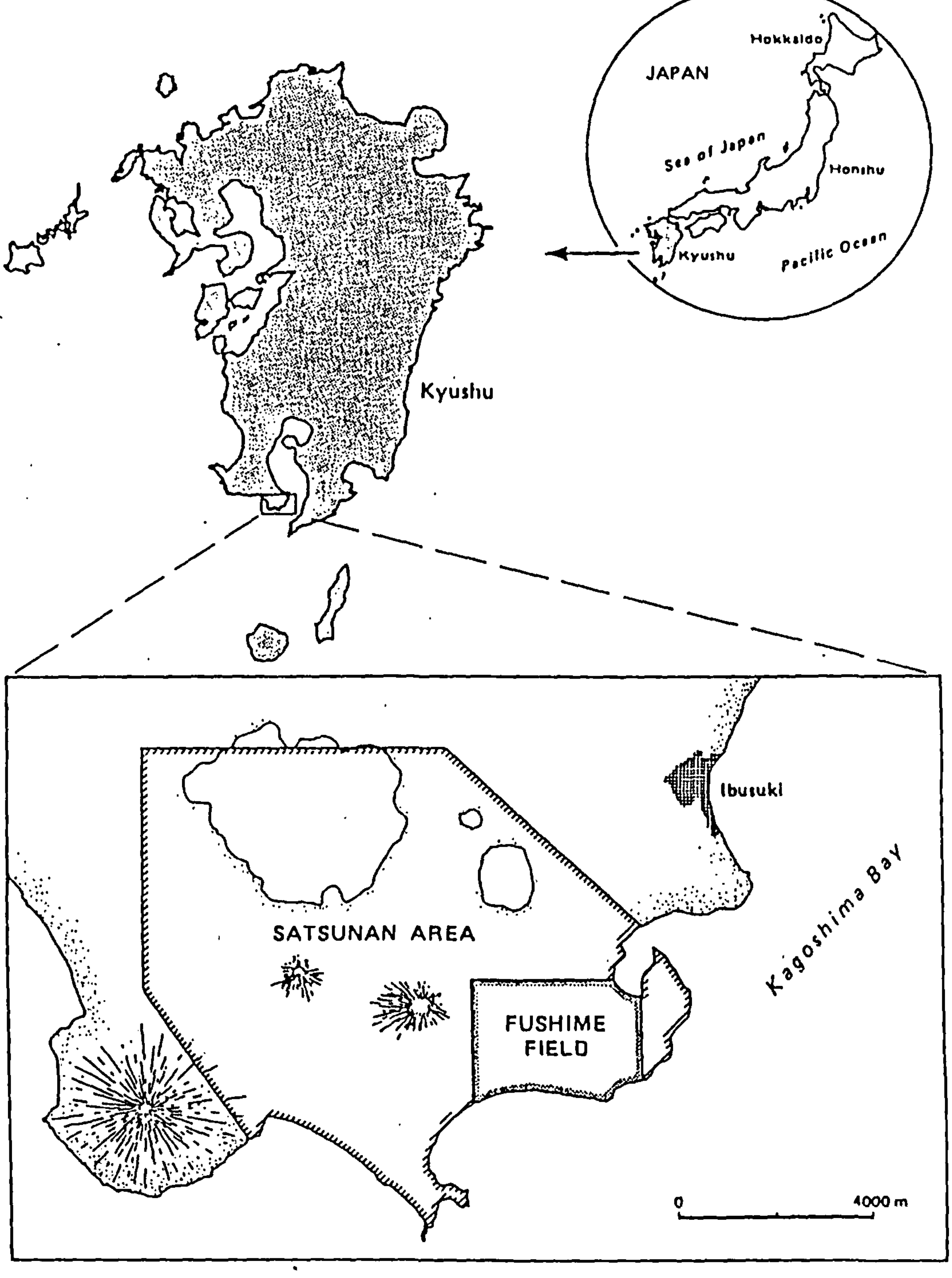
Year	Item
1977, 1981, '82, '84, '85, '86	Geological Surveys Fushime～Nagasakibana, Yahazudake, Vicinity of Lake Ikeda
1977 ～ 1986	Geophysical Surveys Gravity, Sallow Temp., Electrical, Magnetotelluric, Aeromagnetic, Reflection Seismic, Microearthquake
1981, 1983 ～ 1986	Geochemical Surveys Hg, CO_2, Rn, As, He etc.
1977, '78, 1980～1985, '88, '89	Exprolation Drilling(Total 18 Wells) • Prodaction : 9 wells • Injection : 4 wells • Abandonment : 5 wells
Jan. ～ Feb. 1990	30Mw(*) Full Scale Discharge Test • Separation Press. : 11ata(183℃) • Production Steam : 245.8 t/Hr • Production Water : 258.3 t/Hr • Steam/Water Ratio : 0.95

(*)An equivalent steam of 30Mw : 225 t/Hr

(2) Development Schedule

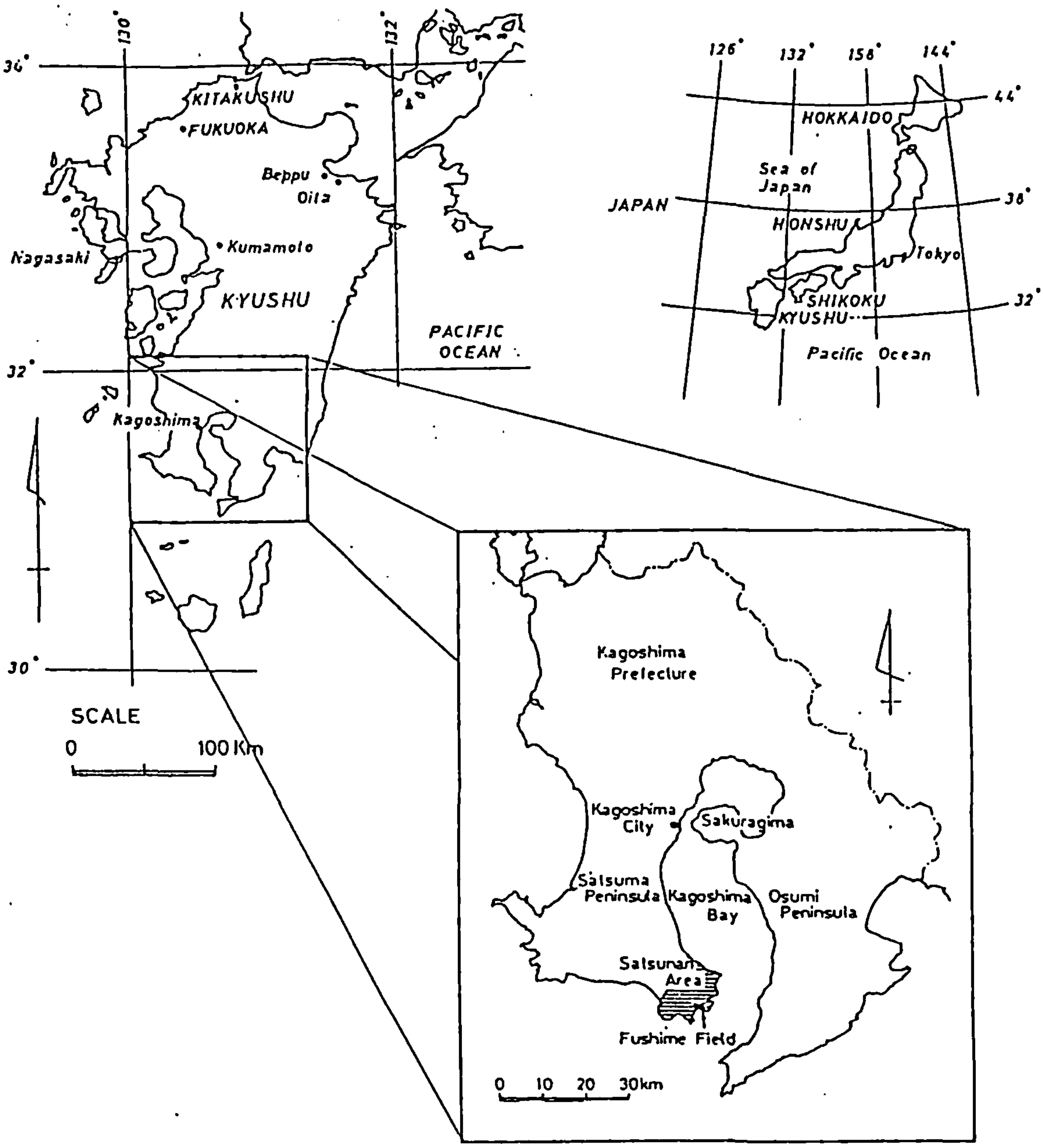
Year	Item
Sep. 1990~Apl. 1992	Environmental Investigation and Assessment
May 1992	Submit to MITI the above Report
Nov. 1992~Jun. 1993	Lay at Electric Power Development Control Council and get a permit of Construction
Jul. 1993	Start Development and construction(Period : 20 mo.)
Mar. 1995	Start Commercial Operation

Nov. 1990



Hokkaido
JAPAN
Sea of Japan
Honshu
Kyushu
Pacific Ocean
Kyushu
Ibusuki
Kagoshima Bay
SATSUNAN AREA
FUSHIME
FIELD
0
4000 m

The Fushime geothermal field



980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
	○	○		○	○	○				
		325.0km 1,069points								
	1m depth 155 points		1m depth 200 points							
	Hg, CO_2, Rn, As,		Hg, CO_2,	Rn, Hg, H_2, He,	Rn, Hg,	Rn, Hg,				
	20km	tubel method 90points			tubel method 132points					
		80points								
		2,023km								
						5.5km				
months		6 months						cotinuous		
G-3										
G-2D 050m G-3 600m	SKG-4D 2,004m SKG-5 2,501m	SKG-6D 2,190m SKG-7D 2,505m SKG-8D 2,505m	SKG-9 2,045m SKG-11D 1,902m SCG-1 redrilling 1,506m	SKG-3(a)D 2,112m SKG-10D 1,935m SKG-12D 1,702m SKG-13D 755m	SKG-14D 1,867m			SKG-15D 1,093m SKG-16D 2,139m	SKG-17 2,000m SKG-18D 2,105m	Full scale discharge Test (30MW)

Item \ Year	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
geological	○				○	○		○	○	○	
gravity		224.7km 836 points				325.0km 1,069points					
shallow temperature	20m depth 75 points	50m depth 43points			1m depth 155 points		1m depth 200 points				
geochemical					Hg, CO_2, Rn, As,		Hg, CO_2,	Rn, Hg, H_2, He,	Rn, Hg,	Rn, Hg,	
electrical					20km	tubel method 90points			tubel method 132points		
magnetotelluric			18.5km² 70 points			80points					
aeromagnetic						2,023km					
reflection seismic		18.3km								5.5km	
microearthquake				2 months		6 months					
heat flow measurements											
enviromental survey	H_2S	H_2S									
well shooting		SKG-1		SKG-3							
exploration drilling	SCG-1 1,195m	SKG-1 2,005m		SKG-2D 2,050m SKG-3 2,600m	SKG-4D 2,004m SKG-5 2,501m	SKG-6D 2,190m SKG-7D 2,505m SKG-8D 2,505m	SKG-9 2,045m SKG-11D 1,902m SCG-1 redrilling 1,506m	SKG-3(a)D 2,112m SKG-10D 1,935m SKG-12D 1,702m SKG-13D 755m	SKG-14D 1,867m		S 1 S 2

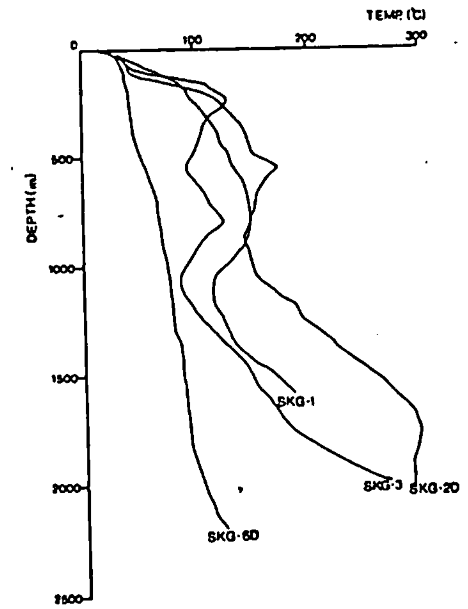
FUSHIME FIELD

COMPONENTS OF GEOTHERMAL WELL PRODUCTION

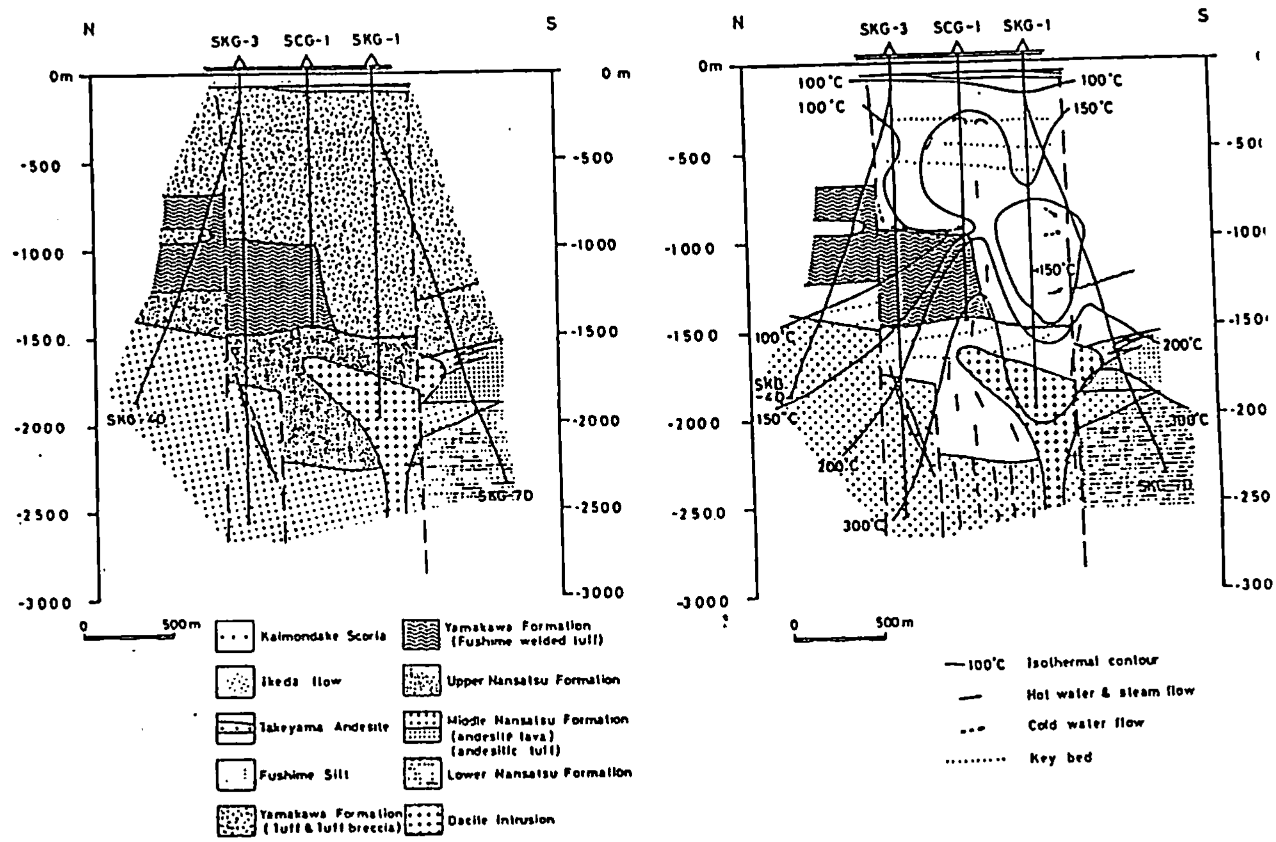
March 23. 1990 Kagoshima Div. Off. Japex Geothermal Kyushu Ltd.

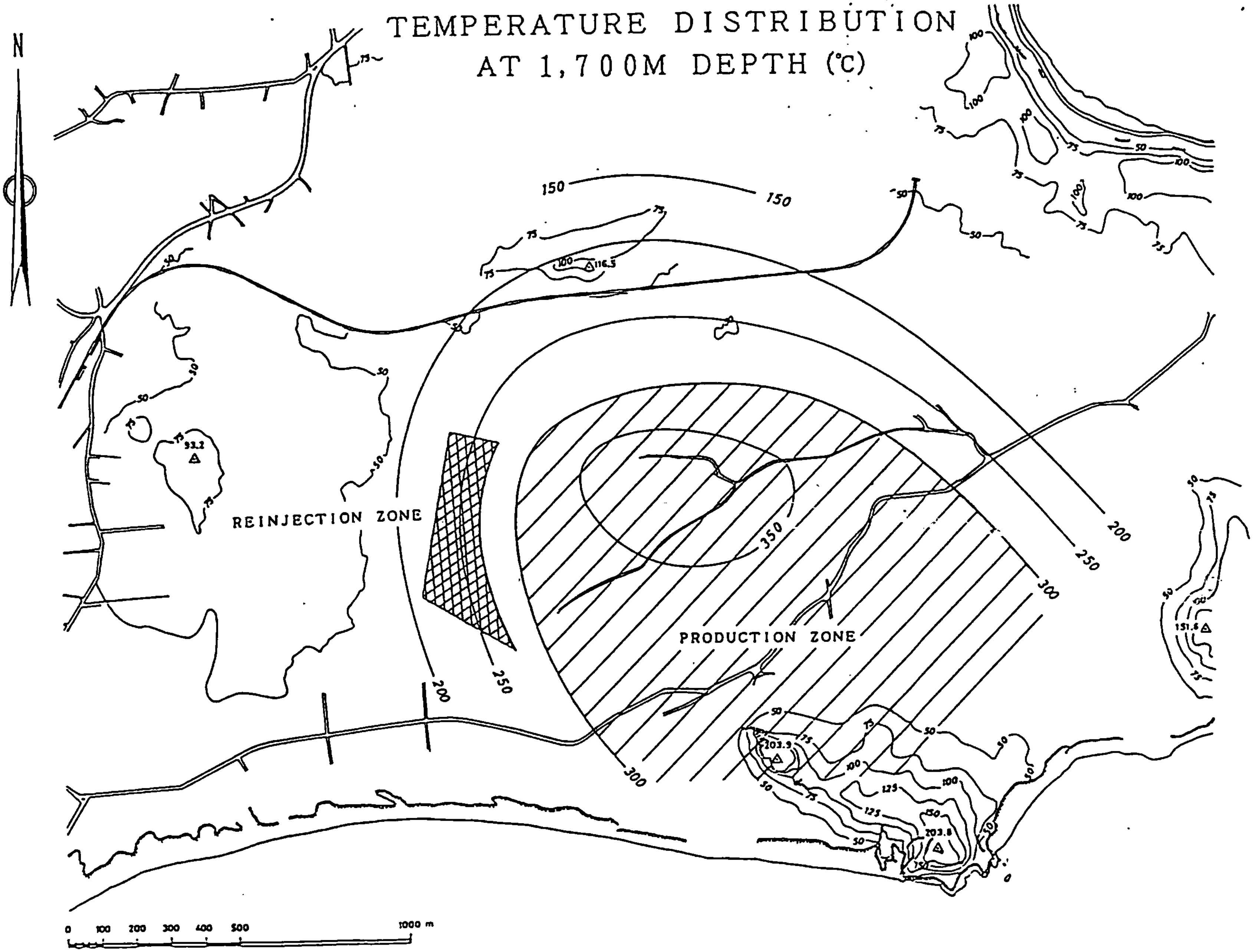
items			mean	maximums	minimums	remarks
production well	well head p. (Kg/cm²G)		———	14.1	12.5	
	steam (t/H)		27.4	64.3	7.1	calcu. v. at Hata
	hot water (t/H)		28.0	48.2	11.8	〃
	enthalpy (Kcal/Kg)		422.1	575.97	281.21	
non-condensable gas in steam amounts and components of	weight %		0.40	1.24	0.15	gas samplings were conducted from two phase flow lines.
	volume %		0.18	0.57	0.07	
	components	CO_2 (vol%)	69.4	93.9	46.9	
		H_2S (vol%)	25.9	46.9	4.6	
		H_2 (vol%)	2.1	3.5	0.6	
		O_2 (vol%)	0.1	0.1	0	
		N_2 other (vol%)	2.3	6.4	0.8	
		total (vol%)	99.8	———	———	
hot water components	pH (25℃)		4.99	7.39	3.87	
	cond (mS/cm)		62.2	93.4	42.0	
	Na^+ (mg/l)		16,400	20,200	9,020	
	K^+ (mg/l)		3,070	6,100	1,270	
	Li^+ (mg/l)		17.7	39.4	7.92	
	Ca^{++} (mg/l)		2,070	3,220	1,350	
	Mg^{++} (mg/l)		9.18	32.8	2.06	
	Cl^- (mg/l)		25,100	39,800	15,800	
	SO_4^- (mg/l)		33.4	51.8	22.7	
	HCO_3^- (mg/l)		0	13.2	30.5	
	SiO_2 (mg/l)		816	1,360	379	two-phase flowline
	Fe (mg/l)		15.2	143	0.11	
	B (mg/l)		68.4	161	27.1	
Na-K-Ca Temp (℃)			———	318.9	239.2	
SiO Temp (℃)			———	337	231	
Deep Cl^- (Na-K-Ca) (mg/l)			———	22,300	12,300	

Downhole Temperature Profiles

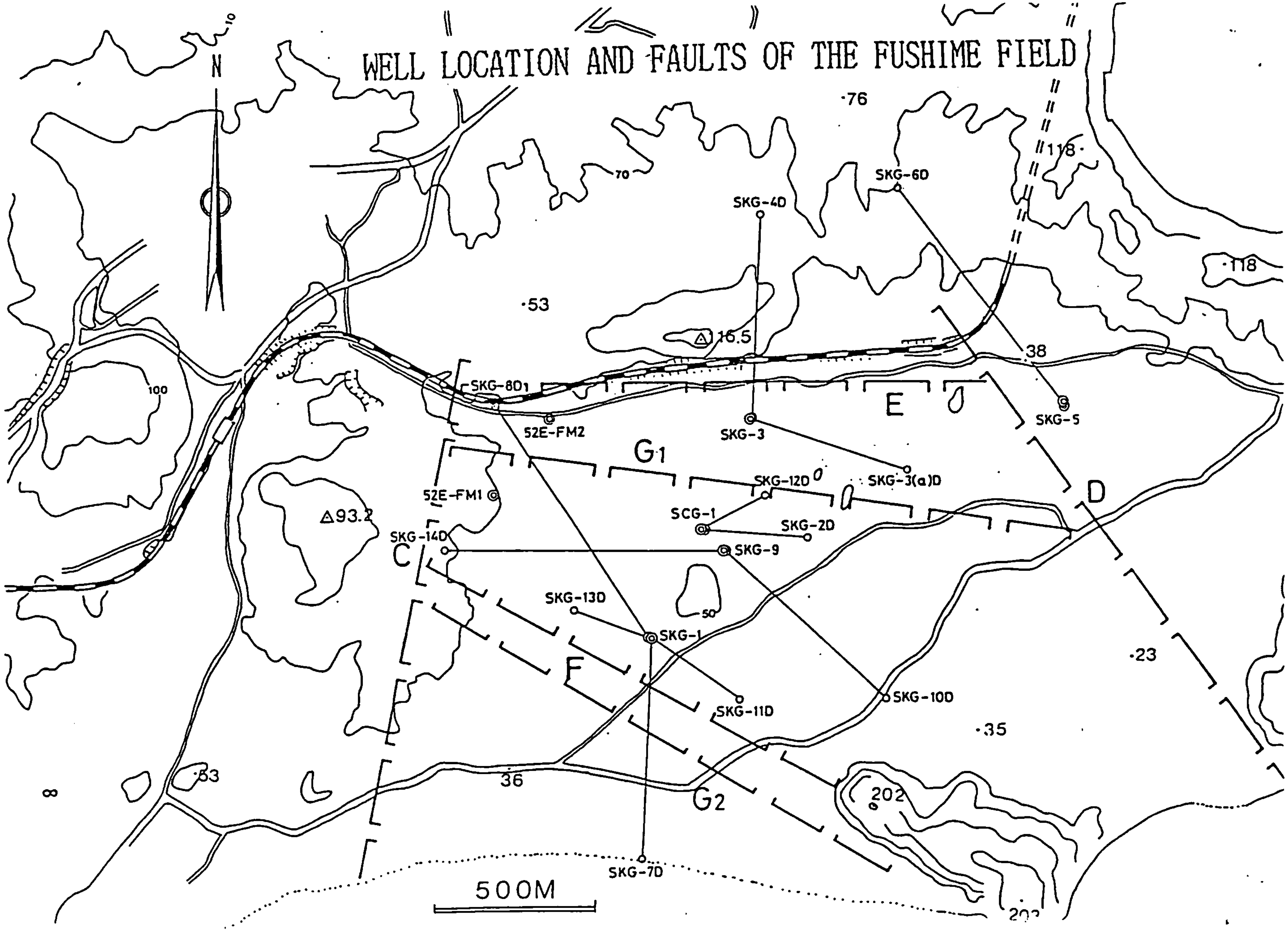


GEOLOGIC CROSS-SECTION THROUGH WELLS AT FUSHIME




TEMPERATURE DISTRIBUTION
AT 1,700M DEPTH (°C)
N
REINJECTION ZONE
PRODUCTION ZONE
150
200
250
300
350
0 100 200 300 400 500 1000 m

WELL LOCATION AND FAULTS OF THE FUSHIME FIELD



全国地熱資源総合調査(第3次)
Nationwide Geothermal Resources Exploration Project (3rd Phase)

広域熱水流動系調査
Regional Exploration of Geothermal Fluid Circulation System

火山性熱水対流系地域タイプ③
Volcano-related Hydrothermal Convection System Type ③

磐梯地域火山地質図
VOLCANO-GEOLOGICAL MAP OF BANDAI AREA

1:50 000

磐梯地域地熱地質編図
COMPILED GEOLOGICAL MAP
OF BANDAI GEOTHERMAL AREA

1:100 000

地質図　2

説明書　1

NEDO

新エネルギー・産業技術総合開発機構
NEW ENERGY AND INDUSTRIAL TECHNOLOGY DEVELOPMENT ORGANIZATION

1991

全国地熱資源総合調査(第3次) 広域熱水流動系調査 火山性熱水対流系地域タイプ③ 磐梯地域火山地質図及び地熱地質編図

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Volcano-related Hydrothermal Convection System Type③

鶴見岳地域火山地質図
VOLCANO-GEOLOGICAL MAP OF TSURUMIDAKE AREA

1:50,000

鶴見岳地域地熱地質編図
COMPILED GEOLOGICAL MAP
OF TSURUMIDAKE GEOTHERMAL AREA

1:100,000

地質図　2
説明書　1

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十勝地域火山地質図
VOLCANO GEOLOGICAL MAP OF TOKACHI AREA

1：50,000

十勝地域地熱地質編図
COMPILED GEOLOGICAL MAP
OF TOKACHI GEOTHERMAL AREA

1：100,000

地質図　2

説明書　1

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全国地熱資源総合調査（第３次）
Nationwide Geothermal Resources Exploration Project (3rd Phase)

広域熱水流動系調査
Regional Exploration of Geothermal Fluid Circulation System

火山性熱水対流系地域タイプ①
Volcano-related Hydrothermal Convection System Type ①

秋田駒地域火山地質図
VOLCANO-GEOLOGICAL MAP OF AKITAKOMA AREA

1：50,000

秋田駒地域地熱地質編図
COMPILED GEOLOGICAL MAP OF AKITAKOMA GEOTHERMAL AREA

1：100,000

地質図　2
説明書　1

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秋田駒地域火山地質図及び地熱地質編図

GEOTHERMAL DEVELOPMENT IN THE UNITED STATES

presentation to

29TH INTERNATIONAL GEOLOGICAL CONGRESS
KYOTO, JAPAN

	<u>MIN</u>
SLIDE 1A. TITLE SLIDE	**0**

SLIDE 1B. GREETING SLIDE

GOOD MORNING. I AM HAPPY TO BE HERE TO SPEAK TO THE 29TH INTERNATIONAL GEOLOGICAL CONGRESS ON GEOTHERMAL DEVELOPMENT IN THE UNITED STATES. MY NAME IS PHILLIP MICHAEL WRIGHT, AND I WORK AT THE UNIVERSITY OF UTAH RESEARCH INSTITUTE.

I AM MAKING THIS PRESENTATION ON BEHALF OF THE GEOTHERMAL RESOURCES COUNCIL (THE GRC), AND I BRING YOU GREETINGS FROM THE BOARD OF DIRECTORS OF THE GEOTHERMAL RESOURCES COUNCIL.

TODAY, I WILL BE DISCUSSING GEOTHERMAL ENERGY DEVELOPMENT IN THE UNITED STATES -- THE CURRENT STATUS OF DEVELOPMENT AND THE OUTLOOK FOR THE FUTURE.

SLIDE 2A. ACTIVE AND PASSIVE GEOTHERMAL ENERGY **0.5**

SLIDE 2B. GEOTHERMAL HEAT PUMP SKETCH

IN THE U.S., WE DIVIDE GEOTHERMAL ENERGY INTO ACTIVE AND PASSIVE APPLICATIONS. THE ACTIVE APPLICATIONS CONSIST OF ELECTRICAL POWER GENERATION AND DIRECT USES SUCH AS HEATING OF HOMES, GREENHOUSES OR BATHS. THESE ARE THE USES WE ORDINARILY THINK OF AS GEOTHERMAL ENERGY. HOWEVER, THE EARTH CAN BE USED AS A SOURCE OR SINK FOR HEAT IN GEOTHERMAL HEAT PUMP APPLICATIONS. I WANT TO BRIEFLY MENTION GEOTHERMAL HEAT PUMPS BECAUSE THEIR USE IS GROWING RAPIDLY IN THE UNITED STATES.

GEOTHERMAL HEAT PUMPS ARE THE MOST ENERGY EFFICIENT METHOD FOR HEATING AND COOLING HOMES AND BUILDINGS AND FOR MANY COMMERCIAL AND INDUSTRIAL HEATING AND REFRIGERATION APPLICATIONS. THERE ARE MORE THAN 125,000 GEOTHERMAL HEAT PUMPS INSTALLED IN THE U.S. AT THE PRESENT TIME, AND GROWTH IS ABOUT 25 PERCENT PER YEAR. BY A ROUGH ESTIMATE, WIDESPREAD USE OF GEOTHERMAL HEAT PUMPS COULD LEAD TO SAVINGS OF 10 % TO 20 % OF THE ELECTRICITY NOW CONSUMED IN THE U.S., LEADING FURTHER TO ENVIRONMENTAL ADVANTAGES.

HOWEVER, THE MAIN TOPIC OF THIS PRESENTATION IS ACTIVE GEOTHERMAL APPLICATIONS -- GEOTHERMAL ENERGY AS WE ORDINARILY KNOW IT.

SLIDE 4A. GEOTHERMAL POWER PLANT

SLIDE 4B. GEOTHERMAL GREENHOUSE.

IN THIS PAPER, I WOULD LIKE TO FIRST REVIEW THE USE OF ENERGY IN THE UNITED STATES, AND THE ROLE THAT RENEWABLE ENERGIES, SUCH AS GEOTHERMAL ENERGY, PLAYS. THEN WE WILL LOOK AT THE LOCATIONS AND GEOLOGIC CHARACTERISTICS OF THE SEVERAL GEOTHERMAL PROVINCES IN THE UNITED STATES. I WILL PRESENT CONCEPTUAL GEOLOGIC MODELS OF SOME TYPICAL GEOTHERMAL RESERVOIRS. I WILL THEN DISCUSS SOME OF THE PROBLEMS IN EXPLORATION AND DISCOVERY OF NEW GEOTHERMAL SYSTEMS IN THE U.S., THE CURRENT STATUS OF THE INDUSTRY AND THE CURRENT STATUS OF GEOTHEMAL R&D.

SLIDE 3A. U.S. ENERGY USE **2.0**

SLIDE 3B. U.S RENEWABLE ENERGY USE

THE ANNUAL CONSUMPTION OF ENERGY IN THE UNITED STATES IS ABOUT 82 QUADS. ONE QUAD IN 10E15 BTU OR 10E18 JOULES. THESE 82 QUADS ARE CONSUMED FOR ALL USES, INCLUDING TRANSPORTATION, ELECTRICAL POWER USES AND HEATING. THE SLIDE SHOWS THAT 41% OF U.S. ENERGY IS FURNISHED BY OIL, 21% BY NATURAL GAS, 23% BY COAL, 7% BY NUCLEAR AND 8% BY RENEWABLE ENERGIES.

OF THE 8% FURNISHED BY RENEWABLE FUELS, 46% IS FROM HYDROPOWER, 47% FROM BIOMASS AND 4% FROM GEOTHERMAL.

THIS MEANS THAT 4% OF 8%, I.E. 0.32% OF ALL U.S. ENERGY IS FURNISHED BY GEOTHERMAL ENERGY. USE OF GEOTHERMAL ENERGY IN THE U.S. IS EQUIVALENT TO BURNING 60 MILLION BARRELS OF OIL PER YEAR.

GEOTHERMAL RESOURCES ARE GENETICALLY LINKED WITH YOUNG VOLCANISM -- WITH THE PACIFIC RING OF FIRE.

SLIDE 4A. RING OF FIRE FROM SPACE **3.0**

SLIDE 4B. ISLAND OF HAWAII

THIS SLIDE SHOWS SOME OF THE FEATURES OF THE PACIFIC RING OF FIRE AS THEY WOULD BE SEEN FROM SPACE. THE SLIDE WAS MADE BY THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION. IT SHOWS WHAT WE ALL KNOW, NAMELY THAT THE WESTERN PART OF THE U.S., BOTH THE LOWER 48 STATES AND ALASKA, ARE NEAR PLATE BOUNDARIES THAT HAVE EITHER SUBDUCTION, AS IN THE JUAN DE FUCA PLATE, OR SPREADING/TRANSFORM FAULTING, AS IN THE GULF OF CALIFORNIA. ALL OF THE YOUNG VOLCANISM AND ALL OF THE HIGH TEMPERATURE GEOTHERMAL RESOURCES IN THE U.S. OCCUR IN ASSOCIATION WITH THESE FEATURES.

THE OTHER MAJOR GEOTHERMAL PROVINCE IN THE U.S., NOT ASSOCIATED WITH THE PACIFIC RING OF FIRE, IS THE CHAIN OF HAWAIIAN ISLANDS.

THE HAWAIIAN ISLANDS COMPRISE A CHAIN OF BASALTIC VOLCANOS

THAT OVERLIE A HYPOTHESIZED MANTLE PLUME THAT HAS POSSIBLY BEEN STATIONARY FOR THE LAST 75-80 MILLION YEARS. THE "HAWAIIAN RIDGE" TRENDS NORTHWESTWARD FROM THE BIG ISLAND OF HAWAII, WHICH IS ON THE SOUTHEAST END OF THE CHAIN AND OVER THE PRESENT HOT SPOT. A MAJOR BEND OCCURS IN THE CHAIN AT A POINT BEYOND KURE ATOLL, WHERE THE CHAIN TRENDS MORE NORTHERLY. THE CHAIN IS THEN KNOWN AS THE "EMPORER SEAMOUNT CHAIN". THE TOTAL LENGTH OF THE CHAIN IS ABOUT 6,000 KM. VOLCANIC ACTIVITY BECOMES PROGRESSIVELY OLDER NORTHWESTWARD, AND REACHES AGES OF 75 - 80 Ma AT THE NORTH END OF THE EMPORER SEAMOUNTS.

THERE IS PRESENTLY NO GEOTHERMAL POWER GENERATION IN HAWAII, ALTHOUGH PRODUCTION DRILLING TO FURNISH STEAM TO A 30 MWe POWER PLANT IN THE EAST RIFT ZONE OF KILAUEA VOLCANO ON THE ISLAND OF HAWAII IS NOW UNDERWAY, AND THE PLANT SHOULD BE ON LINE WITHIN A YEAR.

IN ALASKA, WE HAVE THE CENTRAL VOLCANIC BELT AND THE ALEUTIAN ISLAND CHAIN IN A VOLCANIC ARC ASSOCIATED WITH SUBDUCTION OF THE PACIFIC PLATE. THERE ARE NO GEOTHERMAL POWER PLANTS IN ALASKA.

SLIDE 5A. HEAT FLOW IN WESTERN U.S. **4.5**

SLIDE 5B. GEOTHERMAL PROVINCES IN WESTERN U.S.

THIS SLIDE SHOWS A MAP OF HEAT FLOW IN THE WESTERN ONE-THIRD OF THE UNITED STATES. THE DATA AND MAP WERE COMPILED BY DAVE BLACKWELL OF SOUTHERN METHODIST UNIVERSITY, WHO IS CURRENTLY THE PRESIDENT OF THE GEOTHERMAL RESOURCES COUNCIL. THE MAP IS PART OF THE DNAG SERIES, THE DECADE OF NORTH AMERICAN GEOLOGY PROJECT, PUBLISHED BY THE GEOLOGICAL SOCIETY OF AMERICA. WE SEE THAT THE HEAT FLOW IS ANOMALOUSLY HIGH IN THE WESTERN U.S., HAVING VALUES RANGING FROM 60 TO MORE THAN 100 MWM^{-2} OVER MORE THAN HALF OF THE AREA. THE WESTERN HALF OF THE U.S. IS BY FAR THE MOST ACTIVE TECTONICALLY, AND CONTAINS ALL OF THE KNOWN GEOTHERMAL OCCURRENCES HAVING TEMPERATURES ABOVE 150 °C.

GEOTHERMAL PROVINCES WITHIN THE 48 CONTIGUOUS STATES INCLUDE:

-THE SAN ANDREAS TRANSFORM PROVINCE, INCLUDING:

-THE SALTON TROUGH IN THE SOUTH, WHICH IS AN AREA OF LEAKY TRANSFORM FAULTS ALONG THE NORTHERN PROJECTION OF THE EAST PACIFIC RISE AS IT TRAVERSES THE GULF OF CALIFORNIA AND COMES ONTO LAND IN MEXICO, AND

-THE GEYSERS STEAM FIELD TO NORTH;

-THE CASCADES PROVINCE, WHICH IS COMPRISED OF ANDESITIC VOLCANOS THAT OVERLIE THE JUAN DE FUCA SUBDUCTION ZONE;

-THE BASIN AND RANGE PROVINCE, BELIEVED TO REPRESENT A BACK-

ARC EXTENSIONAL ENVIRONMENT CHARACTERIZED BY N-S TO NNW-SSE BLOCK FAULTING AND THE FORMATION OF SEDIMENT-FILLED BASINS SEPARATED BY UPTHROWN MOUNTIAN BLOCKS;

-SEVERAL PROVINCES OF LESSER IMPORTANCE, INCLUDING THE RIO GRANDE RIFT, THE SOUTHERN AND NORTHERN ROCKY MOUNTAINS, THE DAKOTA MODERATE-TEMPERATURE AQUIFER SYSTEM AND THE BALCONES FAULT ZONE IN TEXAS. THE HIGH HEAT FLOW IN THE MIDDLE ROCKY MOUNTAINS IN COLORADO IS NOT ASSOCIATED WITH KNOWN HIGH TEMPERATURE GEOTHERMAL SYSTEMS, ALTHOUGH THERE ARE SOME OCCURRENCES OF MODERATE TEMPERATURE SPRINGS. HOWEVER, ALL OF THE OTHER HIGH HEAT-FLOW AREAS ARE ASSOCIATED WITH NUMEROUS GEOTHERMAL OCCURRENCES.

SLIDE 6A. SALTON TROUGH GEOTHERMAL PROVINCE **6.0**

SLIDE 6B. EXPLORATION STATUS AND PROBLEMS

THE SALTON TROUGH IS A PULL-APART ZONE FILLED WITH SEDIMENTS FROM THE COLORADO RIVER. IT LIES ALONG THE EXTENSION OF THE EAST PACIFIC RISE ONTO THE NORTH AMERICAN CONTINENT. THIS PROVINCE IS BELIEVED TO BE A SPREADING/TRANSFORM ENVIRONMENT WHERE BASALTIC MAGMA INTRUDES THE CRUST AND THE COLORADO RIVER DELTIAC SEDIMENTS IN SPECIFIC AREAS. SURFACE VOLCANIC ACTIVITY IS KNOWN ONLY FROM THE CERRO PRIETO AND SALTON SEA AREAS. OTHER GEOTHERMAL SYSTEMS HAVE BEEN FOUND THROUGH THE APPLICATION OF GRAVITY PROSPECTING AND HEAT-FLOW STUDIES.

IN THE SALTON TROUGH OF CALIFORNIA, POWER IS BEING GENERATED AT THE EAST MESA, HEBER AND SALTON SEA GEOTHERMAL FIELDS. ALSO SHOWN ON THIS SLIDE IS THE GEOTHERMAL FIELD AT CERRO PRIETO, MEXICO.

SLIDE 7A. PICTURE

SLIDE 7B. PICTURE

THESE PICTURES SHOW THE POWER PLANTS AT THE SALTON SEA AND EAST MESA, RESPECTIVELY.

SLIDE 8A. THE GEYSERS MEGADISTRICT **7.5**

SLIDE 8B. THE GEYSERS MODEL

IN THE GEYSERS AREA IN CENTRAL CALIFORNIA, POWER PRODUCTION IS NOW AT A LEVEL OF 1,400 MWe, WITH AN INSTALLED CAPACITY OF 2,000 MWe. STEAM PRESSURE HAS BEEN DECLINING RAPIDLY SINCE ABOUT 1987.

THE GEYSERS IS IN AN AREA OF YOUNG VOLCANISM, WITH THE CLEAR

LAKE VOLCANIC FIELD HAVING DATES AROUND 1 Ma, DEVELOPED IN THE STRUCTURAL ENVIRONMENT OF THE SAN ANDREAS TRANSFORM FAULT. THE DEVELOPMENT HAS SPREAD OUT FROM THE ORIGINAL AREA OF GEYSERS AND FUMAROLES. THIS IS A VAPOR-DOMINATED SYSTEM, WITH STEAM BEING PRODUCED DIRECTLY FROM THE RESERVOIR.

SLIDE 9A. GEOTHERMAL FIELDS IN THE GREAT BASIN 9.5

SLIDE 9B. THREE MODELS OF B&R STRUCTURAL DEVELOPMENT

IN THE BASIN AND RANGE, POWER PLANTS ARE IN OPERATION AT COSO HOT SPRINGS AND MAMMOTH LAKES IN THE STATE OF CALIFORNIA; STEAMBOAT, BRADY HOT SPRINGS, DESERT PEAK, DIXIE VALLEY, BEOWAWE IN THE STATE OF NEVADA; AND AT ROOSEVELT HOT SPRINGS AND COVE FORT IN THE STATE OF UTAH.

SLIDE 10A. COSO MODEL 11.0

SLIDE 10B. COSO PICTURE

SLIDE 11A. COVE FORT MODEL 12.5

SLIDE 11B. PICTURE

SLIDE 12A. POTENTIAL FOR NEW GEOTHEMAL POWER 14.0

SLIDE 12B. GEOTHERMAL PROVINCES

THIS SLIDE INDICATES THE RESULTS OF AN ASSESSMENT THAT I RECENTLY MADE OF THE POTENTIAL FOR NEW GEOTHERMAL POWER POTENTIAL IN THE LOWER 48 UNITED STATES. THE SLIDE SHOWS THE AREA, THE STAGE OF EXPLORATION AND AN ASSESSMENT OF THE AMOUNT OF NEW POWER THAT COULD BE DEVELOPED OVER THE NEXT 10 - 15 YEARS.

THE BASIN AND RANGE PROVINCE APPEARS TO HOLD THE MOST POTENTIAL FOR NEAR-TERM POWER DEVELOPMENT.

SLIDE 13A. STATUS OF U.S. GEOTHERMAL INDUSTRY 15.5

SLIDE 13B. FUNDING FOR GEOTHERMAL R&D

THE U.S. GEOTHERMAL POWER GENERATION INDUSTRY AT THE PRESENT TIME IS ECONOMICALLY DEPRESSED. THE INDUSTRY HAS CONTRACTED DURING THE PAST 5 YEARS, WITH SOME MAJOR COMPANIES SUCH AS CHEVRON DROPPING OUR AND OTHER MAJORS SUCH AS UNOCAL RECENTLY CUTTING BACK ON WORK FORCE. THE INDUSTRY IS NOW DOMINATED BY SMALL COMPANIES, BUT THERE IS A LOT OF TALENT AND ENTHUSIASM.

THE MAIN REASON FOR THE ECONOMIC DEPRESSION IN THE U.S. GEOTHERMAL INDUSTRY IS THE LOW PRICE FOR NATURAL GAS. GEOTHERMAL

ENERGY HAS A VERY DIFFICULT TIME COMPETING AGAINST GAS PRICES AS LOW AS THOSE OF TODAY. WHEREAS GAS PRICES ARE NOW BELOW $2.50 PER MILLION BTU'S, IT WILL TAKE AN INCREASE IN PRICE TO AROUND $3.50 PER MILLION BTU'S FOR GEOTHERMAL ENERGY TO COMPETE AT ALL BUT THE VERY HIGHEST GRADE LOCATIONS. MUCH OF THE NEW ELECTRICAL GENERATION CAPACITY BEING PUT ON LINE IN THE U.S. IS GAS COMBUSTION TURBINES.

THE UTILITY INDUSTRY IN THE U.S. IS STILL REGULATED IN SUCH A FASHION THAT THE ENVIRONMENTAL COSTS OF GENERATION AND USE OF ELECTRICITY ARE NOT ACCOUNTED FOR IN THE PRICE OF ELECTRICITY TO THE CUSTOMER. UTILITIES HAVE LITTLE INCENTIVE TO USE SUCH ENVIRONMENTALLY ADVANTAGEOUS FUEL SOURCES AS GEOTHERMAL ENERGY. HOWEVER, UTILITY REGULATIONS ARE CHANGING SLOWLY. IN SOME STATES SUCH AS CALIFORNIA AND NEVADA, THE ADVANTAGES OF HAVING A DIVERSE FUEL MIX AND OF USING ENVIRONMENTALLY ADVANTAGEOUS FUELS IS REWARDED. SUCH CHANGES HELP GEOTHERMAL COMPETE BETTER AGAINST NATURAL GAS.

THE DIRECT-USE INDUSTRY IN THE U.S. IS NOT AN ORGANIZED INDUSTRY. INSTEAD, DIRECT-USE PROJECTS ARE ESSENTIALLY ONE-DESIGN. NOT HAVING A SPECIFIC DIRECT-HEAT INDUSTRY UNDOUBTEDLY SLOWS DEVELOPMENT. THE U.S. HAS PLENTY OF GEOTHERMAL RESOURCES SUITABLE FOR DIRECT USE, AND MORE OF THESE WILL COME ON LINE IF AN INDUSTRIAL INFRASTRUCTURE CAN BE ORGANIZED.

THE GEOTHERMAL HEAT PUMP INDUSTRY IS GROWING AT A RAPID PACE IN THE U.S., AND HAVE GREAT POTENTIAL TO MAKE THE U.S. MORE ENERGY EFFICIENT.

UNFORTUNATELY, THE U.S. FEDERAL GOVERNMENT APPEARS TO BE UNINTERESTED IN SUPPORTING DEVELOPMENT OF GEOTHERMAL TECHNOLOGY. WHEREAS THE R&D BUDGETS FOR OTHER RENEWABLE TECHNOLOGIES SUCH AS SOLAR TECHNOLOGY HAVE GROWN DRAMATICALLY IN RECENT YEARS, GEOTHERMAL ENERGY R&D HAS DELCINED. THE SLIDE SHOWS THE RELATIVE PRIORITY OF GEOTHERMAL ENERGY COMPARED WITH MAGNETIC FUSION RESEARCH, ENVIRONMENTAL HEALTH AND SAFETY, AND ENVIRONMENTAL RESTORATION, WHOSE BUDGETS ARE INCREASING.

I NOTE THAT THE MAGMA ENERGY AND GEOPRESSURED R&D PROGRAMS HAVE BEEN TERMINATED BY THE DEPARTMENT OF ENERGY, AND THAT THE HOT DRY ROCK PROGRAM IS SCHEDULED FOR TERMINATION AT THE END OF 1993. THIS WILL MEAN THAT THE U.S. WILL BE DOING NO RESEARCH ON ADVANCED GEOTHERMAL SYSTEMS, BUT CONFINING ITS R&D ONLY TO HYDROTHERMAL ENERGY AND GEOTHERMAL HEAT PUMPS. OF COURSE, THESE POLICIES MAY CHANGE DEPENDING ON THE OUTCOME OF THE PRESIDENTIAL ELECTION IN NOVEMBER.

I THANK YOU VERY MUCH FOR THE OPPORTUNITY TO SPEAK BEFORE THIS MEETING.

END 16.5

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Some useful conclusions re injection - see last p. for extra heat used.

REINJECTION EXPERIMENT AT THE MATSUKAWA VAPOR-DOMINATED GEOTHERMAL FIELD: INCREASE IN STEAM PRODUCTION AND SECONDARY HEAT RECOVERY FROM THE RESERVOIR

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(*Received December* 1990; *accepted for publication June* 1991)

Abstract—A reinjection experiment has been conducted in an attempt to sustain reservoir pressure and steam production and to extract remaining heat energy in the superheated reservoir in the Matsukawa vapor-dominated geothermal field. This experiment was undertaken because the increase in superheat of produced steam and the decline of steam production are the current major issues for stable operation of the power plant. Almost all the reinjected fluid into well MR1 was recovered from well M5, and the steam production of well M5 has increased by approximately 67%.

INTRODUCTION

Matsukawa is a vapor-dominated geothermal field in which most of the wells currently produce dry superheated steam. It is located about 600 km northeast of Tokyo and about 50 km northwest of Morioka, northeast Japan. Matsukawa was the first geothermal power station in Japan, starting its power production in 1966, and it is the only vapor-dominated geothermal power station developed in Japan. The location of the field is shown in Fig. 1.

Power production at Matsukawa has continued successfully for more than 24 years. Current output is 22 MWe, and the power station has continued at full power for more than 22 years. However, increase in superheat of produced steam and decline in steam production are the current major issues for stable operation of the power plant (Hanano *et al.*, 1989). These characteristics are associated with the decline of water content in part of the reservoir. To sustain stable steam production and to extract the remaining heat energy in the reservoir, reinjection of steam condensate into well MR1 has been conducted since 1988. A preliminary experiment was undertaken in 1988, and continuous reinjection has been conducted since 1989. In this report, we describe the results of this reinjection experiment.

The Matsukawa geothermal reservoir has been studied previously (e.g. Akazawa and Muramatsu, 1988; Baba *et al.*, 1970; Hanano and Matsuo, 1990; Hanano and Sakagawa, 1990; Hanano *et al.*, 1989, 1991; Hayakawa *et al.*, 1967; Nakamura and Sumi, 1967; Sumi, 1968; Yoshida, 1984; Yoshida and Ishizaki, 1988). This reinjection experiment was conducted based on the results of these studies.

CURRENT STATUS OF THE MATSUKAWA RESERVOIR

Eleven production wells are now being used to produce steam for 22 MWe output (Fig. 1). However, the most recently drilled production well M12 was completed in January, 1990, after the reinjection experiment described in this report.

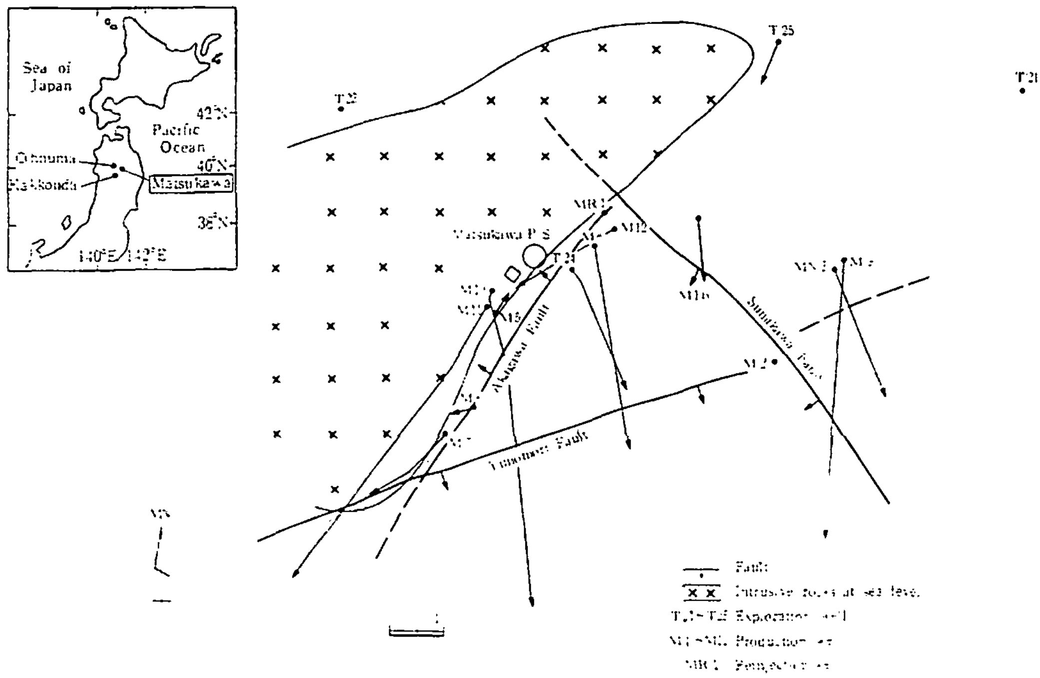

Fig. 1. Location of wells and main fractures at Matsukawa (modified from Akazawa and Muramatsu, 1988). M12 was completed after the reinjection experiment.

A part of the produced steam was considerably wet in the early stages of development; however, the steam became superheated after a certain period of production so that it was mostly superheated steam when power generation began in 1966 (Miyamori, 1968; Hanano and Matsuo, 1990). With continued steam production, the steam temperature and its superheat became higher. The change of steam temperature at the turbine inlet is shown in Fig. 2. Current

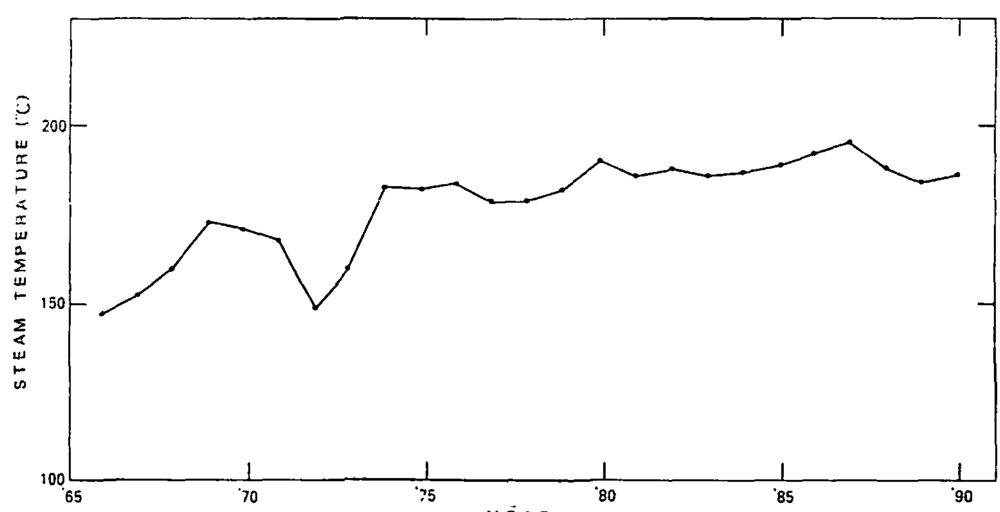

Fig. 2. Record of steam temperature at the turbine inlet. The turbine inlet pressure has been maintained at 3.4 bar-gauge.

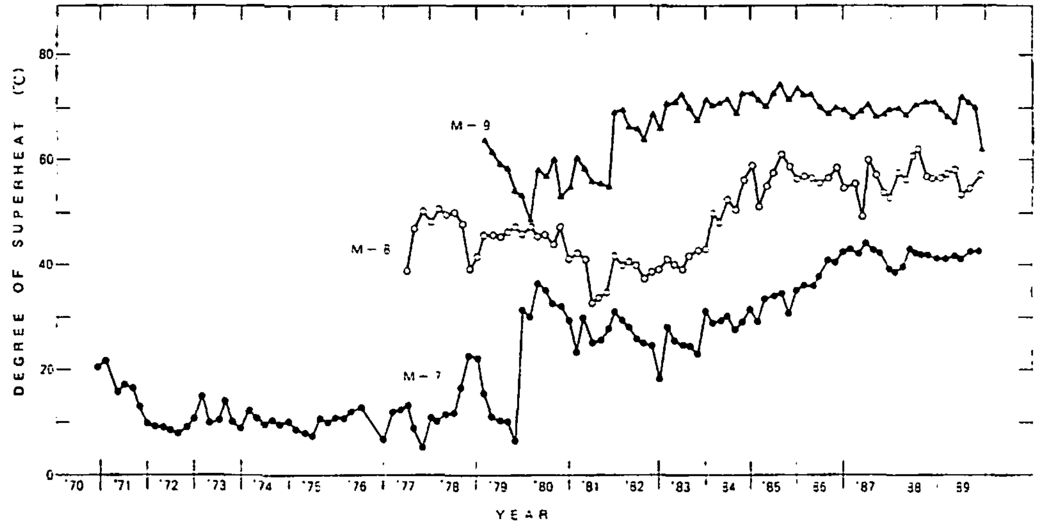

Fig. 3. Record of degree of superheat at the well head of M7, M8 and M9.

degree of superheat at the turbine inlet is approximately 36°C. Figure 3 shows the change in degree of superheat at the well head of M7, M8 and M9. As seen in this figure, the degree of superheat of produced steam is significant at M9, which is located in the eastern part of the developing area. Detailed production histories of all the wells in Matsukawa and of the power plant are reported by Hanano *et al.* (1989).

Hanano and Sakagawa (1990) interpreted the results of their pressure build-up tests, as well as the production record and the chemical data of produced steam. Figure 4 shows the recent shut-in pressure distribution, showing the very steep pressure gradient from southwest to northeast.

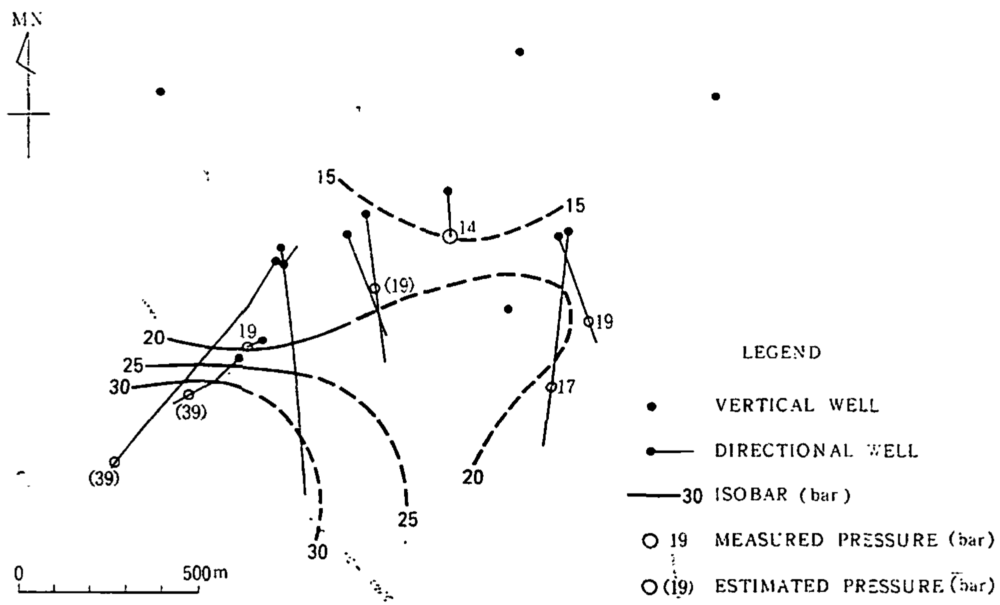

Fig. 4. Shut-in pressure distribution at feed points in October, 1988 (after Hanano *et al.*, 1989). Pressures are absolute.

Through this study, Hanano and Sakagawa found that steam flows from the southwest to the northeast in the reservoir and that recharge occurs only from the southwest. Thus, in the southwest part of the developing area, where the recharge is high, the reservoir pressure and steam production are high and the decline of steam production is less. Reservoir pressure is lower, steam production is less, and decline of steam production is greater in the east and northeast parts, where the recharge is less. Therefore the degree of superheat of produced steam is most evident in the eastern part of the reservoir.

From the above discussions and from the distribution of main fractures shown in Fig. 1, Hanano and Sakagawa (1990) concluded that steam is supplied from the southwest through the Akagawa Fault and the Yunomori Fault. From the shut-in pressure distribution shown in Fig. 4, Hanano *et al.* (1989) concluded that there is a low-permeability barrier, consistent with the model of vapor-dominated systems by White *et al.* (1971), at least both at the top and sides of the reservoir. Without this low-permeability barrier, such low reservoir pressure as shown in Fig. 4 cannot exist stably at a depth of 800–1300 m. However, the true character of the low-permeability barrier still remains unknown.

PRELIMINARY REINJECTION EXPERIMENT (FIRST TRIAL)

As described above, reservoir pressure is decreasing in parts of the Matsukawa reservoir. A decrease in steam production and increase in the superheat of produced steam are also occurring. These phenomena are associated with the decrease in water saturation in the reservoir, which is caused by much less fluid recharge into the reservoir compared with the amount of steam production. However, the superheat phenomenon indicates that there still remains a large amount of heat in the reservoir. This very small recharge is associated with the low-permeability barrier described above, which is one of the typical characteristics of a vapor-dominated system.

The increase in the superheat of produced steam is also observed in other vapor-dominated fields in areas of reservoir pressure reduction. With continued production, a decrease of the two-phase region may result in an acceleration of reservoir pressure and production decline. To overcome this problem, reinjection of steam condensate has been applied in The Geysers and Larderello to maintain the reservoir pressure and steam production and to extract heat that remains in the reservoir (e.g. Chasteen, 1975; Giovannoni *et al.*, 1981; Bertrami *et al.*, 1985; Enedy *et al.*, 1991). This reinjection helps to reduce the decline in steam production. The yearly average of the decrease in steam production in a part of The Geysers area recovered from approximately 18 to approximately 6% after the start of the reinjection (UNOCAL Corp., 1985, personal communication). Therefore, the reinjection experiment of drainage water from the Matsukawa power plant was planned to extract heat remaining in the reservoir and to reduce the decline in steam production.

The reinjection experiment at Matsukawa was carried out in two stages; a preliminary stage (first experiment) and a long-term stage (second experiment). Since this was the first attempt to reinject at Matsukawa, we chose the following items as the main objectives of the first stage.

(1) Examination of the basic concept of reinjection at Matsukawa.
(2) Selection of a suitable location for reinjection.
(3) Collection of data and its examination for the coming large scale reinjection.

(1) *Examination of basic concept of reinjection at Matsukawa*

Since this was the first reinjection experiment at Matsukawa, we referred to the results and experience at Larderello to examine the basic concept for reinjection at Matsukawa.

From the Larderello experience, it appears that reinjection into a superheated reservoir is successful only when there is a large enough surface area of fractures contacted by the reinjected fluid for efficient heat exchange with rocks of the reservoir. This is accomplished, for example, by a vertical fracture system around the reinjection wells to allow the reinjected fluid to descend to the deep part of the reservoir to boil (e.g. Giovannoni *et al.*, 1981: Bertrami *et al.*, 1985). Of course, the boiling can take place near the reinjection well. However, the vertical fracture system must be significant if the horizontal distance between the reinjection well and a production well is limited. This mechanism to recover steam by reinjection is validated by a numerical simulation study (Calore *et al.*, 1986).

Thus, the important factors for successful reinjection in a superheated reservoir are summarized as follows (e.g. Chasteen, 1975: Giovannoni *et al.*, 1981: Bertrami *et al.*, 1985; Calore *et al.*, 1986: F. D'Amore, 1988, personal communication):

(a) The part of the reservoir where the fluid is to be reinjected should be very well superheated (low reservoir pressure but high formation temperature).

(b) The reinjection well should not be located at the recharge zone of hot fluid and/or steam (up-flow zone), so as not to break through directly to good production wells.

(c) There should be a large enough surface area of the fractures for efficient heat exchange and/or a vertical fracture system to allow the reinjected fluid to descend to the deep part of the reservoir to boil.

(d) The feed points of reinjection wells should be deeper than those of the production wells so as not to break through directly to production wells.

(e) The reinjection wells should be located as far from the production wells as possible so as not to break through directly.

It is very important to trace the flow paths of the reinjected fluid and the rate of its return in any type of geothermal reservoir. Accordingly, a tracer test is usually applied. Thus, a tracer test utilizing the reinjected fluid itself was planned by referring to the Larderello examples (e.g. Nuti *et al.*, 1981; D'Amore *et al.*, 1987). However, the isotopic composition of the reinjected fluid at Matsukawa is not stable because it is a mixture of steam condensate and river water. The gas–steam ratio of the produced steam has large regional variations (e.g. Yoshida and Ishizaki, 1988). Thus, the reinjected fluid itself could not be used as a natural tracer at Matsukawa.

Another option would be an artificial tracer such as injection of tritium with the reinjection water (e.g. Gulati *et al.*, 1978). However, the injection of tritium is not practically possible in Japan because of difficulties in obtaining legal permission. Therefore, the tracer test was not done in this series of experiments.

(2) *Selection of a suitable location for reinjection*

From examination of Figs 1 and 4, the most suitable location for reinjection in Matsukawa to meet the conditions described above is thought to be a deep zone of the northeast area such as around M1b and M9. However, drilling of a deep well in this area would require an additional drilling base, and it would have taken a long time to get permission from the government agencies, because the whole area around Matsukawa is government property. Drilling of a deep well is also costly and risky. Thus, a reinjection well MR1 (total depth; 1000 m) was drilled where permission was easily obtained (Fig. 1). Although this location did not fulfil completely the conditions for ideal reinjection as described above, it is relatively close to the superheated area and is clearly away from the recharge zone. Thus, it was thought to be suitable for the first experiment.

The casing program and logging records of MR1 are shown in Fig. 5. As seen in this figure, the temperature profiles measured after reinjection show a small decrease between 550 and 750 m, suggesting the existence of several feed points within this zone. However, there was lost circulation at 597 m, the pressure profiles measured after reinjection pivoted at around 550–

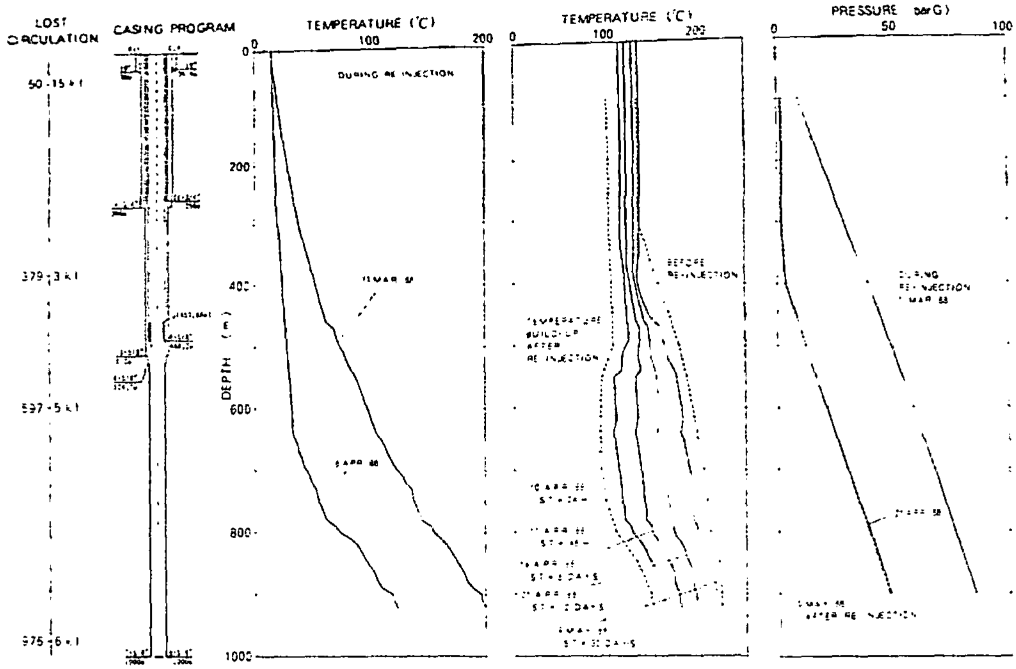

Fig. 5. Logging record of MR1.

600 m, and the temperature profile measured on 6 April 1988 bent at around 650 m, suggesting that the primary feed point is slightly shallower than 650 m. Thus, we assumed that the primary feed point of MR1 is around 600 m.

(3) *The results of the first experiment*

The results of the first reinjection experiment are shown in Fig. 6. As seen in this figure, this experiment was started on 3 March 1988 and ended on 2 February 1989. During this period, fluid was reinjected intermittently. The total amount of reinjection was approximately 80,000 tons.

As seen in Fig. 6, there was a clear influence on steam production in this experiment. After test no. 2, the well-head pressure of M1b increased. After the experiment, the steam temperature of M1b decreased slightly. The change in the gas–steam ratio of produced steam was not obvious.

M5 showed a small increase in steam production (Fig. 6). M5 had been producing a very small amount of hot water with steam before this experiment, so that the steam temperature did not change. Although it is not shown in Fig. 6, the amount of this hot water increased slightly and became evident from 6 October 1988 onwards. The steam chemistry of M5 did not change.

As described above, there was a notable change in steam production in this first experiment. Thus, an increase in steam production was set as a target for the next experiment.

SECOND REINJECTION TRIAL

The second experiment has been continuing since 18 August 1989 (Fig. 7). Since there was a small change in steam production and steam temperature in the first experiment, a longer and larger rate of reinjection was planned for the second reinjection experiment. As seen in Fig. 7, there was no notable change at first, but in early September, two weeks after the start of reinjection, the steam temperature of M1b decreased significantly. However, M1b showed only this decrease in steam temperature and did not show any other change.

As seen in Fig. 7, the steam production rate of M5 increased suddenly on 6 October 1989, from approximately 15 t/h to 25 t/h on average. At the same time, though it is not shown in Fig. 7, production of hot water also increased from nearly zero to approximately 10 t/h. This increase occurred at the total cumulative reinjection of 36,000 tons. Because of the difficulties of tracer testing in this area as described above, the precise evaluation of the recovery rate of reinjected

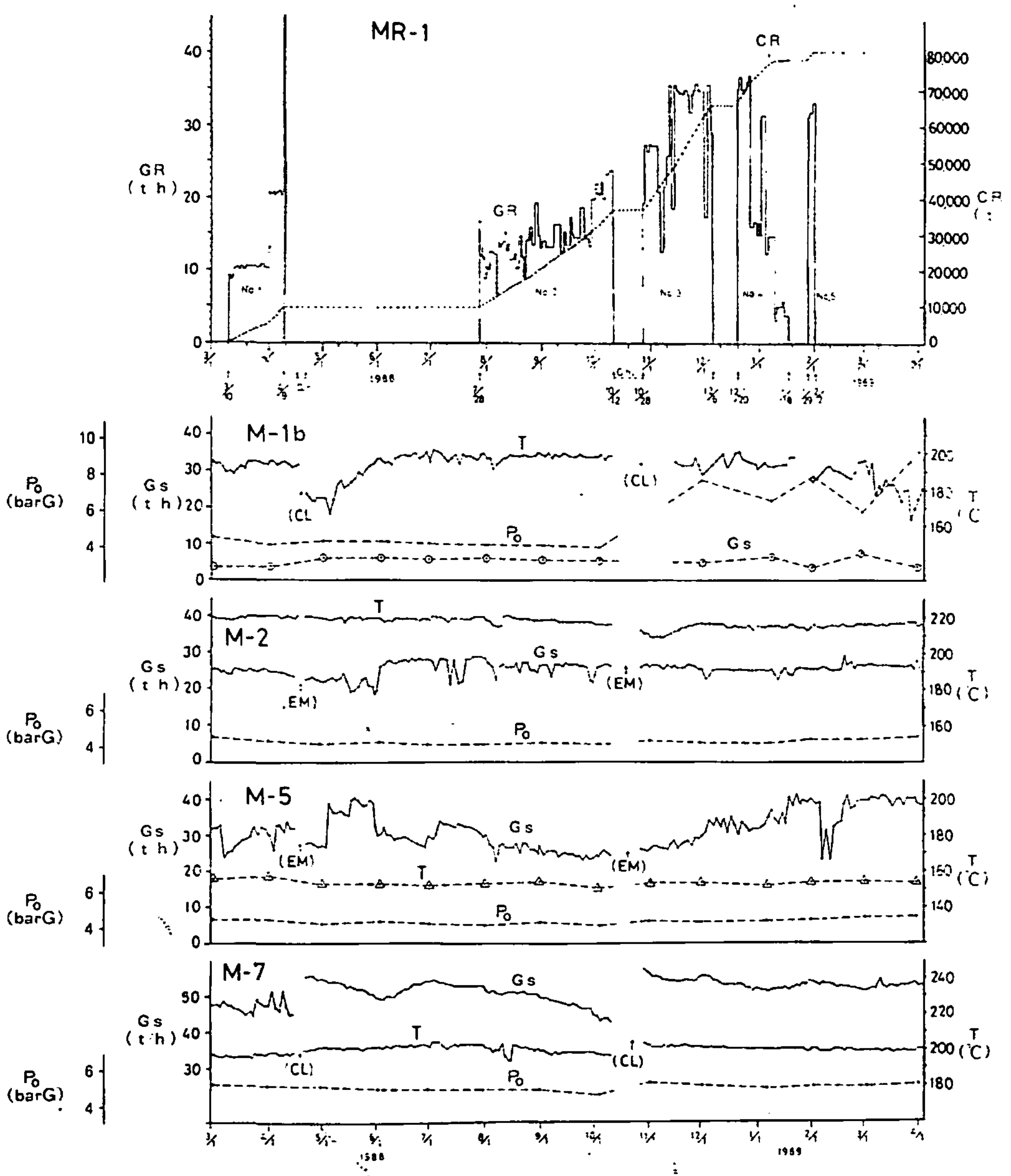

Fig. 6. Record of the first reinjection experiment. (CL), the well closed; CR, cumulative reinjection; (EM), the well emitted; GR, reinjection rate; Gs, steam production rate; OH, power plant overhaul; T, steam temperature; Po, well head pressure in bar-gauge.

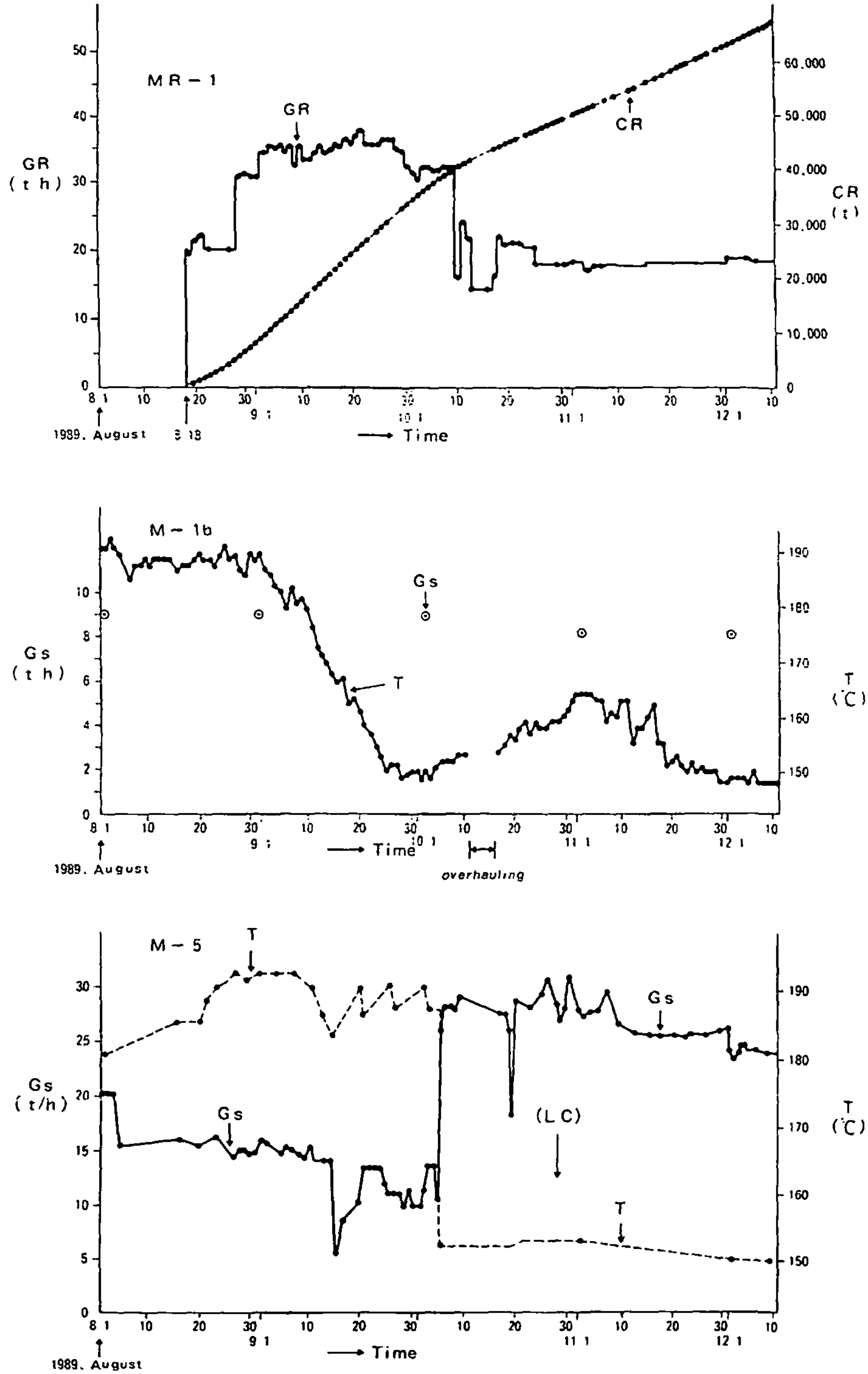

Fig. 7. Record of the second reinjection experiment. CR, cumulative reinjection; GR, reinjection rate; Gs, steam production rate; (LC), lost circulation in the drilling at M12; T, steam temperature. Well head pressures had been constant at 3.9 bar-gauge in M1b and 4.0 bar-gauge in M5.

fluid was not possible. However, from a simple mass balance, by assuming that production of the original steam had not changed, almost all the fluid reinjected into MR1 was thought to be recovered from M5 as both steam and hot water.

The pH of the hot water of M5 is around 4 and is slightly acidic. M5 has been producing this acidic hot water for years prior to the reinjection experiment described above; but the water rate was immeasurably small. This production is believed to be a result of damage to the casing pipe caused by shallow acidic water. This shallow acidic water is believed to be a result of expansion of the dry steam zone due to exploitation and mixture of this gaseous steam and O_2-rich water. Regardless of the increase in hot water production caused by the reinjection experiment, M5 is thus to be abandoned in future.

As described above, the second reinjection experiment was successful, and steam production increased as planned. Also, the increased hot water at M5 has been utilized for hot water supply for direct use, which has been in operation for many years.

DISCUSSION

Increased injection into MR1 resulted in an increase in steam and hot water production in M5 in the second experiment (Fig. 7). The steam production rate of M5 increased from approximately 15 t/h to 25 t/h (increase by approximately 10 t/h or 67%), and at the same time approximately 10 t/h of hot water started to be produced. Thus, approximately 100% of the reinjected fluid into MR1, approximately 20 t/h on average, was recovered from M5 as approximately 10 t/h of steam and 10 t/h of hot water. The reasons for this success are thought to be as follows:

(1) Both MR1 and M5 have their primary feed points on the Akagawa Fault (Fig. 1). Although there are some other production wells that have their feed points on the Akagawa Fault, the reinjected fluid into MR1 moved solely to M5 because M5 is the nearest production well from MR1 of all the production wells that have their feed points on the Akagawa Fault.

(2) The feed point pressure of MR1 during reinjection was approximately 59 bar-abs. at 600 m (Fig. 5). This pressure is much higher than the reservoir pressure around M5, at most 20 bar-abs. (Fig. 4). On the other hand, the primary feed point of M5 is thought to be 1120 m and is deeper than that of MR1. Therefore, the reinjected fluid, which is much heavier than the steam normally flowing along the Akagawa Fault, moved towards M5 from MR1 along the Akagawa Fault because of the difference in flow potential and elevation.

(3) M1b is located approximately at the same distance from MR1 as M5, and the reservoir pressure is lower at M1b than at M5. However, the reinjected fluid did not flow into M1b. This is probably because M1b has its primary feed point on the Sumikawa Fault, so that flow restriction between MR1 and M1b must have been greater than that between MR1 and M5.

(4) It took 50 days to show an increase in steam production at M5 after the start of reinjection at MR1 in the second experiment. This was a notably long time if we consider the distance between MR1 and M5 (approximately 300 m) and the difference in the flow potential as described above. This means that the reinjected fluid did not move smoothly and easily along its flow path from MR1 to M5. Thus, the Akagawa Fault on which the reinjected fluid moved towards M5 from MR1 cannot be a continuous single fault plane, but must be a series of relatively small isolated fractures.

(5) According to Hanano and Sakagawa (1990), steam flows from southwest to northeast along the Akagawa and Yunomori Faults in the Matsukawa reservoir. Since M1b is located at the lower reaches of M5, the steam flowing towards M1b along Akagawa Fault must have been cooled by the reinjected fluid as monitored in Fig. 7.

(6) The above reasons apply not only to the second experiment but also to the first

experiment. The first reinjection experiment was done intermittently, and individual reinjection periods were not always as long as those of the second experiment, except for test no. 2 (Fig. 6). This may explain the difference in effects of the reinjection between the first experiment and the second experiment. However, the reason why there was no clear steam increase in the first experiment still remains in question.

The recovery rate of the reinjected fluid was not evaluated by tracer analysis, as described above. Due to this difficulty, a precise evaluation of heat extraction by this reinjection experiment is not possible. However, despite this difficulty, the following approximate evaluation may be made.

The approximate average reinjection rate is 20 t/h, and its temperature is approximately 20°C, so that the total heat energy of the reinjected fluid is approximately 0.5 MWt (relative to 0°C). This has been recovered as both saturated steam and saturated hot water of 150°C of approximately 10 t/h each, so that the total heat energy produced is around 9.4 MWt. Thus, the heat energy recovered by this reinjection is around 8.9 MWt. Since the shortest distance between the feed points of MR1 and M5 is approximately 300 m, the heat extraction rate of unit fluid flow distance is around 30 kW/m. Assuming a single fracture of 100 m width for this heat exchange, the heat flux extracted from this fracture plane is evaluated to be 300 W/m^2. Since the natural vertical heat flux that penetrates the Matsukawa reservoir is approximately 1.5 W/m^2 (Hanano and Matsuo, 1990), the heat flux extracted by this reinjection is approximately 200 times greater than the natural one. Therefore, extremely efficient heat extraction has been achieved in this reinjection experiment.

CONCLUDING REMARKS

The reinjection experiment conducted at Matsukawa has been successful, and extremely efficient heat extraction has been achieved. However, the reinjection rate in this experiment is not always large enough. Thus, we are planning to continue this series of experiments and collect data for the coming full-scale field-wide reinjection.

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FLUID FLOW PROCESSES IN THE BEPPU GEOTHERMAL SYSTEM, JAPAN*

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Abstract—The Beppu geothermal system is centred beneath the late Quaternary volcanoes of Tsurumi and Garandake at the northern end of the Ryukyu volcanic arc. The deep fluid has a temperature of at least 250–300°C, and an inferred chloride concentration of 1400–1600 mg/kg. Apart from fumarolic areas near the summits of the two volcanoes, most thermal activity occurs at low elevation along the two main outflow paths towards the coast. The hot spring waters of downtown Beppu have originated from outflow along the Asamigawa Fault, with their chemistry indicating predominantly dilution of the deep fluid by groundwater. The second outflow zone towards the hot spring area of downtown Kamegawa coincides with a ridge of lavas. Here boiling, steam loss, and subsequent mixing with steam-heated groundwaters have significantly modified both the deep fluid and host rocks. The area of the geothermal system above 200°C is at least 15 km² at sea level, and the total natural heat output is inferred to be at least 250 MW. Most of this heat output occurs as subsurface hot water outflows towards the coast due to the 1300 m of topographic relief across the system.

INTRODUCTION

Beppu has a long history as a resort area in Kyushu Island, southwest Japan, which is famous for its onsen (hot spring bathing) and its jigoku (literally "hells"; fumaroles and steaming ground). In order to enhance the flow of hot water, wells were drilled as early as 1880 (Yusa, 1985). The total flow of hot water and steam from wells has been between 400 and 700 kg/s since the mid 1920s, with over 2000 wells in existence today. The wells range up to 700 m in depth, and temperatures of over 200°C have been measured. Apart from bathing and house heating, the geothermal fluid is also used for small-scale agricultural applications and a small electricity generating plant.

Systematic measurements of the physical and chemical characteristics of the thermal activity and wells began in 1924 with the establishment of the Beppu Geophysical Research Station of Kyoto University. Since then, over 300 papers have been published on the Beppu geothermal system (Japanese language bibliographies have been compiled by the Balneological Society of Japan, 1973; 1985). Nearly all the papers are in Japanese. Brief English language summaries are contained in guidebooks for fieldtrips organised during international conferences (Shirozu *et al.*, 1970; Yuhara *et al.*, 1980; Taguchi and Hayashi, 1987).

This paper is the result of a recent, complete review of all aspects of the Beppu geothermal system (Allis *et al.*, 1988). The full review is an English language report which has had limited circulation within Japan. Those parts of the report which are suitable for publication in an international journal have been divided into two papers. This paper is predominantly concerned

*Contribution no. 2, Foreign Visiting Scientist Section, Beppu Geophysical Research Laboratory, Kyoto University.

with reviewing the physical and chemical characteristics of the system, and establishing the hydrothermal processes influencing the thermal activity.

TECTONIC SETTING

The Beppu geothermal system is situated near the northern end of the Ryukyu volcanic arc, in northeastern Kyushu (Fig. 1). The oceanic lithosphere of the Philippines plate is at present being subducted in a northwest direction beneath the Asian plate at around 4 cm/yr along this part of the plate boundary zone (Seno, 1977). Subduction begins at the Nankai trough about 250 km to the southeast of Beppu, and the seismic subduction zone extends to about 100 km depth, directly beneath Beppu.

Much of the deformation occurring in northeastern Kyushu is obscured by the large outpouring of recent volcanics, but the available evidence indicates a tensional regime. Numerous short, normal faults, which mostly trend east–west and cut the slopes of the volcanoes, suggest active rifting (Ikeda, 1979). However focal mechanism solutions from microearthquake activity near Beppu indicate that a component of dextral shear is also present on southwest trending faults (Sudo, 1987). A negative Bouguer gravity anomaly of up to −40 mgal encloses much of the volcanic zone within which the Beppu system is situated (Fig. 1). The anomaly delineates a 2000 km^2 subsidence zone sometimes referred to as the Beppu-Shimabara Graben. Three dimensional modelling of the gravity suggests that the pre-Tertiary, granitic basement rocks lie at 1–2 km below sea-level beneath Beppu, and that they deepen to over 3 km depth further east in Beppu Bay (Komazawa and Kamata, 1985).

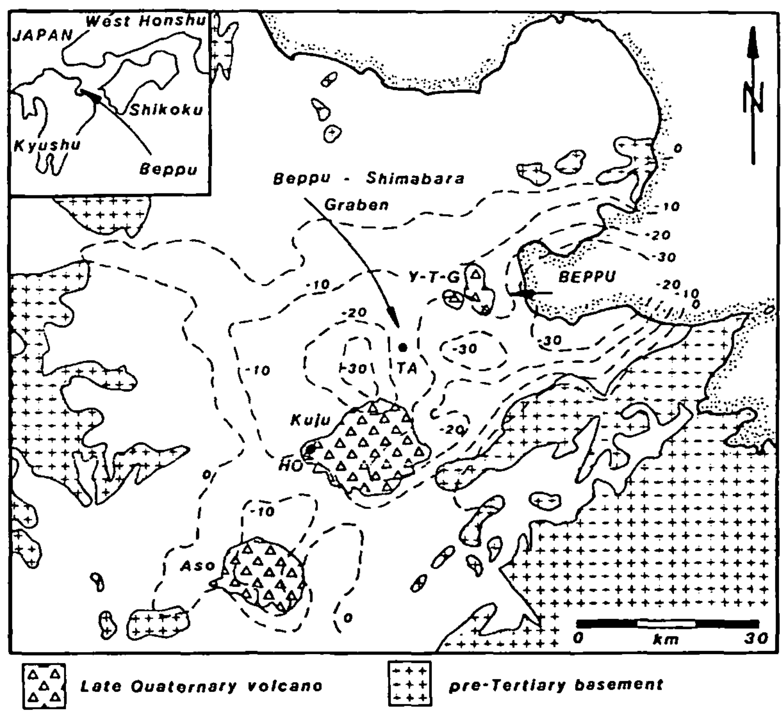

Fig. 1. Location of Beppu in the northeast of Kyushu, Japan. The dashed contours are regional Bouguer gravity anomalies in mgal (after NEDO, 1987; topographic density of 2.2 Mg m^3). Y-T-G is the Yufu-Tsurumi-Garandake volcanic centre. HO is the Hatchobaru-Otake geothermal power stations and TA is the site of the planned Takigami power station.

The present phase of volcanism in central and northeastern Kyushu may have begun about 5 My ago, and has probably been contemporaneous with subsidence of the Beppu-Shimabara Graben (N.E.D.O., 1987). The volcanism has been predominantly andesitic to rhyolitic in composition, with the late Quaternary volcanics being almost entirely andesitic. There are three late Quaternary volcanic centres: Aso, Kuju, and Yufu-Tsurumi-Garandake (Fig. 1). High temperature geothermal resources occur in several places in the volcanic zone. Apart from Beppu, possibly the most well-known is the geothermal system on the west side of Kuju which is being exploited by the Hatchobaru and Otake power plants. The Takigami system, 10 km west of Mt. Yufu, is about to have a 50 MW power plant installed (Fig. 1).

The Beppu geothermal system is located on the eastern flanks of the Yufu-Tsurumi-Garandake volcanic centre. The volcanoes rise up to 1.5 km above sea-level, with the geothermal activity spread between the summits of Tsurumi and Garandake, and the coastline 8 km to the east. An apparently separate geothermal system is situated on the southwestern slopes of Mt. Yufu, around the town of Yufuin. The volcanic centre last erupted lavas between 1000 and 2000 years ago, and its recent phase of activity may have begun about 0.5 My ago (Yufu volcanics, Kobayashi, 1984; Hayashi and Taguchi, 1987). These lavas are mostly hornblende andesite or dacite. Older pyroxene andesite lavas (Hohi volcanics, 0.7–2 My ages, Hayashi and Taguchi, 1987) surround these recent volcanics, and presumably underlie the region (Fig. 2).

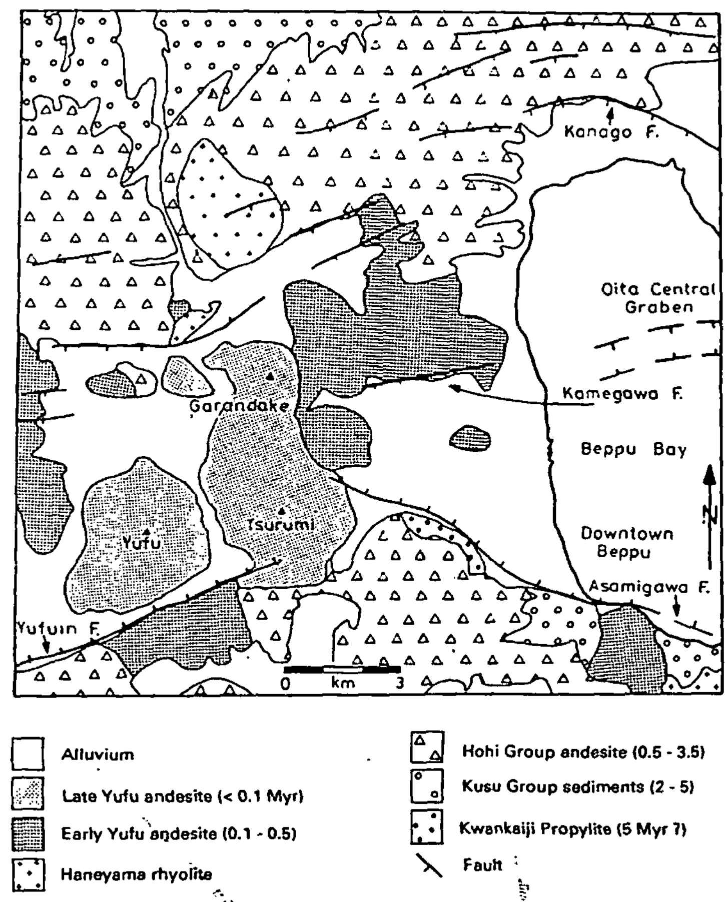

Fig. 2. Simplified geology of the Beppu region.

Much of the Beppu city area is situated on a volcano-sedimentary fan deposit on the lower slopes of Tsurumi and Garandake. Drillers' logs suggest that the thickness of alluvial sediments and volcanic breccias reaches a maximum of 500 m midway along the coast between downtown Beppu and downtown Kamegawa (Fig. 2). This may mark the axis of subsidence within the Beppu-Shimabara Graben.

There are two major faults associated with the Yufu-Tsurumi-Garandake volcanic centre that have strong topographic relief for distances of over 10 km, and which show up clearly on Landsat imagery. They are the Asamigawa and Yufuin Faults (Fig. 2). Some highly productive geothermal wells in Beppu are located close to the Asamigawa Fault. An elongate outcrop of high grade hydrothermal alteration (Kankaiji propylite) on the upthrown, south side of this fault indicates it has been a focus for fluid outflow. On the northern side of the Beppu geothermal system is the Kamegawa Fault. Although high temperature fluids are also found near to this fault, they are spread over a relatively broad area coinciding with an east-trending ridge of lavas. The Kamegawa Fault may therefore not be a significant, high permeability path for outflowing geothermal fluids.

PHYSICAL STATE OF THE GEOTHERMAL SYSTEM

Natural features

The natural thermal manifestations of the Beppu geothermal system were mostly concentrated in two areas, on the northern and southern sides of the fan deposit (Fig. 3). These two areas are known as the Beppu and Kamegawa thermal zones, after the towns that grew up around the hot springs. The towns have now merged to become Beppu city. In addition to these

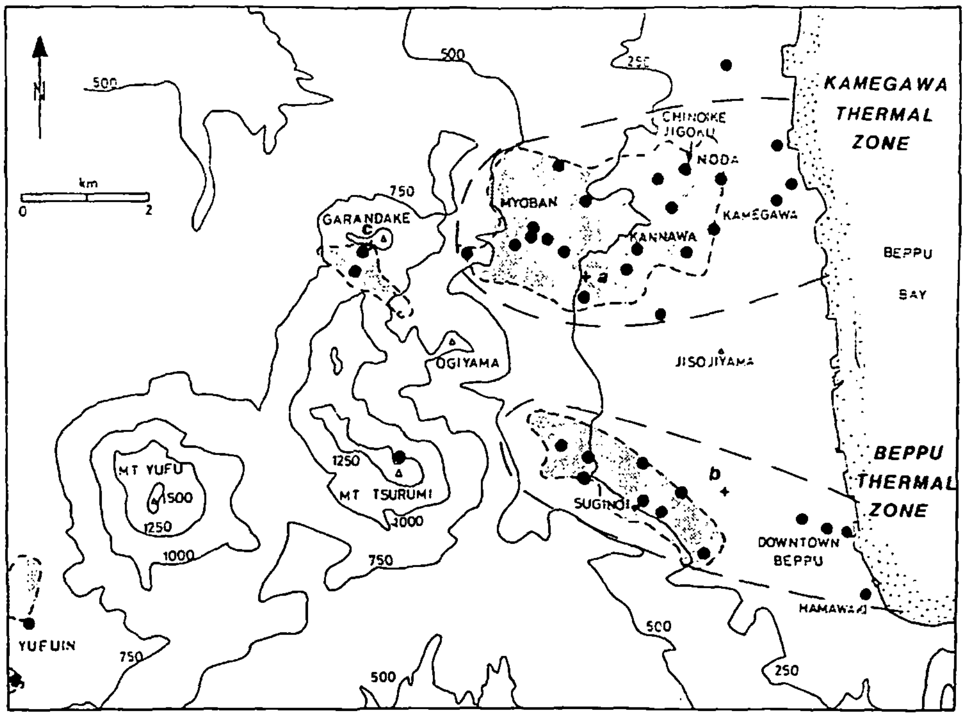

Fig. 3. Distribution of original sites of natural thermal features (circles) as well as the areas of surface rock alteration. Labelled areas are referred to in the text. a–c are the sites of the wells referred to in Fig. 4.

two thermal zones there are areas of fumarolic activity near the summits of Garandake and Tsurumi.

There is virtually no information about the original hot springs in the thermal zones because intensive drilling of wells, as well as development of the towns during the early 1900s, resulted in most springs disappearing. All hot water in the two downtown areas is now extracted through wells. Only one natural hot spring exists today. This is the Chinoike Jigoku ("blood pond hell"), on the northern side of the Kamegawa thermal zone. This spring is actually an overflowing pool, 1000 m^2 in area, with a narrow throat 26 m deep. Most of the pool has a temperature of 60–80°C, but the inflow to the throat is at 136.8°C. The heat output is about 7 MW (Yuhara *et al.*, 1978). The bright red colour of the pool is caused by hematite precipitating in the very acidic waters (Yoshida *et al.*, 1978). The precipitate also contains the following metal concentrations (mg/kg): 23 Au, 383 Ag, 4440 As, 180 Sb, 442 Pb, 104 Zn, 578 Cu, (Koga, 1961). More recent analyses of the precipitate failed to detect anomalous gold (<0.1 mg/kg) but confirmed the concentration of arsenic (M. Aoki, Geological Survey of Japan, pers. comm. Oct., 1988).

The thermal activity at higher elevation, especially above 100 m.a.s.l. in the Kamegawa thermal zone, consists of mudpools, fumaroles, and steam-heated ground. In the thermal areas near the summits of Garandake and Tsurumi, superheated steam is exiting from fumaroles. Recent heat discharge estimates have been made using airborne infrared technology (Yuhara *et al.*, 1987). Although there were large uncertainties due to calibration problems, the heat output of the Garandake thermal area was estimated to be 20 MW, compared to 1 MW from the Tsurumi thermal area. Qualitative visual observations suggest that the other steam-heated thermal activity around the Beppu system is small compared to that near the summit of Garandake.

The surface hydrothermal alteration at Beppu is confined to two main areas which roughly coincide with the areas of thermal activity (Fig. 3). On the northern side of the Beppu system there is a zone of intense acid–sulphate alteration which extends eastwards from Garandake to almost the coastline. The steam-heated thermal activity and the very acidic fluids (pH < 3) discharging from some wells in this area indicate that the alteration is continuing today. In places the alteration has been sufficient to completely reduce the andesite to opaline silica. The silica deposits have been mined since the early 1950s as a source of silica for water glass and white cement. The deposit near the summit of Garandake is still being mined today. Oxidation of H_2S in ascending steam by downward percolating groundwaters, and subsequent interaction of the acidic fluids with the surrounding rocks, has caused the alteration. On the southern side of the Beppu system, a low temperature, acidic style of alteration is presently overprinting the older, high temperature hydrothermal alteration of the Kankaiji propylite (Yusa, 1969). The Kankaiji propylite was mined between 1903 and 1916, yielding 144 kg of gold and 257 kg of silver (old records of Beppu city, 1933).

Subsurface temperatures and pressures

Unfortunately downhole measurements in completed wells at Beppu are rare because the wells are generally private, their owners wish to use the wells immediately, and there is no provision made at the wellhead for running a probe at some later date. All subsurface temperature and pressure data must therefore be inferred from bottomhole temperatures and water levels measured by the drillers during drilling. A large amount of obviously unreliable data has been culled out to obtain a consistent data set. Even so, the uncertainties in temperature between wells could be at least 20°C. Many wells are boiling at the wellhead when discharging, and excess steam in the discharge fluid, combined with difficulties in making accurate flow measurements, means wellhead enthalpy is an unreliable indicator of downhole conditions.

A typical example of the thermal conditions in many wells in Beppu city is shown in Fig. 4a. This well is located on the upper slopes of the city, and shows a potential for downflows below about 150 m depth. Below this depth, the decline in water level with increasing depth implies a vertical pressure gradient of about 70% of a hydrostatic gradient. This subhydrostatic gradient probably exists in the transition zone between a cool, near-surface aquifer and a deep, hot water aquifer. In this case the well is not quite deep enough to penetrate the main hot water zone which is probably at the boiling point.

The two other examples in Fig. 4 show characteristic profiles for different parts of the Beppu

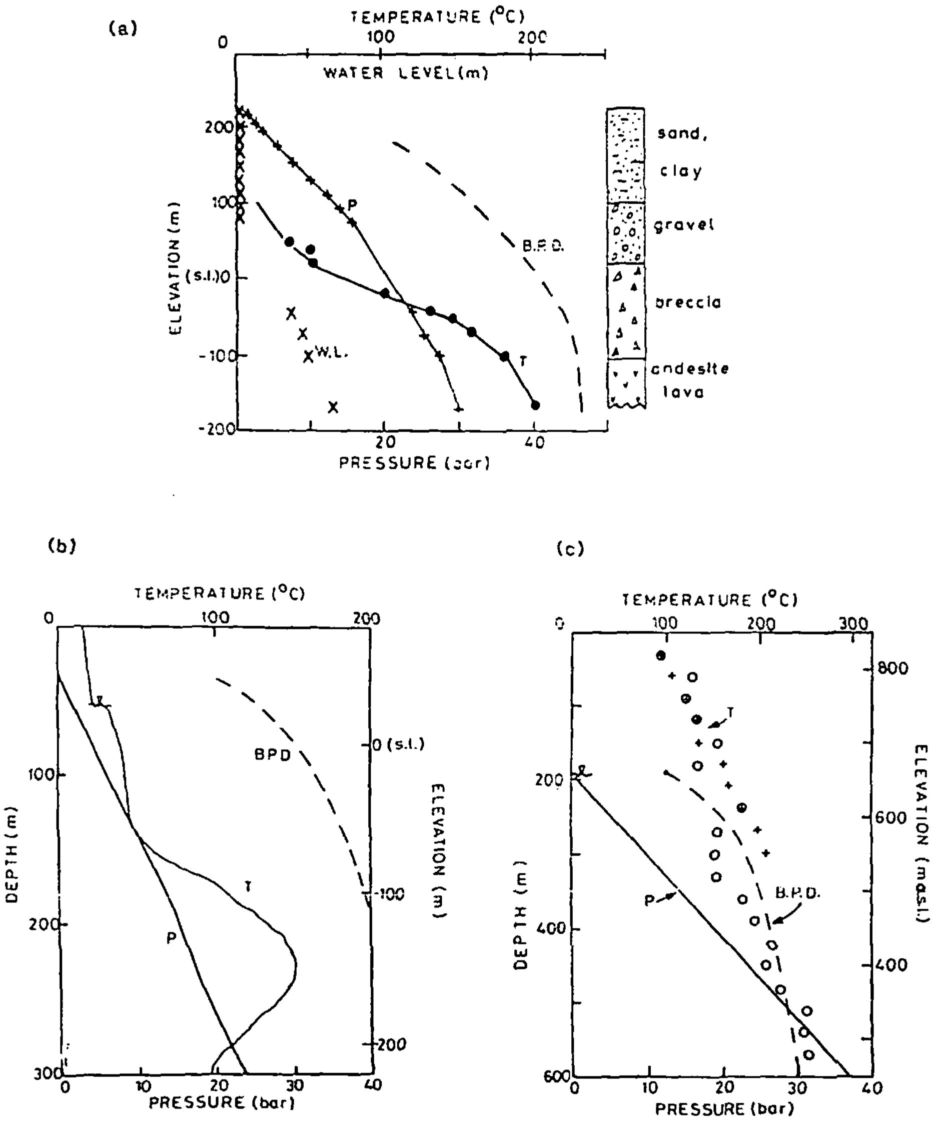

Fig. 4. (a) Vertical variation in water level (W.L.), and bottom hole temperature (T) measured during the drilling of a well in the upper Beppu thermal zone. The pressure profile P is derived from the water level measurements, and the boiling point for depth profile (BPD) is based on the pressure profile. (b) Temperature and pressure profiles in a well on the grounds of Kyoto University, Beppu. (c) Temperatures and pressures in a well near the summit of Garandake. The BPD applies to the pressure curve (water level) measured after completion of the hole.

system (see Fig. 3 for locations). The temperature inversion in the monitor well recently drilled on the grounds of Kyoto University, Beppu (Fig. 4b) indicates the hot water aquifer that probably feeds the original hot spring area closer towards the coast. This well contrasts with the exploration drillhole near the summit of Garandake, which appears to be over part of the deep upflow zone (Japan Geothermal Development Promotions Centre, 1979; Fig. 4c). The maximum temperature of close to 250°C occurs at the bottom of the well, where the temperatures are controlled by saturation conditions. The pressure and the boiling point curves shown in this figure probably only apply to the lower part of the well. The temperatures in the upper part of the well were measured when the well had only been drilled to 300 m depth. They show that two phase conditions are probably present from the surface.

The temperatures in wells near the coast midway between the Beppu and Kamegawa thermal zones indicate a uniform temperature gradient of around 70°C/km (Fig. 5). The gradient extrapolates to a zero-depth temperature which is similar to the mean annual ground temperature at Beppu. It is also similar to the gradient compiled from many wells in Oita city, 10 km to the east of Beppu city (Kikkawa and Kitaoka, 1984). Thus the gradient of 70°C/km may be indicative of the regional conductive heat flow. Although the thermal conductivity of the sediments at Beppu or Oita has not been measured, it is likely to be in the range 1.5–2.0 W/m°C, which is typical for poorly compacted sediments. The regional heat flow is therefore likely to be at least 100 mW/m^2. This places the southern Beppu Bay area within the high heat flow anomaly of central Kyushu (Ehara, 1984).

The lateral temperature variations across the Beppu system are shown in Fig. 6a at an elevation of −100 m.a.s.l. The map shows two outflow zones of geothermal water that coincide with the two zones of surface thermal activity. Beneath the original hot spring areas around downtown Beppu and Kamegawa, the temperatures are in the range 50–70°C. This is probably the maximum temperature in the hot water aquifer beneath downtown Beppu because wells are not generally drilled below −100 m.a.s.l. here. However the hot aquifer may be at greater depth

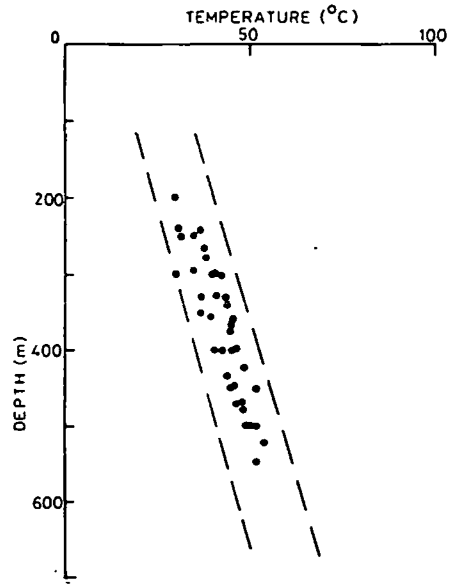

Fig. 5. Composite temperature-depth plot for wells from between the Beppu and Kamegawa thermal zones. The dashed lines indicate the spread of data compiled in a similar way from many wells in Oita City (Kikkawa and Kitaoka, 1984).

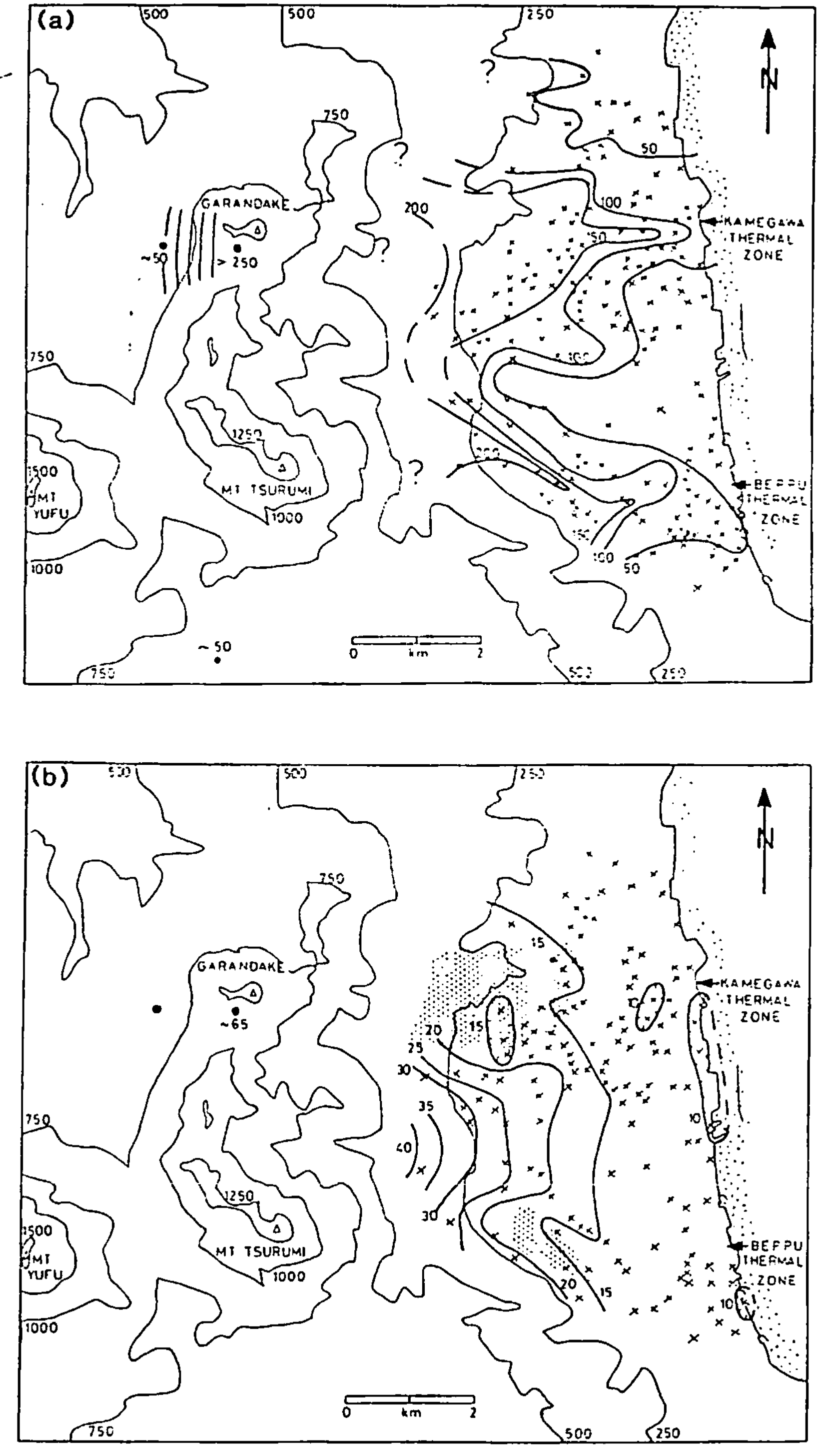

Fig. 6. (a) Isotherms in °C at 100 m below sea-level inferred from bottom hole measurements reported in the driller's logs. Crosses mark the data points. (b) Isobars (bars gauge) at 100 m below sea-level, inferred from water level measurements reported in drillers' logs. A pressure of 10 bar is equivalent to hydrostatic pressure from sea-level. Stippled areas are two phase zones inferred from the isobars and isotherms.

beneath the downtown Kamegawa area because wells are often drilled to −200 m.a.s.l. where temperatures slightly above 100°C are encountered. Both the Beppu and Kamegawa thermal zones have temperatures in excess of 200°C towards the western edge of the drilled area of Beppu city. The maximum temperature recorded within the city is 248°C at −300 m.a.s.l. near the western limit of the Beppu thermal zone. This, coupled with the equally high temperature in the well near the summit of Garandake around 4 km away, points to a 15 km^2 deep high temperature resource area beneath the eastern flanks of Tsurumi and Garandake. Much cooler temperatures in wells 1 km west of Garandake, and 3 km south of Tsurumi, suggest the high temperature anomaly is confined to beneath the two volcanoes, with the main outflow being to the east.

The horizontal pressure gradients across the Beppu system at −100 m.a.s.l. are shown in Fig. 6b. This confirms the strong eastwards outflow that is implied by the topography. Fluid pressures towards the west of the drilled area are significantly higher in the central and southern parts of the system than in the north. Along the 250 m.a.s.l. topographic contour, fluid pressures are 20–30 bar in the south–central area compared to 15–20 bar in the north. When compared to the temperatures in Fig. 6a it is apparent that the fluid is at, or very close to, being two phase in the north, whereas temperatures are significantly below the boiling point in the centre and much of the south of the drilled area (at −100 m.a.s.l.). This is consistent with the acidic discharge fluids and the intense alteration that are present in much of the Kamegawa thermal zone. The areas of two phase conditions at −100 m.a.s.l. inferred from drillhole data are stippled in Fig. 6b.

Figure 6b has several pressure minima which appear to be due to drawdown effects. The three anomalies near the coast contain wells with water levels up to 10 m below sea-level (i.e. 9 bar at −100 m.a.s.l.). There is a sufficient number of wells to suggest that these pressures are real, and not due to water level measurement problems. Supporting evidence comes from sea-water intrusions at several places along the coast (Kikkawa and Kitaoka, 1977; Kitaoka, 1978). The 15 bar low anomaly within the Kamegawa thermal zone coincides with a heavily exploited area of Kannawa where some wells now discharge super-heated steam.

FLUID CHEMISTRY

The *onsen* at Beppu have long been noted for their diverse chemical constituents and their wonderful healing powers. The principal thermal water types are a high temperature, near-neutral sodium chloride water, a near-neutral bicarbonate water, and a sulphate water which is often acidic. A wide range of mixtures between these end members exists in different parts of the system, and at different depths. These differences show up on a $Cl–SO_4–HCO_3$ trilinear plot (Fig. 7). A chloride-rich water is present towards the western end of the two thermal zones (Kankaiji and Myoban-Kannawa). However, shallow wells here (<200 m depth) also encounter a bicarbonate-, or sulphate-rich water, depleted in chloride. These are steam-heated waters. Chloride is less dominant in the waters of the two downtown areas, with the downtown Beppu area having a mixed bicarbonate–chloride water compared to a mixed chloride–sulphate–bicarbonate water in downtown Kamegawa. The Noda area (northwest of downtown Kamegawa) has a chloride–sulphate mixture with low bicarbonate concentrations, due to the very low pH of these waters.

The lateral variations in the concentrations of the major chemical constituents are shown in Fig. 8 using hexaplots. Apart from the complications due to shallow and deep wells, the general trend for higher chloride concentrations in the Kamegawa thermal zone (occasionally in excess of 2000 mg/kg in the separated water at the wellhead) than in the Beppu thermal zone (generally <1000 mg/kg) is apparent. The highest sulphate concentrations (400–600 mg/kg) are typically restricted to the western parts of the Kamegawa thermal zone. However, the highest bicarbon-

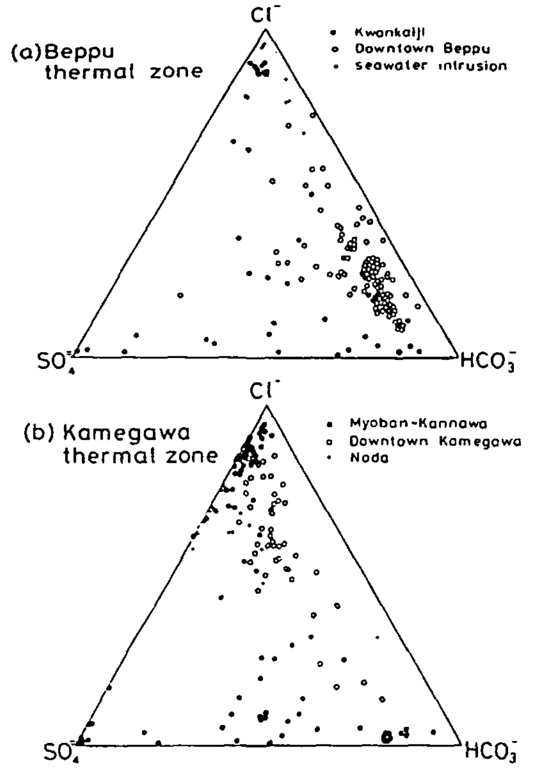

Fig. 7. Trilinear $Cl-SO_4-HCO_3$ plots derived from equivalent concentrations in discharge waters from the Beppu and Kamegawa thermal zones. The labelled areas are shown on the map in Fig. 3.

ate concentrations (up to 1000 mg/kg) occur in the Beppu thermal zone. The very saline water example in Fig. 8 is from an area of sea-water intrusion in downtown Beppu.

The amount and composition of gases in steam separated at the wellhead at Beppu is very variable (Koga and Noda, 1973). Gas concentrations range up to about 10% by weight, with significantly higher concentrations occurring in the Beppu thermal zone than in the Kamegawa thermal zone. The gas is predominantly CO_2 with minor H_2S and traces of NH_3 and F_2. The molar ratio of CO_2/H_2S is typically in the range 30–100. Shallow wells tapping a steam zone in the Myoban area have relatively high H_2S concentrations, whereas fluids in the downtown Kamegawa area have relatively low H_2S concentrations. This trend in H_2S concentration along the Kamegawa thermal zone is consistent with progressive boiling and gas loss from a fluid undergoing depressuring as it flows towards the coast. The small amount of data for the Beppu thermal zone indicates a similar trend.

Geothermometers

The silica concentrations in the Beppu waters are highly variable and in general give little information about a high temperature water at depth. This is partly due to the variable pH of the waters, and doubt over the appropriate silica phase controlling the equilibration process. Amorphous silica equilibrium is suspected for the near-neutral waters of downtown Beppu because the host rocks are recent volcanic breccias and sediments containing glass.

The graphic Na–K–Mg geothermometer of Giggenbach (1986) has been applied to the Beppu waters because of its ability to incorporate large amounts of data and the mixing relationships it

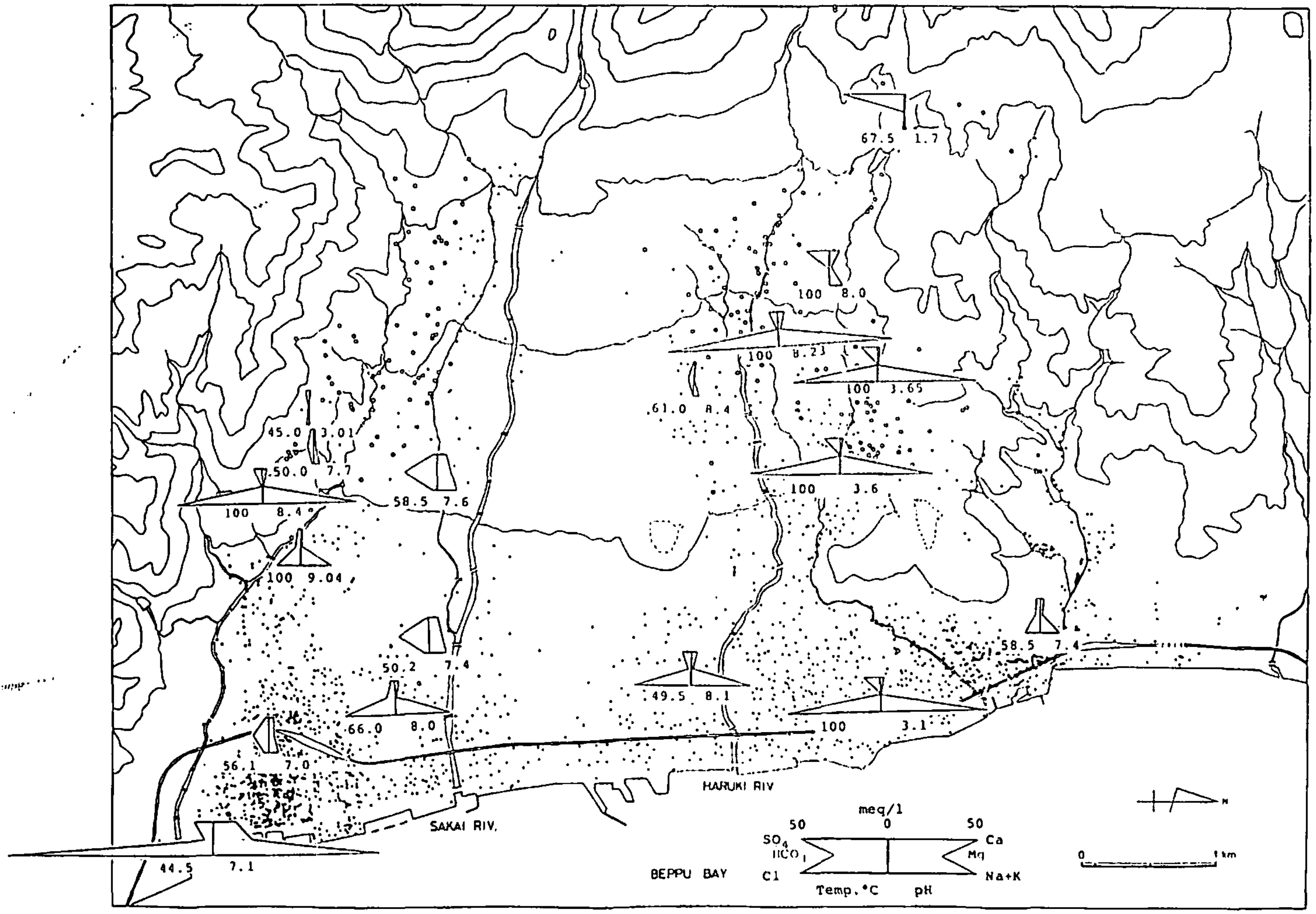

Fig. 8. Examples of hexaplots of the major ionic concentrations of discharge waters in different parts of the Beppu system. Dots show the distribution of wells in Beppu City (after Kikkawa and Yusa, 1976).

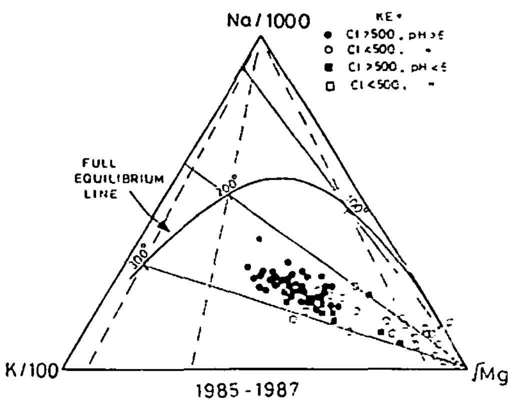

Fig. 9. Application of the Na–K–Mg geothermometer to Beppu discharge waters for the period 1985–1987. The data imply a deep water temperature (i.e. full equilibrium) of between 250–300°C.

sometimes reveals (Fig. 9). Extrapolation of the trend exhibited by all Beppu data implies a full equilibrium, fluid temperature of 250–300°C. The low discharge temperature waters and the low chloride concentration waters plot close to the Mg corner, as would be expected from extensive dilution with cool groundwaters. The acidic waters show slightly more scatter, but their trend is not significantly different from the neutral pH waters.

CHLORIDE–ENTHALPY TRENDS

A large amount of data on the chloride concentrations of separated water, and the respective flows of steam and water from the wellhead at atmospheric pressure, has been collected by the Geophysical Research Station, Kyoto University, Beppu. The mass flows can be combined to give a discharge enthalpy, and the chloride concentrations can be corrected for the steam fraction to give the average concentration of the total discharge. This enables a chloride–enthalpy plot to be constructed, and possible fluid flow relationships to be investigated (Fig. 10). A characteristic of the Beppu system is for fluids from the Beppu thermal zone to be clustered in the low enthalpy–low chloride corner of the graph, whereas many of the Kamegawa thermal zone wells discharge a wide range of fluids suggestive of excess steam through to steam loss by boiling. This pattern is not simply due to the well distribution in the two zones. Apart from the few Beppu thermal zone wells with low enthalpies and high chloride concentrations (due to sea-water intrusion), the maximum chloride concentration in the higher enthalpy wells is 1300 mg/kg in the Beppu zone, compared to close to 2000 mg/kg in the Kamegawa thermal zone. These differences need not indicate different fluid origins in the two thermal zones. Figure 10 shows that a single parent is capable of devolving into the two fluids found in each thermal zone.

The bottomhole temperature data and the geothermometry are consistent with a liquid parent temperature of 250–300°C, or an enthalpy of 1100–1350 kJ/kg. With the constraints of steam loss or gain, or dilution, the data in Fig. 10 require a single parent fluid to have a chloride concentration of at least 1400 mg/kg for this enthalpy range. Assuming that some dilution and some steam loss occur in the deep upflow zone as the fluid rises towards the two outflow zones tapped by the wells, then the deep parent fluid could have a deep chloride concentration of at least 1600 mg/kg (shown in Fig. 10). The essential difference between the fluids in the two thermal zones appears to be that dilution dominates along the flowpath between the deep parent and the Beppu thermal zone, whereas boiling and steam loss is important in the Kamegawa thermal zone. The Kamegawa thermal zone has 200°C fluids with chloride concentrations of up

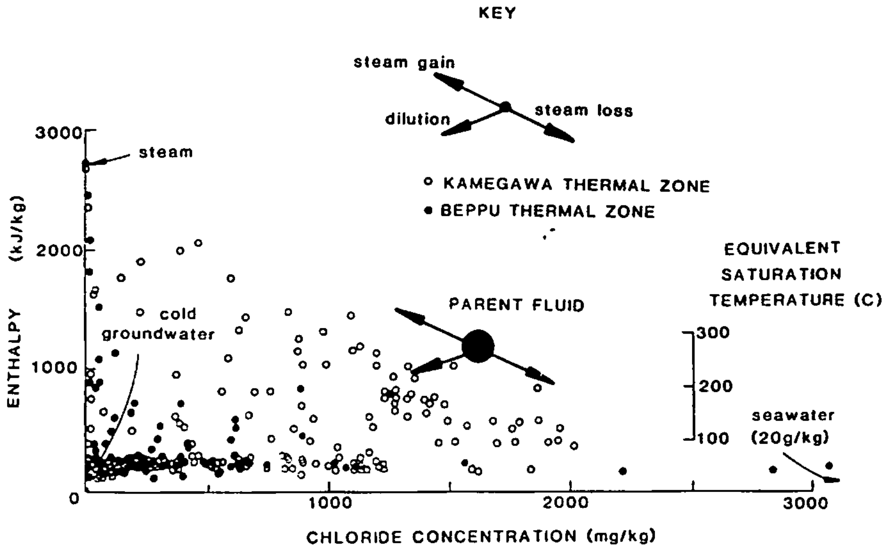

Fig. 10. Chloride–enthalpy plot of well discharges in Beppu City. Note that wells from the Beppu thermal zone generally have lower chloride concentrations and enthalpy values than those from the Kamegawa thermal zone (with the exception of the steam-heated groundwaters).

to 2000 mg/kg because these fluids have cooled in the upflow zone by steam loss. The Beppu thermal zone contains 200°C fluids with chloride concentrations of less than 1300 mg/kg because these fluids have cooled in their upflow zone by dilution.

The data in Fig. 10 are too scattered to be more specific about the fluid flow process occurring within the two thermal zones. Several wells discharge fluids with enthalpies of 600–1000 kJ/kg, and very low chloride concentrations. These are steam-heated groundwaters, which are probably mixing with the outflowing chloride waters further along the outflow path (e.g. as shown in Fig. 8). Therefore the dilution line applying to any particular area does not necessarily pass through the cold groundwater point (60 kJ/kg enthalpy, 10 mg/kg chloride). Many wells have chloride–enthalpy values which plot above all reasonable dilution lines. These wells have excess steam in their discharges, either because they tap a natural steam zone, or because the pressure decline around the feedzone to the well has been sufficient to dry-out the adjacent countryrock. Both situations are likely to be present in the Beppu system.

Most of the wells with fluid discharge temperatures below 100°C have to be pumped, and they therefore have relatively low flowrates. Conductive cooling in the upper part of the well may be the reason for the band of data with enthalpies of 160–250 kJ/kg (40–60°C). A small proportion of this data can be attributed to mixtures with cold sea-water. Very few wells have been drilled in areas where discharge temperatures are significantly below 40°C so there is a natural, low enthalpy cut-off to the data.

DISCUSSION AND CONCLUSIONS

The presence of two different fluid flow processes along the paths to the two outflow zones of the Beppu geothermal system explains several other characteristics besides the difference in chloride concentrations. The intense acidic alteration of the rocks, the low pH fluids, the broad area of steam-heated thermal activity and the abundance of shallow, high enthalpy well discharges are all consistent with boiling and steam loss from the fluid flowing to, and along the

Kamegawa thermal zone. Here, steam zone(s) have formed at shallow depth within the upper flanks of Garandake. The relatively high gas content of the Beppu thermal zone on the other hand may be due to dilution with groundwater and, consequently, a lack of boiling along this flow path (generally most gas separates with the first steam). Referring back to the isotherms and the isobars in Fig. 6, the horizontal temperature gradient in the Kamegawa thermal zone may be strongly influenced by the rate of steam loss, and hence the rate of pressure decline along the flowpath. However, in the Beppu thermal zone, the horizontal temperature gradient is presumably largely controlled by the rate of mixing with cool groundwaters. Relatively high tritium concentrations have been found in many of the well discharges along the Beppu thermal zone indicating that dilution with young ground water is rapid (Kitaoka, 1979). Modelling of the shallow hydrology suggests turnover times of the order of 10–50 yr, and relatively high transmissivities of 100–800 darcy-m (Kitaoka, 1984; Yusa, 1984).

Figure 11 summarises our present understanding of the hydrology of the Beppu geothermal system. The deep, high temperature parent fluid of at least 250–300°C and 1400–1600 mg/kg chloride is inferred to be present beneath the cones of Tsurumi and Garandake. The area of the system with a temperature of at least 200°C at sea-level is conservatively estimated to be 15 km^2. This assumes the western and southern flanks of Tsurumi are relatively cool. The fumarolic area on top of Tsurumi suggests that at least the northern flank of the volcano is underlain by geothermal fluid. The two phase zones in Fig. 11 are based on the temperatures and pressures measured in drillholes, and also on a qualitative interpretation of the aeromagnetic anomaly pattern over the volcanic centre. The cones of Yufu and Tsurumi have prominent positive magnetic anomalies in contrast to Garandake, which is non-magnetic (aeromagnetic survey

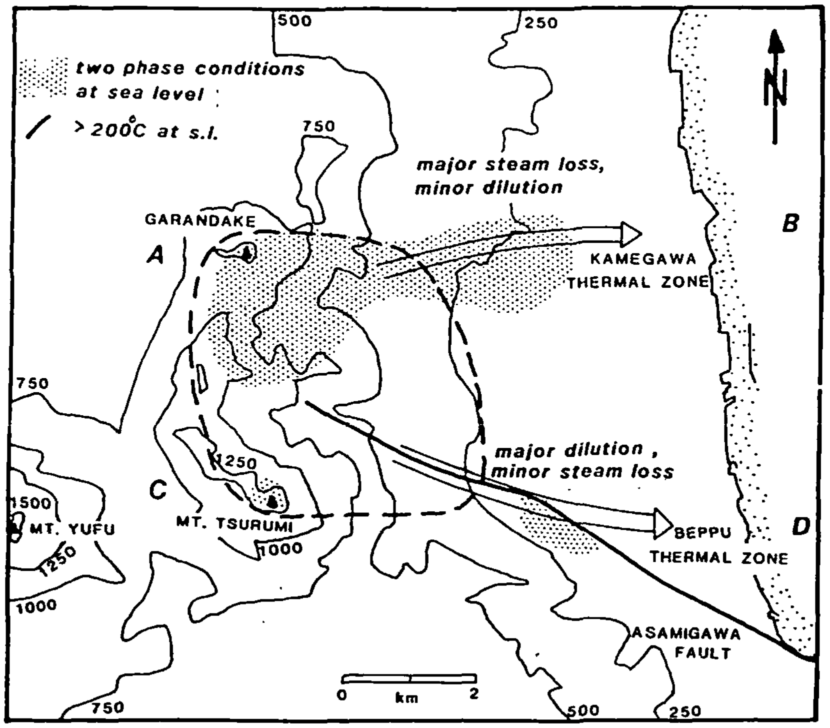

Fig. 11. Summary map of the major fluid flow patterns of the Beppu geothermal system. A–B and C–D mark the cross-sections in Fig. 12.

published by Electric Power Development Company 1978). The cone of Garandake appears to have had its magnetite destroyed by intense hydrothermal activity, such as that at present occurring beside the quarry near its summit. Here, acidic hydrothermal fluids have reduced the andesite to silica, which is now being mined. The temperature profiles in the 600 m deep well here indicate two phase conditions down to the bottom of the well (250 m.a.s.l.), so steam and gas are rising from below this elevation. The relatively high sulphidation state and acidic conditions that can occur in this situation often cause magnetite to be replaced by pyrite or pyrrhotite. A study of the magnetic properties of the surface rocks of the volcanic centre and numerical modelling of the aeromagnetic data are in progress.

The interesting feature of the aeromagnetic anomaly map is that the cone of Tsurumi is magnetic. This suggests that the two phase zone associated with the Tsurumi fumarolic area is relatively small in volume. If so, this would be consistent with the inferred lack of steam loss from fluids within the Beppu thermal zone that flow from the flanks of Tsurumi. The higher fluid pressures found beneath the lower flanks of Tsurumi compared to Garandake (Fig. 6) may be typical of the whole of the volcano. Tsurumi is over 300 m higher than Garandake, so this factor alone could be causing the higher fluid pressures at depth. The western end of the Asamigawa Fault is deeply incised into the northern flanks of Tsurumi, and forms a natural groundwater catchment that would also inhibit boiling at depth. The high productivity of wells drilled on the Asamigawa Fault in Beppu city indicates that this fault is a high permeability path for fluid flow along the Beppu thermal zone. Towards its western end it may also provide a high permeability path for downflowing groundwater.

The lack of thermal activity around the upper flanks of Tsurumi, apart from the small fumarolic area near its summit, and the inferred dominance of downwardly infiltrating groundwater rather than upflowing geothermal fluid, suggests high horizontal temperature gradients within the cone. A relatively narrow, pipe-like two phase zone may link the fumaroles near the summit and the high temperature zone at depth. Thermal stresses related to the high temperature gradients may be causing the high level of microseismicity originating from within the cone (Sudo, 1987). There is no evidence of magmatic gases (e.g. SO_2 and HCl) in the fumaroles of Tsurumi or Garandake, but detailed sampling and analysis do not appear to have been carried out.

Speculative cross-sections corresponding to the Tsurumi–Beppu thermal zone and the Garandake–Kamegawa thermal zone are shown in Fig. 12. The large difference in the area of two phase conditions in each cross-section reflects the difference between upflowing steam beneath the flanks of Garandake and infiltrating groundwater beneath the flanks of Tsurumi. In the case of the Tsurumi–Beppu thermal zone the depicted outflow of geothermal fluid may be restricted to the Asamigawa Fault, except near the coast where the fluids spread out into the fan deposit. Flow along the Garandake–Kamegawa thermal zone may not be confined to any particular fault. The thermal zone coincides with a ridge of lavas which outcrops almost all the way to the coast. In contrast to the relatively narrow zone of surface hydrothermal alteration along the Asamigawa Fault, rising steam and gas has caused a 6 km^2 area of intense, acid-sulphate alteration over the upper part of the Kamegawa thermal zone (Fig. 3). High primary permeability within the lavas may be controlling the outflow of geothermal fluids within the Kamegawa thermal zone.

The Beppu system has all the characteristics of a typical, andesite, volcano-hosted geothermal system (Henley and Ellis, 1983), similar to many others around the Pacific margin. Apart from super-heated fumaroles near the summits of Garandake and Tsurumi, the surface thermal activity in the outflow zones is (was) modest compared to that in many rhyolite-hosted systems around the world. The total surface heat output of the natural state of the system probably did not exceed 50 MW. However, the thermal areas are widely spread, being within a total area of

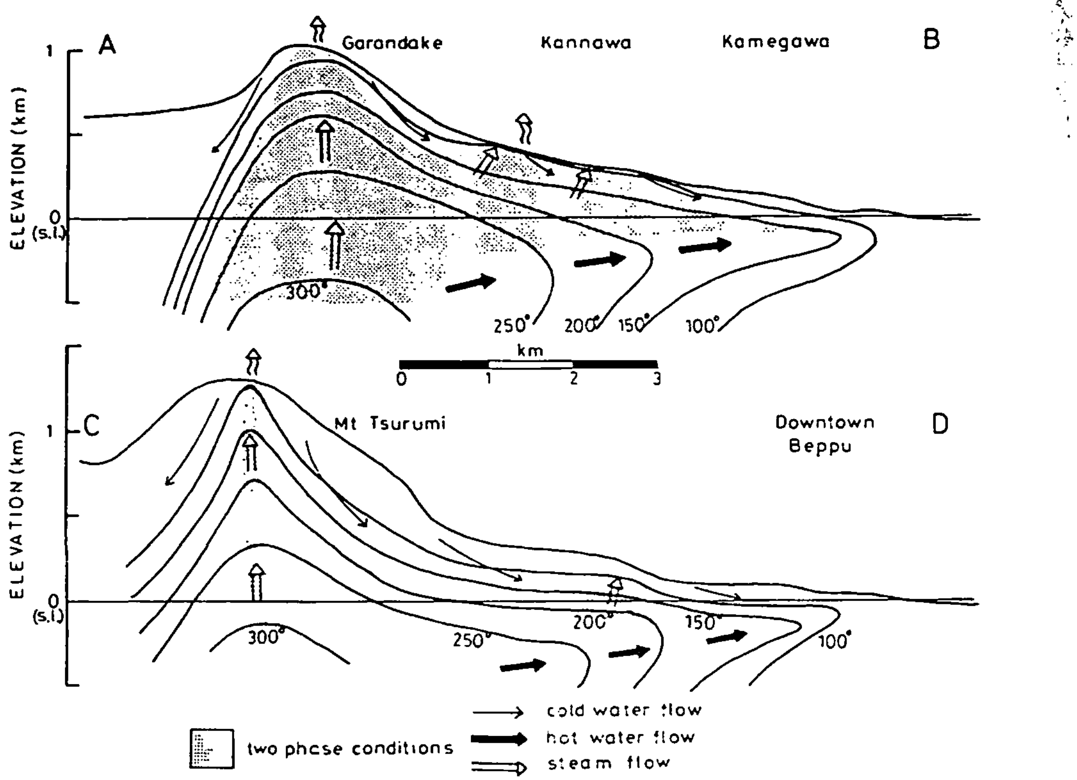

Fig. 12. Speculative west-east cross-sections through the Beppu geothermal system. A–B coincides with the Kamegawa thermal zone: C–D coincides with the Beppu thermal zone.

around 30 km^2, and well data indicate a deep, high temperature resource area of at least 15 km^2. This is indicative of a large geothermal system. The total output through wells has averaged around 500 kg/s for the last 50 yr, with remarkably little drawdown. The natural flow through the drilled area of Beppu city is therefore probably also of the same order. The average chloride concentration from the wells is around 600 mg/kg, so assuming representative chloride and enthalpy values for the deep, parent fluid (1500 mg/kg; 1200 kJ/kg) this implies a total, natural heat output of at least 240 MW, indicating that the Beppu system is indeed relatively large. Most of the heat is dissipated through subsurface mixing with cold groundwaters and, prior to the exploitation of the system, it was largely discharged as warm seepages through the sediments near the coastline. The original, hot "sand baths" along the Beppu beaches, as well as a bottom water temperature survey of Beppu Bay (Nomitsu *et al.*, 1940) indicated warm seepages offshore. The relatively subdued thermal activity of the Beppu geothermal system is a consequence of the 1300 m of topographic relief. A similarly sized geothermal system in a region of low topographic relief, such as many of those found in the Taupo volcanic zone of New Zealand, would have had boiling springs and possibly geysers, sinter sheets, and large areas of steaming ground.

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NEDO "DEEP-SEATED GEOTHERMAL RESOURCES SURVEY" UPDATE

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ABSTRACT

The recent progress of NEDO's Deep-Seated Geothermal Resources Survey is presented in this paper. Since FY 1992, NEDO has been conducting a research project to confirm the existing conditions of the deep geothermal reservoirs located in basement and/or intrusive rocks underneath the shallower reservoirs (over 2,000m deep from the surface). A 4,000m drillhole Wedge-1 (WD-1), which stands for "Well for Deep Geothermal Evaluation", actually started to be drilled from early January 1994 at the Kakkonda geothermal field, northern Honshu island, Japan (Figure 1). The drilling process of WD-1 involves mud loggings, cuttings and cores surveys, and various kinds of electrical loggings including formation micro-imager (FMI). Several borehole surveys based on new investigation methods for deep geothermal reservoirs, such as micro-earthquake activity monitoring, synthetic fluid inclusion, and vertical electro-magnetic profiling (VEMP) surveys, are also included. The WD-1 has been reached to a depth of 1,505m with 13 3/8" casings.

We have already obtained new results during the survey project (especially about the shallow reservoir system) which are important to be interpreted over the entire geothermal system, including the deep reservoir system.

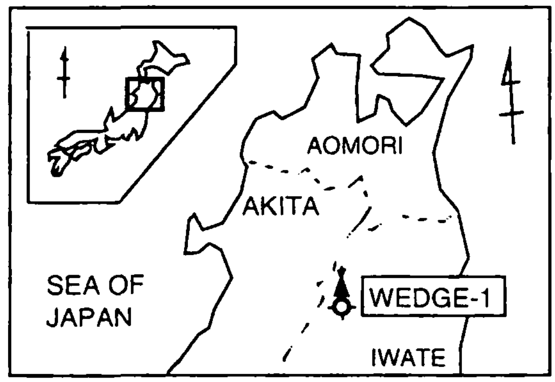


Figure 1 : Map showing the location of Wedge-1 drillhole in northern Honshu, Japan.

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). The time period of the project is from FY1992 to FY1997. NEDO is planning to drill a drillhole which would be the deepest and hottest in Japan (to a depth of 4,000m and over 350-400℃). 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 50MWe power plant has been in operation since 1978, and a the second power plant (30MWe) is scheduled to begin operation in 1996. For both of them, Tohoku Electric Power Inc. (TEP) is the operator of both power plants and Japan Metals and Chemicals Co., Ltd. (JMC) and Tohoku Geothermal Energy Co., Ltd. (TGE) are the steam supplier. JMC recently identified a neo-granitic pluton and its related potential reservoir by data from two deep drillholes as deep as 2.5 - 3.0 km in addition to various data for shallow reservoirs in Kakkonda (Doi et al., 1990).

Geological features of the Kakkonda geothermal field have already been described in detail by several authors, including, Nakamura & Sumi (1981), Sato (1982), Doi et al.(1990), Kato et al. (1993), and Hanano & Takanohashi (1993). A description of the neo-granitic rock has been given by Kato & Doi (1993), and the age is estimated to be 0.34 - 0.14Ma 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. NEDO's Deep-Seated Geothermal Resources Survey has been primarily reported by Sasada et al. (1993).

Since some knowledge in terms of geological and geophysical point of view, for example, the fracture system in the shallow reservoir to a depth of 1,505m, has been obtained throughout the survey, we present the latest results as follows.

DRILLING RECORD

A drilling chart of WD-1 to a depth of 1,505m is shown in Figure 2. The drilling started from January 6th, and a 13 3/8" casing setting finished on July 20th. Lost circulations of mud at depths of 42m, 273-280m, 980m, 1,291m, 1,327m, and 1,345m were withheld by cementing and LCM delayed the drilling schedule. Three-stage-cementing was applied to set the 13 3/8" casing to a depth of 1,500m.

LATEST PROGRESS OF THE SURVEY

Cores and Cuttings Investigations

A geological section drawn based on the investigation of cuttings and cores to a depth of 1,505m is shown in Figure 3. The order from the bottom, middle Miocene Kunimitoge Formation, middle to late Miocene Takinoue-Onsen and Yamatsuda Formations are observed. These formations are composed mainly of andesitic/dacitic lapilli tuff, tuff breccia, tuffaceous sandstone, and black shale filling the Tertialy sedimentary basin. An andesite sheet which has altered intensively exists in the top of the Kunimitoge Formation.

Alteration mineral analysis of cores and cuttings has been made to a depth of 1,505m using a microscope and XRD. The result is summarized in Figure 3. Laumontite appears at depths shallower than 300m and wairakite appears sporadically in place of laumontite deeper than 300m. Mixed layered Illite/smectite changes to illite at a depth over 550m. Anhydrite appears at a depth over 930m. The top of the first appearance of anhydrite in the WD-1 is 500-900m shallower than that in the other drillholes located in the east side of Kakkonda. The drilling site of the WD-1 is assumed to be an upflow zone of deep hydrothermal fluids by Kato et al. (1993), which is consistent with the results of the drilling of WD-1.

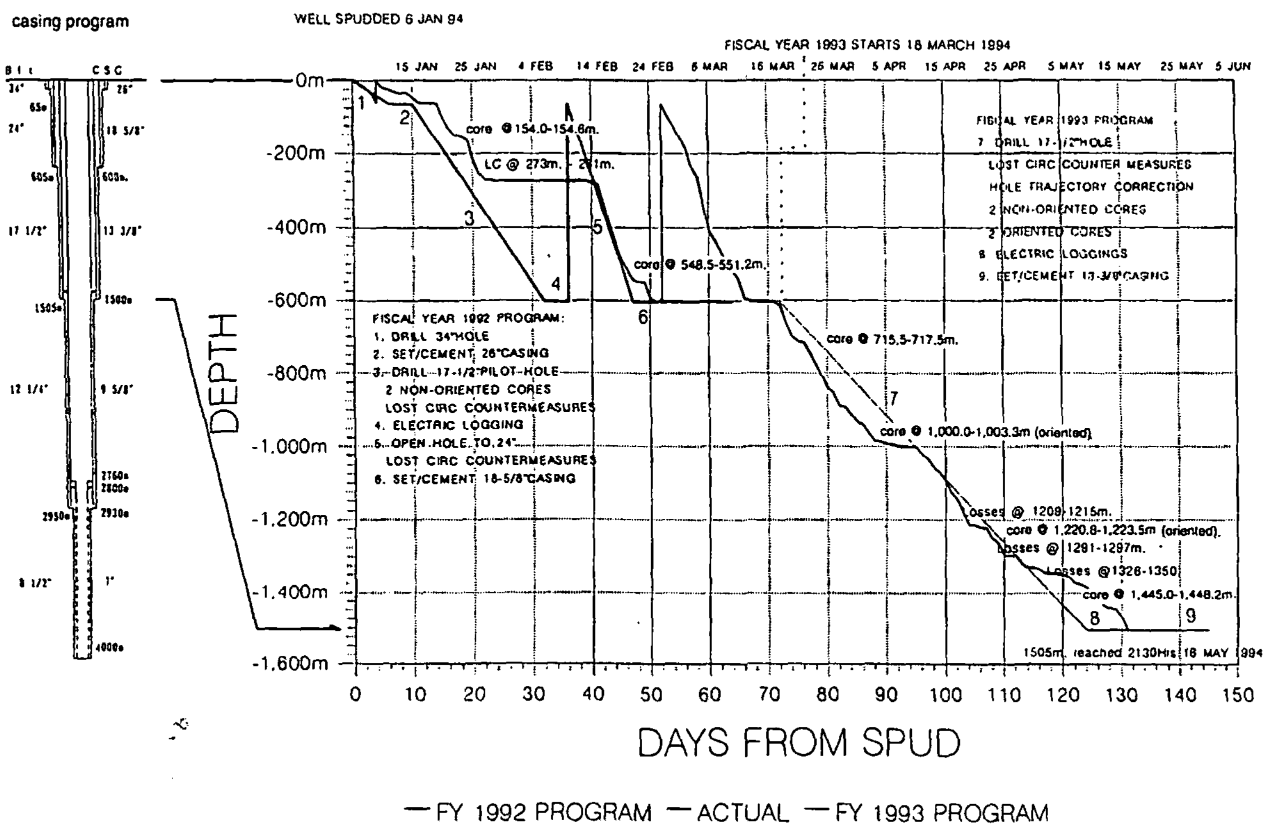
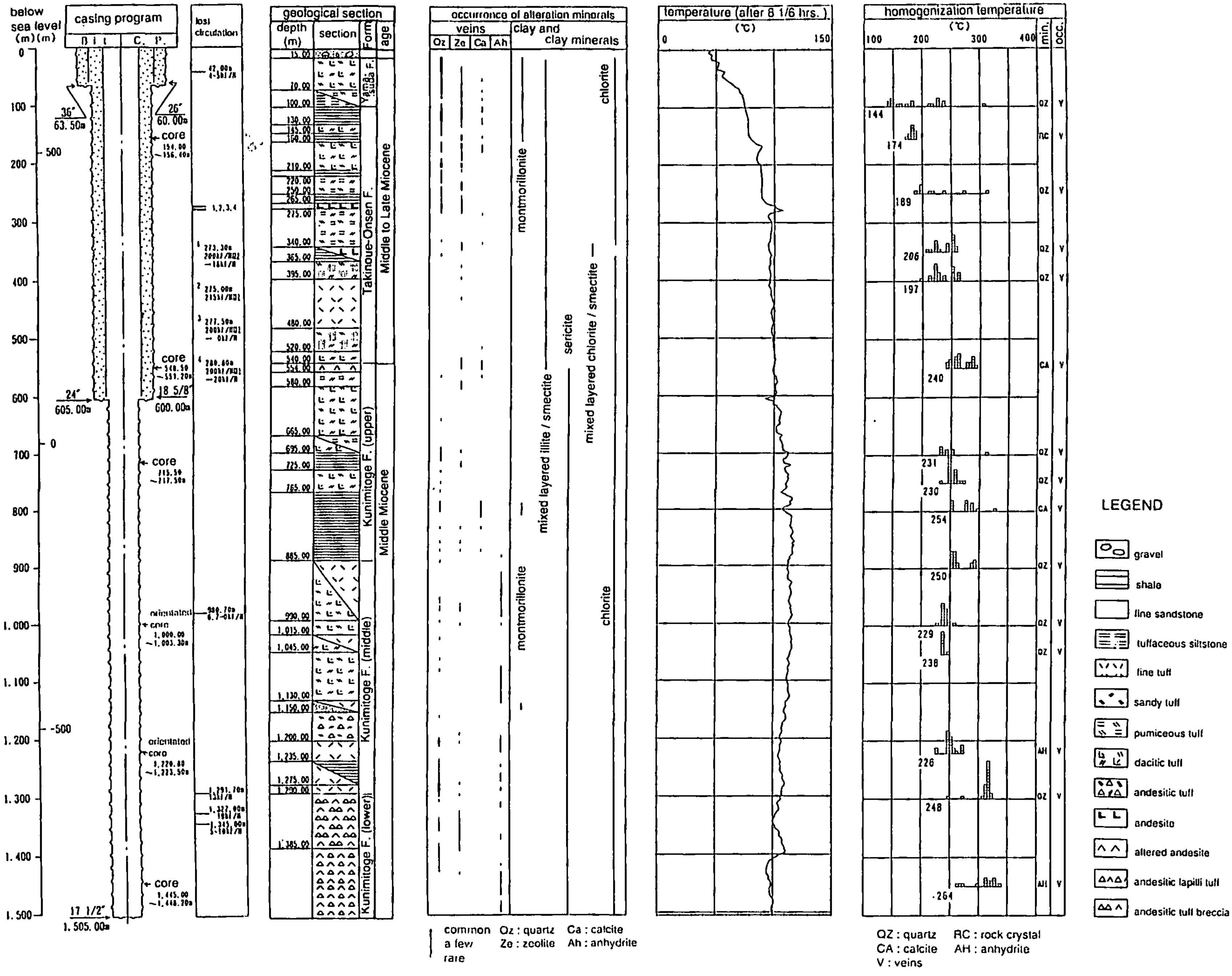


Figure 2 : Drilling chart of Wedge-1 (WD-1) to a depth of 1,505m (above).

Figure 3 : Geological composite log including geological section, appearance and extinction of alteration minerals, temperature (after 8 1/6 hrs.), and fluid inclusion filling temperatures (Ths) with number of minimum Th in WD-1 to a depth of 1,505m (right).


below sea level (m)(m)
casing program
Bit
C. P.
36"
63.50m
26"
60.00m
core
24"
605.00m
18 5/8"
600.00m
17 1/2"
1.505.00m
oriented core
lost circulation
geological section
depth (m)
section
Form.
age
Yamasuda F.
Takinoue-Onsen F.
Middle to Late Miocene
Kunimitoge F. (upper)
Middle Miocene
Kunimitoge F. (middle)
Kunimitoge F. (lower)
occurrence of alteration minerals
veins
Qz
Ze
Ca
Ah
clay and clay minerals
chlorite
montmorillonite
mixed layered chlorite / smectite
sericite
mixed layered illite / smectite
common
a few
rare
Qz : quartz
Ze : zeolite
Ca : calcite
Ah : anhydrite
temperature (after 8 1/6 hrs.)
(℃)
0
150
homogonization temperature
(℃)
100
200
300
400
min.
occ.
QZ : quartz
CA : calcite
V : veins
RC : rock crystal
AH : anhydrite
LEGEND
gravel
shale
fine sandstone
tuffaceous siltstone
fine tuff
sandy tuff
pumiceous tuff
dacitic tuff
andesitic tuff
andesite
altered andesite
andesitic lapilli tuff
andesitic tuff breccia

Fluid Inclusion Grothermometry

Fluid inclusion measurments were made with quartz, anhydrite and calcite crystals. This result is also shown on Figure 3. Most populations contain liquid rich inclusions with uniform liquid-vapour ratio of all the crystals. The maximum Th recorded for the No.6 core taken at a depth of 1,445m ranges from 264 to 338℃.

Fracture Analysis Using Orientated Cores

Six cores, including two orientated cores, have already been taken to a depth of 1,505m. 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 1,220m in depth. Fracture analysis of cores using the orientated cores has been done (see Figure 4). 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 with a horizontal NNW-SSE minimum principal stress axis. This is consistend with the stress field estimated by fracture analysis on the surface (e.g. Koshiya et al., 1993, 1994) and stress analysis using micro-earthquake activities in Kakkonda (e.g. Sugihara, 1993).

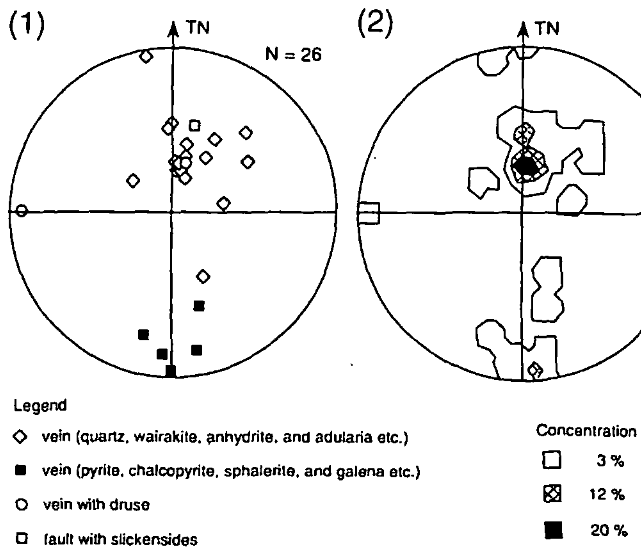


Figure 4 : Poles-plot of several kinds of veins observed in No. 2 orientated core in an interval of depth 1,220.8 - 1,223.5m in WD-1 (1), and counters of these concentration (2). Both are on Schmidt Net (lower hemispheric plot).

Open-Hole Loggings

Two sets of borehole loggings have been conducted at a depth interval from 0 to 605m and from 605 to 1,505m. 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 3.

The result of FMI shows that drilling induced fractures with a strike of ENE-WSW to E-W with vertical dipping (see Figure 5) are found in many intervals continuously from 0 to 1,505m in depth. This suggests that the axis of principal stress is a horizontal NNW-SSE minimum. Furthermore, this indicates that the relative horizontal stress in Kakkonda does not change at least from the surface to 1,505m (e.g. Koshiya et al., 1993).

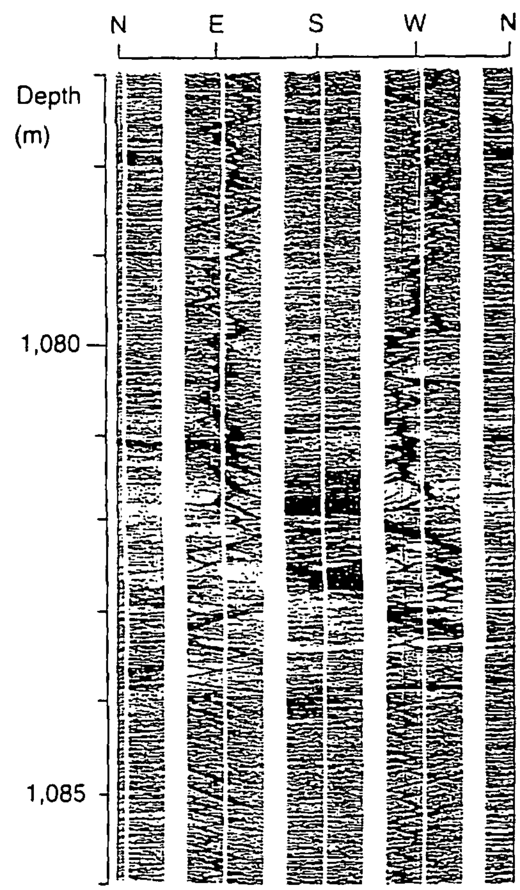


Figure 5 : An example of drilling induced fracture detected by formation micro-imager (FMI) in an interval of depth 1,077-1,086m in WD-1.

Vertical Electro-Magnetic Profiling Survey

The vertical electro-magnetic profiling (VEMP) method is a way to obtain multi-frequency three-component magnetic field data in a borehole using movable controlled sources (loop or grounded-wire sources) on the surface (Figure 6). A VEMP survey was carried out in the open hole of WD-1 at depths from 605m to 1,505m. Numerical simulations of the VEMP method had been made in advance to determine an adequate magnitude of the sources.

A controlled source magnetotelluric (CSMT) survey will be made during FY1994, and the data will be used for a combined analysis of VEMP and CSMT to more precisely grasp the resistivity structure in Kakkonda.

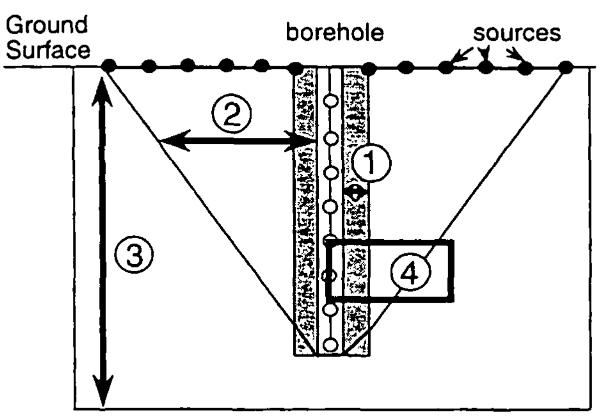


Figure 6 : Schematic model of a vertical electro-magnetic profiling (VEMP) survey and its combined study with borehole induction, VEMP, and CSMT (or MT).

Micro-Earthquake Activity Survey

A survey of a micro-earthquake hypocenter is considered to be a useful method for exploration of deep fractures associated with hydrothermal fluid flow (e.g. Walter & Weaver, 1980). To determine a location of a micro-earthquake hypocenter accurately, a shooting survey had been done using a pre-existing borehole located near WD-1. The structure of the seismic wave speed was estimated in Kakkonda, specially in a shallower part where the speed of seismic waves decreases drastically.

In addition to the shooting survey, two micro-earthquake observation points will be added to the pre-existing ones on the east side of WD-1 (i.e. east edge of the Kakkonda field) where no standing observation center is sited. After this, a continuous survey of micro-earthquake hypocenters will be carried out from the end of 1994.

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 1,505m. 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.

Memory-Gauge Temperature Survey for Application of Top Drive Drilling System

A top drive drilling system will be applied for depths over 1,505m (recovery temperature is more than 260℃) in order to cool the drillhole effectively. Applying the top drive system, no kelly is needed, and it enables almost continuous mud pumping when pulling down drill pipes into a drillhole. Since a bit is usually directly exposed to high temperature when it is pulled down in such a deep geothermal drillhole, it will be specially advantageous for a bit.

Applying the top drive system, borehole temperatures were monitored in advance using memory-gauge tools during mud circulation with different pumping rates at a depth of 1,505m in the WD-1 and simulated the bottom-hole temperature.

Vertical Seismic Profiling Survey

As another project, NEDO plans to carry out a vertical seismic profiling (VSP) survey using WD-1 (1,505m M.D.) to prove the effectiveness of the tools (especially against high temperature) made throughout the project. In this case, we expect to predict the profile of the top of the neo-granitic rocks and the development of deeper fractures. This prediction is very important not only for a deep survey but also for an appropriate drilling plan.

GEOTHERMAL MODEL

Summarizing preexisting 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-seated 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 extension of the neo-granitic pulton is more than 2.0 x 2.5 km (Doi et al., 1993). The present temperature of the neo-granitic rock is greater than 350°C. Contact metamorphic minerals, such as cordierite and biotite, are observed over the top of the neo-granitic rock. The upper limit of the biotite-cordierite zone exists at 600 - 700m above the contact of the neo-granitic rock, while that of the biotite zone is at 700 - 1000m (Kato & 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-granitic rock during deep drilling (see Figure 7). According to the results of the cuttings investigation using a microscope to a depth of 1,505m, biotite has not been detected yet. Probably the top of the neo-granitic 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.

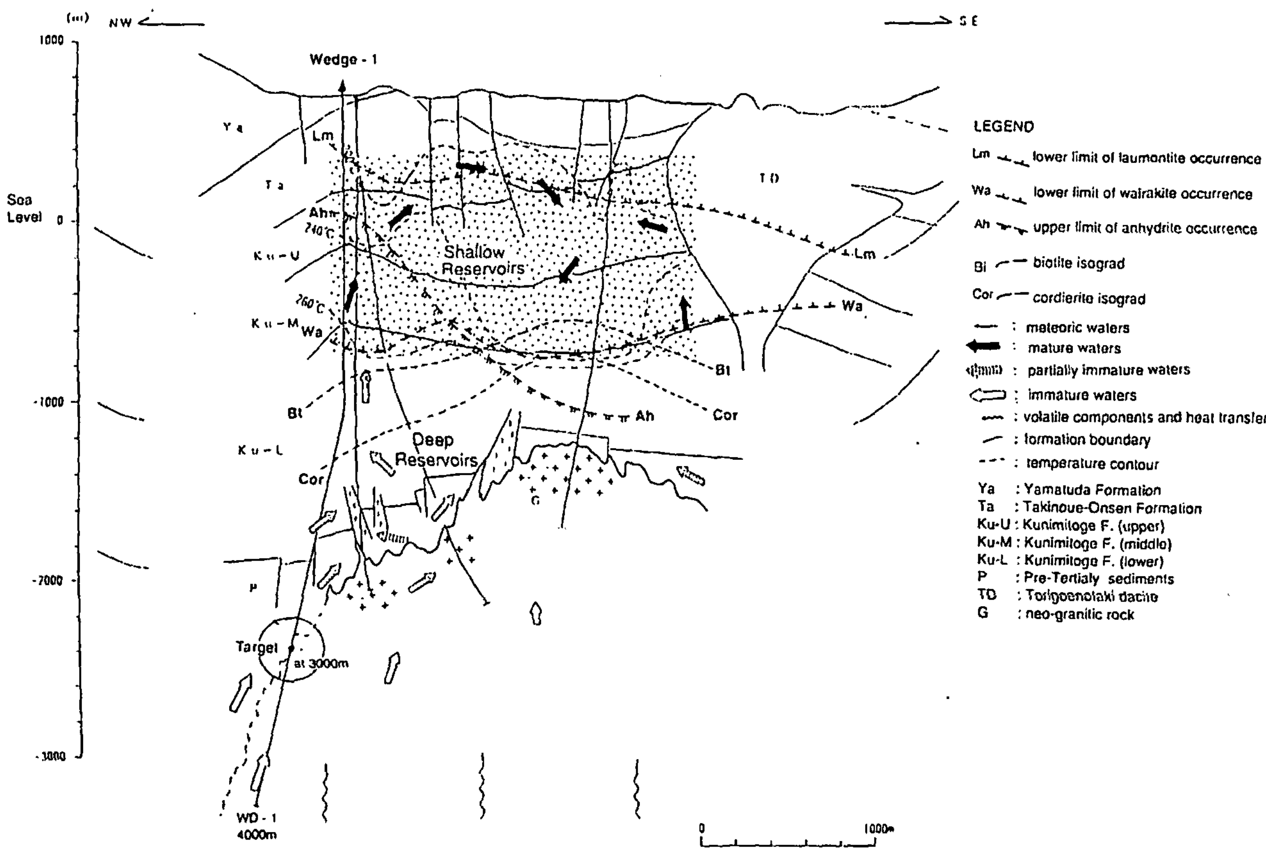


Figure 7 : The first geothermal model on the geological cross section associated with the neo-granitic pluton in the Kakkonda field.

SUBSEQUENT SCHEDULE

The schedule of the survey project is shown in Table 1. WD-1 has been drilled to a depth of 1,505m (M.D.). In FY 1994, after various kinds of borehole surveys using WD-1, including VSP, we will restart drilling from the end of January 1995 with another rig which has the ability to drill deeper to 4,500m in depth. WD-1 will be drilled to 3,000m approximately by the end of May 1995.

In FY 1995, after a fluid injection test, the first flow test will then be undertaken at around the 3,000m level for three months with PTS logging, PT monitoring, tracer, and erosion & corrosion tests using test casing to the end of 1995. Once the test casing is withdrawn from the bottom of WD-1, it will be remedied by cementing at a depth for the interval of slitted-anchors and side track with pack-stock nearly from the bottom of the 13 3/8' casing pipes. This will be the most difficult operation of the entire drilling process.

The drilling will restart after the remedy for the first flow test from 3,000m to 4,000m in FY 1996. The drilling of this interval must be extraordinarily fascinating because the drillhole will go across many deep fractures suggested by micro-earthquake monitoring surveys. The second flow test is planned to be a long-term one after the drilling is over when the drillhole hits promising reservoirs. This flow test will also include PT monitoring, tracer, and erosion & corrosion tests etc. Integrated analysis will be conducted in the last two years.

CONCLUSIONS

Three factors essential for deep geothermal resources, namely, heat supply from a heat source, hydrothermal fluid flow and its recharge system, and formation of fracture systems which make up geothermal reservoirs, will be investigated in this project. From the results of various surveys of WD-1 to a 1,505m depth, fracture system, the alteration pattern of the rocks, and the structure of seismic wave speeds, etc. from the surface to the shallow reservoir in Kakkonda are being revealed throughout the survey project at the moment.

As the latest knowledge in terms of geological and geophysical aspects taken in the survey project will be added to the first geothermal model through the drilling to a depth of 1,505m, the model will become reliable and useful for planning of deep drillings and exploration of deep geothermal resources.

Table 1. Schedule of the Deep-Seated Geothermal Resources Survey

	1992	1993	1994	1995	1996	1997
Drilling and Surveys	600m	1500m	3000m		4000m	
Flow Test, etc.				at 3000m		at 4000m
Integrated Analysis						

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