Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

GEOTHERMAL DEVELOPMENT IN HACHIJOJIMA

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Key Words: geothermal, hachijojima island

ABSTRACT

Hachijojima is a gourd shaped volcanic island in the Pacific Ocean. Nishiyama volcano and Higashiyama volcano consist of basalt lava and associated pyroclastic rocks. A promising geothermal resource was found in south Higashiyama, associated with an uplift of Tertiary rocks consisting of mainly andesite lava and related pyroclastic rocks, overlain by Quaternary volcanic rocks.
Steep high-temperature (over 250℃) and high-pressure gradients occur in the deeper portion of the system near the Tertiary-Quaternary contact, indicating the presence of a cap rock. The cap rock formed by deposition of hydrothermal minerals. Geothermal fluid ascends from the deeper portions to shallow depths along vertical fractures through the cap rock.
These vertical fractures form the geothermal reservoir in the Tertiary formation. Three wells were drilled into these vertical fractures, and approximately 30t/h of superheated steam from each well was obtained during flow tests. The geothermal fluid is mainly a mixture of seawater and meteoric water in an approximate ratio of 1 to 2, based on chemical analysis, with a portion of volcanic gas included. 3.3 MW geothermal power station has been operating since March 1999.

1. INTRODUCTION

Hachijojima is an island located about 300 km south of Tokyo (Fig.1). It is approximately 70km^2 in area and has a population of about 9,500. This island has two large volcanoes, Mt. Nishiyama and Mt. Higashiyama. Mt. Nishiyama is an 854m high stratovolcano, and Mt. Higashiyama is a dissected complex volcano 701m high.
Geothermal exploration on Hachijojima began in 1984 by the Tokyo Electric Power Co. (TEPCO) , was completed in 1989. Based on the results of geological survey, geophysical exploration and geochemical exploration throughout the island, the south Higashiyama area was chosen as the most promising area. From 1989 to 1991, a geothermal development promotion survey of eight wells drilled by the New Energy and Industrial Technology Development Organization (NEDO) confirmed that a high-temperature zone of more than 300℃ existed under the south Higashiyama area.
Since 1992, TEPCO has continued geothermal exploration, obtaining an outline of the scale of the geothermal reservoir, with the exploitation site chosen to be the northern part of Nakanogo in the south Higashiyama area. Three wells (HT-1, HT-2, HT-3) were drilled at this site in 1995, and a steam-dominated geothermal resource was confirmed by subsequent flow tests. 3.3 MW geothermal power station has been operating since March 1999.
This paper summarizes the history of exploration, and proposes a geothermal model of Hachijojima geothermal system.

2. GEOLOGY OF SOUTH HIGASHIYAMA

2.1 Geology

Hachijojima is a gourd shaped volcanic island. Quaternary basaltic rocks and andesitic rocks are present at the surface of the island. Nishiyama is a stratovolcano that has erupted in 1487, 1518, 1522-1523, 1605 and 1707 (Isshiki, 1959). There is no record of the eruption history of Higashiyama volcano, and it is a well-dissected complex volcano.
The surface geology of south Higashiyama comprises an old volcanic body, the first stage of a stratovolcano, the latter stage of a stratovolcano, a volcanic cone, and parasitic volcanic bodies (Fig.2). These Quaternary volcanic rocks completely cover the surface. The old volcanic body likely formed at the time Hachijojima island was formed, and is comprised of erupted lava and pyroclastic rocks. Most of the body has suffered marine erosion, and only a few outcrops occur on the seashore. The first stage of the stratovolcanic body consists of basaltic to andesitic rocks, which formed small stratovolcano depressions and calderas in the old Higashiyama body. The latter stratovolcano is a large-scale volcanic body with a large caldera. The central cone and parasitic volcanoes consist of lava and scoria. Basaltic lava is extensive in south Higashiyama. Some scoria cones and basaltic lava occur along the ring structure, indicating that this was the location of the latest volcanic activity in this area.
The Tertiary system (T), pre-Higashiyama pyroclastic rocks (Qv) and old Hachijojima conglomerate (Qc) do not outcrop and were seen only in NEDO and TEPCO wells (Fig.3).
The Tertiary system (T) is lithologically divided into altered

andesitic rocks and basaltic rocks in ascending order.The top of the Tertiary formation experienced the greatest uplift beneath the project site.

On the western and eastern side of this uplift zone, pre-Higashiyama volcanic rocks (Qv) and old Hachijojima conglomerates (Qc) occur between the Higashiyama volcanic body and Tertiary rocks. Pre-Higashiyama volcanic rocks (Qv) are basaltic rocks and pumice tuff. Pre-Higashiyama volcanic rocks (Qv) are covered by old Hachijojima conglomerates (Qc), which consist of sand, gravel, sandstone and pumice tuff.

2.2 Geological structure

The surface of the south Higashiyama area is characterized by two ring structures with a radius of 0.5km and 1.3km (Fig.2). Suga (1994) called this ring structure, from east Kashidate to Nakanogo, the Nakanogo caldera. The geological columns of NEDO (1993) indicate that the uplift of Tertiary rocks is located beneath these ring structures. There are parasitic scoria cones and basaltic lava on the western edge of the ring structures and fissure-erupted basalts in the south-center of the ring structures. The wells drilled in this zone, N2-HJ-5, N3-HJ-7, N3-HJ-8, HT-1, HT-2, and HT-3, all show a temperature of more than 300℃ in the Tertiary formations.

The project site lies in this uplift zone in the south-central part of the ring structures. The upheaval occurred along many fractures in the Tertiary system. We assume the directions of these fractures to be dominantly NE-SW. Some of these fractures comprise the reservoir of geothermal fluid (Fig.4).

2.3 Alteration

There are limited areas of alteration at the surface. However, kaolinite, alunite, and α-cristobalite occur near the summit of Mt. Higashiyama, with a genetic relationship to the volcanic activities (Fig.2).

We analyzed the drill cuttings every 50 meters, with X-ray diffraction of oriented and unoriented samples. NEDO also analyzed cuttings every 40 m while drilling. The results of these analyses were used to classify clay minerals and zeolites.

Montmorillonite occurs in the lower temperature parts of Quaternary formations, and in the shallow part of the Tertiary formation. Chlorite is common and wide spread in Tertiary formations, indicating that the chlorite is associated with an older period of alteration. Wairakite occurs only in zones with a temperature greater than 200 ℃, based on NEDO and TEPCO logging data, which indicate the present hydrothermal activity (Fig.3).

Below these Tertiary rocks, high temperatures exceeding 250 ℃ were detected, with vein minerals including quartz, calcite and anhydrite. These vein minerals seal the fractures in the top of Tertiary system, and playing a role of cap rock.

3. GEOTHERMAL STRUCTURE IN SOUTH HIGASHIYAMA

3.1 Temperature distribution

Based on the results of well tests by NEDO and TEPCO, high temperature zones greater than 250℃ exist in N2-HJ-5, N3-HJ-7, HT-1, HT-2 and HT-3, located in the uplift zone in the Tertiary formations. At depths greater than 1,000m below sea level in this uplift zone, the temperature distribution indicates up-flow, with a minimum temperature of 250℃ and a maximum over 300℃ in Tertiary rocks (Fig.3,4). Outside of this uplift zone, the temperature decreases steeply to about 150 to 200℃.

Temperature profiles in this uplift zone show that the temperature increases steeply with increasing depth below the top of the Tertiary volcanic rocks from 200 to 300 m depth. The temperature increases by about 150 to 200℃ over a 100 to 200 m depth interval. These temperature profiles indicate the existence of an impermeable zone at the boundary between the Quaternary and Tertiary volcanic rocks. A discontinuity in reservoir pressure at about 200 m bsl also supports the existence of an impermeable zone at the top of the Tertiary formation .

3.2 Resistivity and temperature distribution

From the results of Controlled Source Audio Magneto Terrulic method (CSAMT) and Magneto Terrulic method (MT), the resistivity in south Higashiyama is relatively low. In the zones of uplift and at temperatures over 250℃, there are low to moderate resistivity values (10～50 Ω m) which are horizontally discontinuous (Fig.4,5). These discontinuous zones are elongate NE-SW in the area of the project site, and are most likely to the zones caused by structurally controlled of geothermal fluid flow.

Vertically continuous zones of low resistivity extend to deeper portions, indicating flow of geothermal fluid or alteration, in zones along fractures in Tertiary volcanic rocks. Regarding these vertical resistivity distributions, there are zones of high resistivity (over 100 Ω m) corresponding to Quaternary volcanic rocks, and extremely low resistivity zones (less than 5 Ω m) along the boundary between Quaternary volcanic rocks and Tertiary volcanic rocks. These low-resistivity zones correspond to the outline of the deduced cap-rock (Fig.5).

In the south Higashiyama area, the low-resistivity zones at shallow depths are related to porous rocks such as the Hachijojima conglomerates, saturated with seawater and meteoric water. Also, in the northern area, outside the uplift zone, relatively low-resistivity zones occur widely, caused by penetration of meteoric water.

3.3 Chemistry of hot springs and well discharges

In the early stages of the geothermal survey, there were three hot springs along the seashore of south Higashiyama. From the chemical analysis data by the local government for Nakanogo, Yuhama and Borawazawa, these low Cl and high Tritium content hot springs are thought to contain a mixture of seawater and meteoric water. Island residents often pumped this hot water for bathing purposes. Since 1992, the Hachijo local government drilled five deep wells to obtain bathing water, Kashidate, Nakanogo Aigae, Igouna and Sueyoshi. The hot water from these new wells has high Cl and low Tritium concentrations compared with that of the hot springs. The composition of these new wells suggests that the origin of hot water is a mixture of seawater and meteoric water which had been stored underground for a long time. Geochemical temperatures from SiO_2 and Na-K-Ca for these shallow reservoirs are approximately 150℃ (Table 1).

The flow test for four wells, N2-HJ-5, HT-1, HT-2, and HT-3, indicates the existence of a high-temperature geothermal fluid at depth. The geothermal fluid discharged from HT-2 and HT-3 is superheated steam with no hot water. N2-HJ-5 and HT-1 produce steam with a small fraction of hot water (Table 1). The gas concentration in steam is from 0.6 to 2.36 vol%, dominated by CO_2 (73 to 92 vol%), and H_2S (4 to 19 vol%). Of the minor gases, H_2 dominates, from 2.5 to 7 vol%.

The hot water discharged from N2-HJ-5 and HT-1 have pH6 and are the Na-Cl type Na: 8,290 mg/l, Cl: 14,400 mg/l in HT-1. The tritium concentration of hot water is as low as 0.2 to 0.3 T.U. indicating an integrated residence time of at least 60 years. The possibility of a recent mixture of seawater and meteoric water in the reservoir is very small. The NaCl concentration of geothermal fluid evaluated by fluid inclusions is approximately 1.0 to 1.2 wt%, about half that of the hot water mentioned above. The concentrations of seawater and meteoric water are approximately 3.5 wt% and 0 wt% NaCl, respectively. Thus, the geothermal fluid might be a product of mixing seawater and meteoric water with the ratio of 2 to 1.

4. GEOTHERMAL MODEL

The high-temperature geothermal resource in the south Higashiyama area exists in fractures of the Tertiary formation, as deduced from gravity discontinuities and the pattern of resistivity anomalies. These fractures serve as conduits for the ascent of geothermal fluid, and act as a geothermal reservoir.

The heat source of the geothermal fluid is likely the magma chamber associated with the volcanic rocks and parasitic volcanoes found in south Higashiyama. Ring structures occur in these areas and parasitic volcanoes exist on top of these structures. Moreover, the largest uplift of the Tertiary formation occurs inside these ring structures. These fractures channel the upflow of geothermal fluid.

Although Hachijojima is surrounded by the Pacific Ocean, the geothermal resource maintains a high temperature, indicating impermeable zones prevent the direct penetration of seawater into the deep geothermal system (Fig.6). Temperature profiles of wells in the project site increase steeply from the top of the Tertiary formation with increasing depth. In conjunction with a pressure discontinuity, this indicates the existence of a low-permeability cap rock covering the Tertiary formation. This cap rock domes over the uplift of Tertiary rocks directly beneath the project site. The cap rock also prevents the penetration of seawater and ground water into geothermal system.

5.POWER STATION

5.1 Fundamental design

The Hachijojima geothermal power station is located in the Fuji Hakone Izu national park. Therefore, the power station is designed to preserve natural environment.

5.2 Output

The rated output (3,300kW) was determined by the reservoir capacity and the electricity demand of Hachijojima. (This output is about 30% of the electricity demand of Hachijojima.) Before the commercial operation of the geothermal power station, all electricity demand of Hachijojima had been supplied by the diesel power station. At present, the diesel power station is used for the middle and the peak load, and the geothermal power station fulfil an important role as the base load.

5.3 Environmental Protection

The power plant equipment is arranged in consideration of harmony between the environment and economic efficiency. For example, The length of the two-phase flow and steam piping is minimized because the equipment is arranged inside the site originally made for drilling the well (Fig.7).

5.4 Process cycle

The two-phase flowing fluid from production wells is piped into a separator for the steam and hot water. Separated steam is expanded into the turbine from a design pressure of 0.69 MPa down to pressure below atmosphere (vacuum). After expansion in the turbine, the steam and noncondensable gas are exhausted to the condenser. The steam condensate is pumped to the cooling tower, which is made of concrete to reduce noise.

Part of the condensate is used to produce hot water of 43℃ through heat exchanger with agricultural water (Fig.8). This hot water is supplied to greenhouses from December to March.

The noncondensable gas and some steam are removed from condenser by the ejector which uses a stream of steam and noncondensable gas as the motive fluid. The noncondensable gas is treated by H_2S abatement system. This system can remove over 90% of H_2S.

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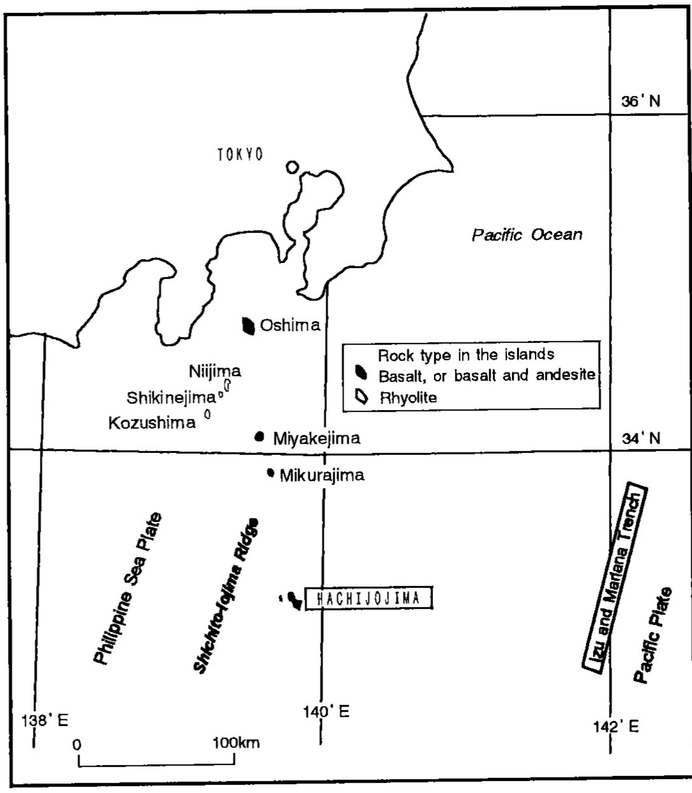

Fig. 1 Location of Hachijojima

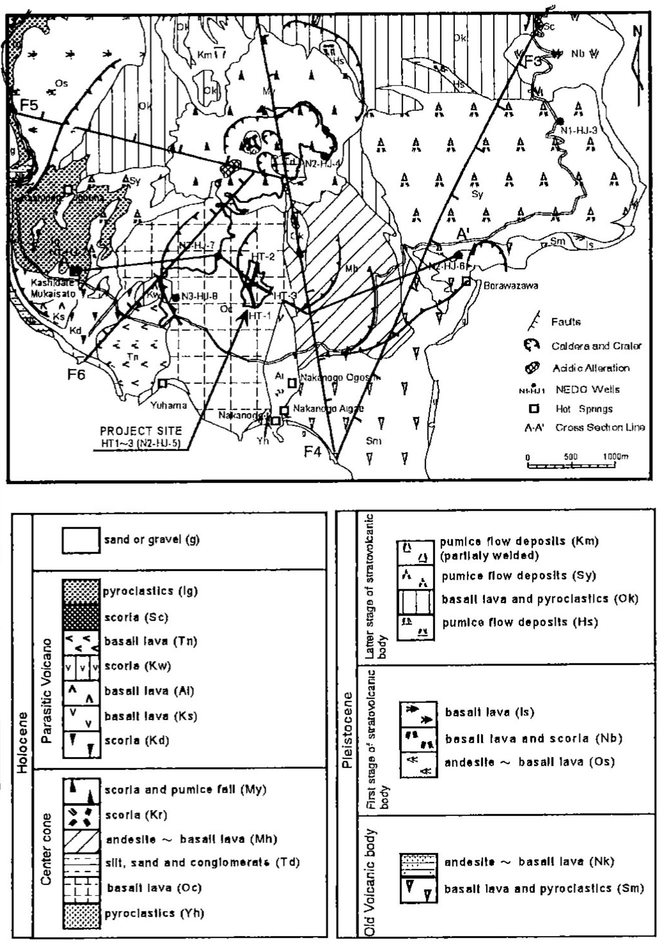

Fig. 2 Geological map of south Higashiyama

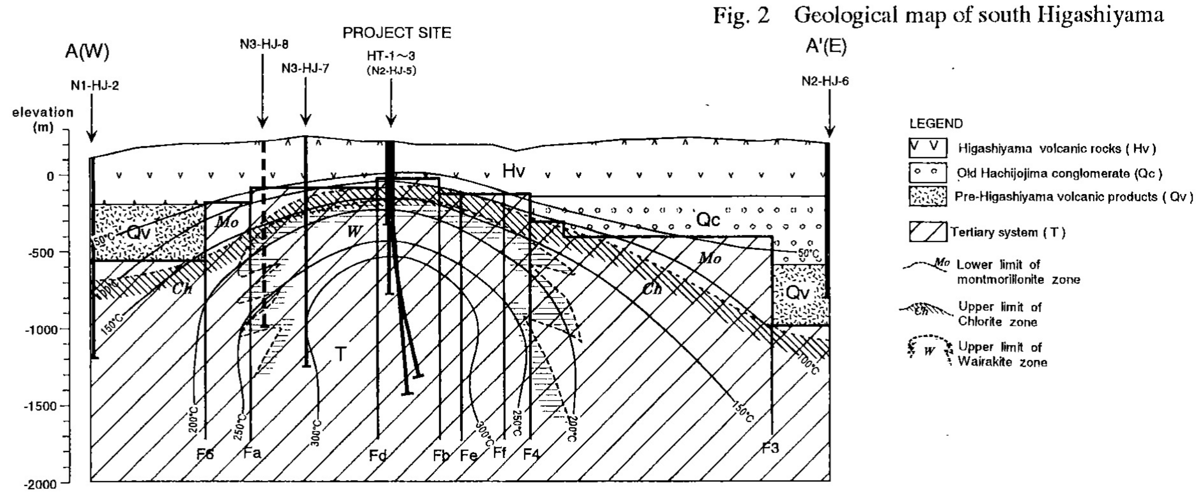

Fig. 3 Temperature distributions of temperature logging

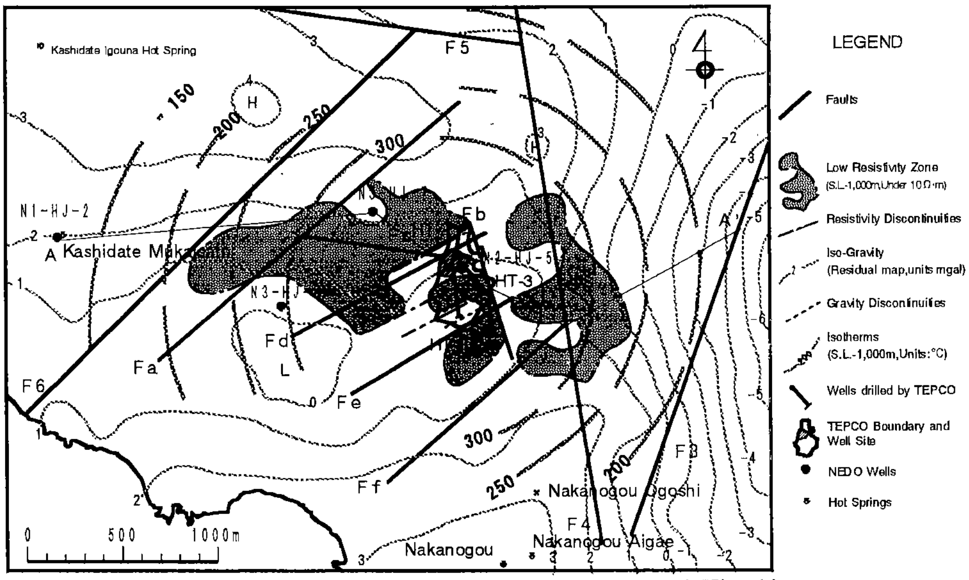

Fig. 4 Fracture estimated from intergrated exploration result of south Higashiyama

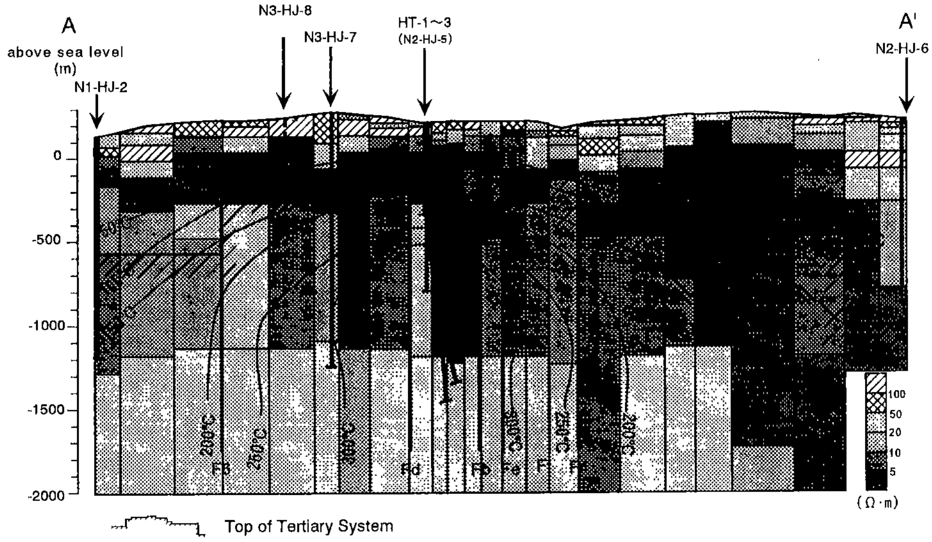

Fig. 5 Two-dimensional resistivity analysis and temperature distribution from temperature logging (Section A-A', Fig.2, 4)

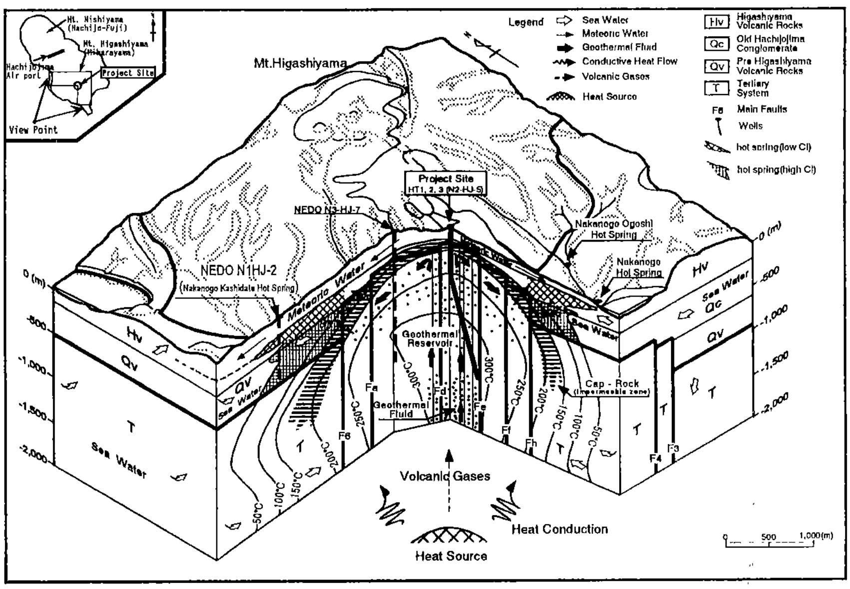

Fig. 6 Geothermal model of south Higashiyama

Table 1 Chemical composition of steam and hot water in exploration wells and hot springs

Steam								
Sample No	HT-1		HT-2		HT-3		N2-HJ-5	
Sampling date	1995/10/29		1995/11/13		1996/2/3		1991/4/17	
Steam flow rate	32 6t/h		23t/h		32t/h		5 48t/h	
Water flow rate	0.4t/h		0t/h		0t/h		0.792t/h	
Steam	Vol%	ppm/all	Vol%	ppm/all	Vol%	ppm/all	Vol%	ppm/all
water/gas ratio								
H_2O	99.301	–	99 413	–	98.730	–	97.640	–
gas	0 699	–	0.587	–	1.270	–	2 360	–
gas								
CO_2	88.206	6,165 60	73 080	4,289.80	76 030	9,655 81	92 500	21,830 00
H_2S	9.090	635 39	19 490	1,144 06	16 520	2,098 04	4.200	991.20
Residual gases	2 704	189 01	7.430	436 14	7.450	946 15	3 300	778.80
Residual gases								
H_2	91.900	173 70	90 400	394 27	93 300	882.76	85 100	662 76
N_2	7.880	14 89	8.750	38 16	4 810	45.51	12.500	97 35
CH_4	0.220	0.42	0.270	1.18	0 220	2.08	0 240	1 87

Hot Water												
Sample No.	HT-1		N2-HJ-5		Kashidate Mukaisato		Nakanogou Ogoshi		Borawazawa		Yuhama #1	
Sampling date	1995/10/29		1991/4/17		1993/4/13		1995/4/27		1989/8/23		1989/8/23	
Steam flow rate	32.6t/h		5 48t/h		–		–		–		–	
Water flow rate	0.4t/h		0.792t/h		386 l/min		434 l/min		43 l/min		97 l/min	
Temperature(℃)	–		96 0		57.8		64.2		40.5		36 2	
pH	6.20		8 50		6.40		6.28		6.95		6 50	
T.S M(mg/l)	34,400		–		30,110		20,820		1,000		4,100	
Chemical comp	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Na	8,290 00	360 43	461.00	20 04	8,870 0	385 65	6,180 0	268 70	95.0	4 13	909.0	39.52
K	464 00	11.87	30 40	0 78	223.0	5 70	217 0	5 55	11.2	0.29	77 4	1.98
Ca	1,020 00	50.87	7 15	0 36	861 0	42 94	380 4	18 97	66 3	3 31	147.0	7.33
Mg	2.52	0	0 21	0	854 8	71.23	764.9	63 74	36 4	3 03	83 7	6 98
Cl	########	405.63	138 00	3.89	17,177 0	483 86	11,053 0	311 35	144 0	4.06	1,900 0	53 52
SO_4	479 00	9.98	518 00	10 79	1,100 0	22 92	1,588.0	33 08	163 0	3 40	225 0	4.69
HCO_3	18 70	0 31	319 00	5 29	317.3	5 26	610.2	10 12	75.6	1 25	67 3	1 12
Tritium(Tr)	<0.24		0 31±0.10		–		–		0 54±0 08		6 1±0 3	

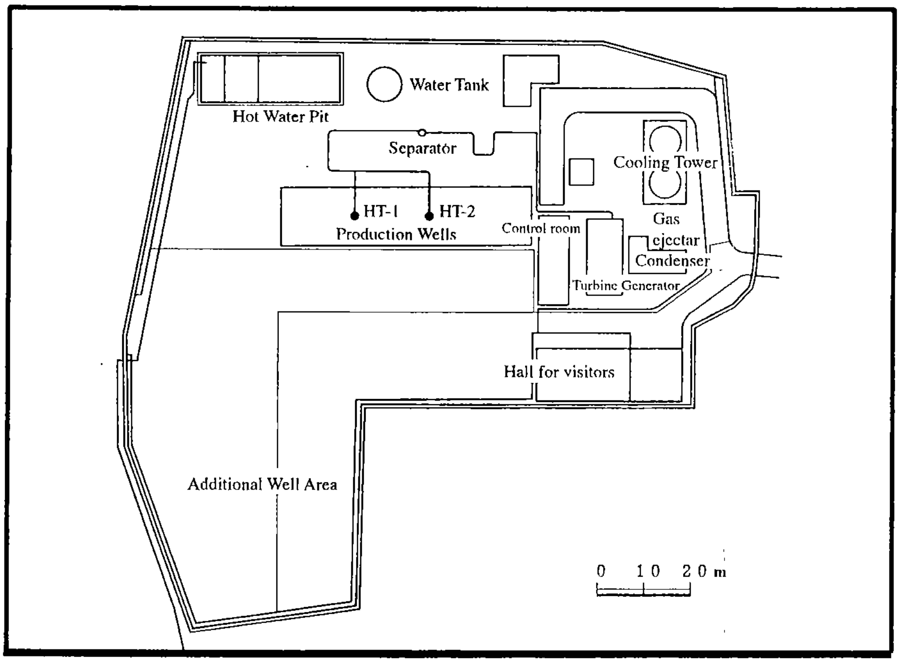

Fig. 7 Power station equipment layout

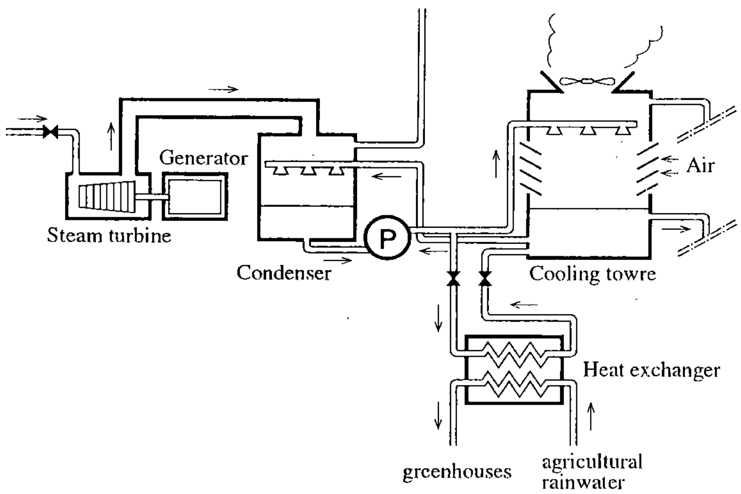

Fig. 8 Heat supply system