REVIEW OF 15 YEARS EXPERIENCE OF THE OGACHI HOT DRY ROCK PROJECT WITH EMPHASIS ON GEOLOGICAL FEATURES

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SUMMARY – The Ogachi hot dry rock (HDR) experiments, which lasted from 1986 to 2001, are reviewed. The Ogachi site, situated on a horst in the central part of a caldera, has two artificial reservoirs at depths of 700 m and 1000 m. The characteristics of the two reservoirs are different in that the lower one, which extends to the NNE is 30 times larger in volume than the upper one extending to the east. Water recovery during circulation tests was at best 25% using two wellbores. The reason for these features was discussed mainly from geological standpoints.

1. INTRODUCTION

Hot dry rock (HDR) heat mining is a technology that extracts heat from rock that is hot but lacks natural fluid flow. HDR has huge energy resources and its technology is environmentally friendly with little emission of carbon dioxide (Armstead and Tester, 1987). The Central Research Institute of Electric Power Industry (CRIEPI) has conducted 15 years of HDR testing in Japan. This paper outlines its experiments and reveals some of its geological features that were crucial to our testing and probably should be kept in mind in other HDR fields.

2. GEOLOGICAL FRAMEWORK

The Ogachi HDR test site (Figure 1) is situated inside a Neogene caldera, the Ogachi caldera, which was formed during 6-1 Ma (Takeno, 1988; Ito, 2000). The caldera is –30 km long and –20 km wide. The basement of the Ogachi site is

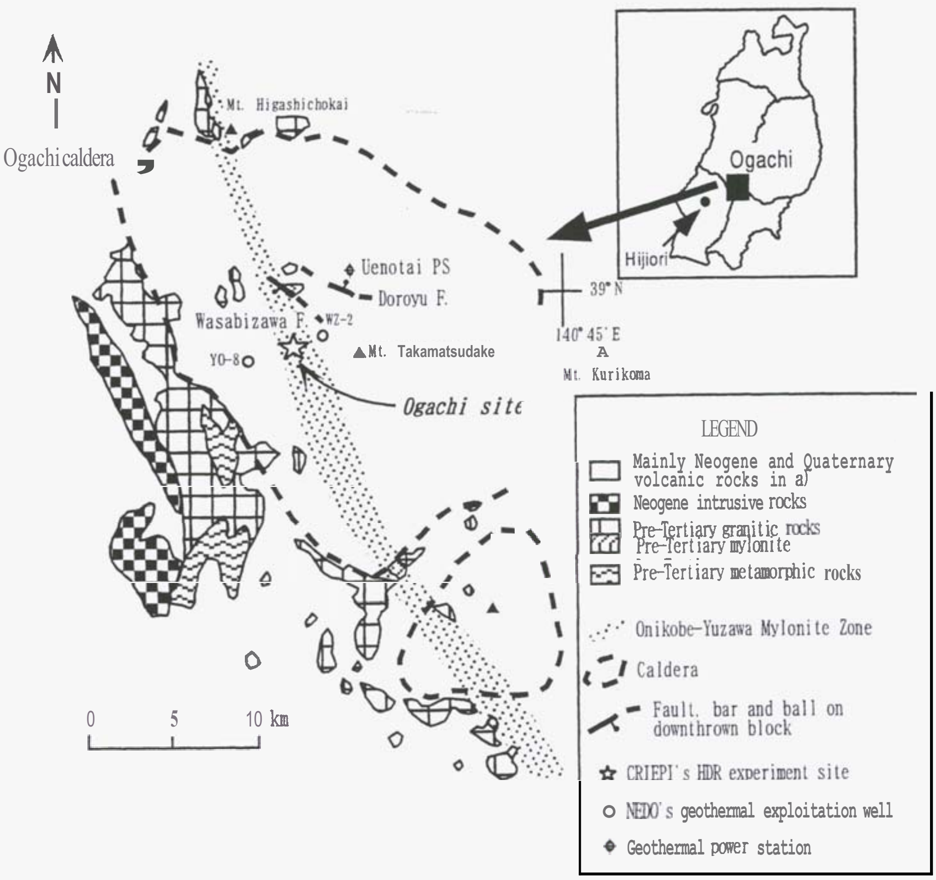


Figure 1. Generalized geological map around the Ogachi HDR test site. Modified from Sasada (1984). The position of calderas are from Takeno (1988).

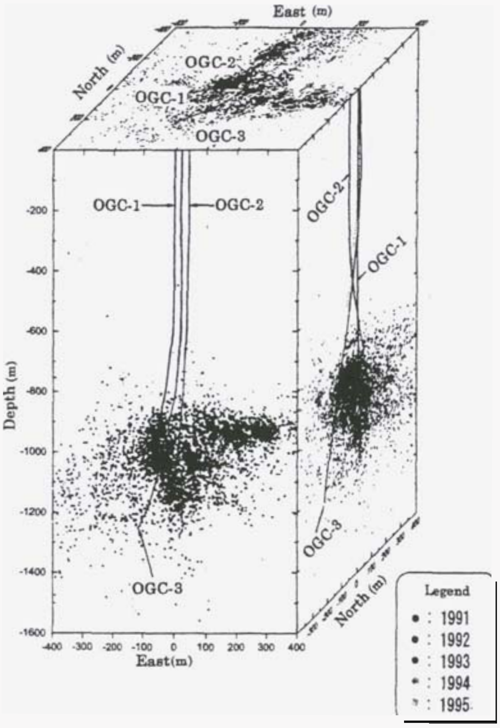


Figure 2. AE hypocenter distribution with well trajectories (Kaieda and Sasaki, 2002).

mylonitized granodiorite, which intruded ~100 Ma ago. Mylonitization took place before 52 Ma in a NNW trending zone (Sasada, 1984). Outcrops of the granodiorite occur mainly at the western rim of the caldera and sporadically inside the caldera.

The Ogachi site was selected for HDR test place mainly because granitic basement resides at relatively shallow depth (300 m depth) and geothermal gradient is very high (200 "C /km) and linear, indicating a hot dry rock is expected at shallow level in the crust.

The Ogachi site is located to the western fringe of a horst in the central part of the caldera. Geophysical surveys, such as seismic reflection, electromagnetic, gravity and y–ray spectrometry, revealed that no major faults are expected within 500 m from the Ogachi site. A major vertical fault with the offset of 500 m is expected –500 m to the west of the Ogachi site from a seismic reflection survey (Suzuki and Kaieda, 2000).

Stress analyses using drilling-induced tensile fractures (DTFs) from wellbores drilled around the Ogachi site indicate that a normal faulting stress is dominant in the horst area, whereas a reverse faulting stress is dominant at the fringe of the horst and in the deep sheeted basement area (Okabe *et al.*, 2002). The stress at the Ogachi site deduced by DTFs and a stress inversion method with fault plane solutions of AE is a reverse faulting type with the maximum principal stress direction of E-W or WNW-ESE (Ito and Okabe, 2001; Kaieda and Sasaki, 2002).

3. OUTLINE OF THE OGACHI EXPERIMENT

3.1 Drilling and hydraulic stimulation

Following preliminary hydraulic stimulation tests at Akinomiya site in the Ogachi caldera during 1986-1988, an injection well (OGC-1) was drilled almost vertically into the mylonite to a depth of 1000 m in 1990, which was later extended to 1027 m in 1995. Two artificial reservoirs were created by injecting pressurized water in OGC-1 at open-hole sections of 711-719 m and 990-1000 m during 1991-1992. Microearthquake, or acoustic emission (AE), hypocenter distribution showed that the upper reservoir extended 800 m to the east and the lower one 1000 m to NNE (Figure 2) (Kaieda and Sasaki, 2002). In 1993 a production well (OGC-2) was drilled to a depth of 1100 m to intersect both the upper and lower reservoirs. At a depth of 1060 m, drilling mud was lost at a rate of -20 l/min. Continuous core samples of 6.5 cm in diameter were obtained from open-hole sections of 700-1100 m.

A third well (OGC-3) was drilled to a depth of 1300 m in 1999. At its bottom, the maximum temperature was 250 °C. It was drilled through an AE cloud and steal casing was set to a depth of 700 m. At least three zones of major mud loss were encountered below a deprr of 1100 m. Spot core samples with a total length of 12.5 m were obtained. As inferred from Figure 3, the Ogachi site is conductive above 1100 m depth and not

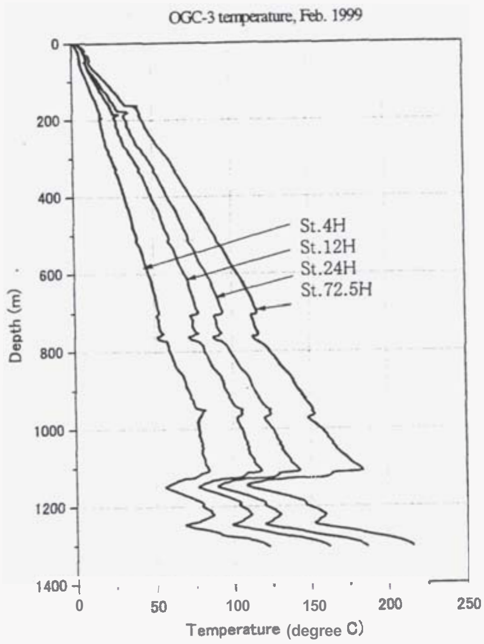


Figure 3. Temperature logging results just after completion of well OGC-3. St: standing time in hours.

necessarily conductive below this depth.

3.2 Circulation tests

Several circulation tests were carried out in OGC-1 and OGC-2 during 1993-1997 (Table 1). Because of a low fluid recovery rate of 2% during the first circulation test both wells were stimulated on several occasions after which the recovery rate was improved to 25% in 1995 (Kaieda *et al.,* 2000).

3.3 Reservoir evaluation

Many AE events were observed during hydraulic stimulation operations and water circulation tests (Figure 2). The AE hypocenters clustered in two distinct directions (NNE and E) initially but they dispersed in all directions around the wellbores as further testing went on. Several tracer tests conducted during water circulation experiments indicate that the lower reservoir is 30 times larger than the upper one and the reservoir volume tends to decrease over time mainly because permeability around the wellbores has increased (Kiho *et al.,* 1999). The increased permeability corresponds with the AE events occurred around the wellbores.

A simulation code, GEOTH3D, was developed by CRIEPI using a model that AE magnitude corresponds with permeability of rock mass (Yamamoto *et al.,* 1997). A revised code simulates the circulation test in 1995 in good agreement (Suenaga *et al.,* 2000).

4. NATURAL FRACTURE INVESTIGATION

Natural fractures were investigated both on core samples and by borehole imaging tools, such as borehole televiewer (BHTV), ultrasonic borehole imager (UBI) and formation microimager (FMI). Natural fractures in the upper and lower reservoirs are found to be remarkably different: the upper reservoir, at depths less than 900 m is more densely fractured and thick hydrothermal veins are far less common than in the lower reservoir. These features are supposedly due to hydrothermal brecciation associated with the Neogene caldera formation and they could greatly affect the HDR reservoir system (Ito and Kitano, 2000).

4.1 Fracture orientation

Orientation of natural fractures were revealed by borehole imaging tools (Figure 4): fractures in the upper reservoir (−700-900 m depth) show high dip and no dominant trend, those in the lower reservoir (900-1100 m depth) exhibit dominant NE-NNE trend with high dip especially in well OGC-2, which coincides with AE propagation. Fractures deeper than 1100 m trend NE-SW dipping shallowly to NW (Ito and Okabe, 2001).

4.2 Flowing fractures

In well OGC-3 water entry and/or exit points were detected as temperature anomalies (Figure 5). The testing was conducted as follows: At first OGC-3 was cooled by water injection and then temperature recovery was monitored by an optical fiber thermometer while injecting water into OGC-1. High temperature anomalies, which are assumed to be hot water exits from well OGC-1, were detected at 770 m and 960 m. Low temperature anomalies, which correspond to major mud loss zones, were detected at 1140 m and 1240 m. The high temperature anomaly points correspond to where many AE events occurred (Figure 2) and the low temperature anomaly points correspond to where few AE events were detected (Kaieda *et al.,* 2002). Pressure-Temperature-Spinner (PTS) logs in well OGC-3 conducted during this experiment indicate that water coming from well OGC-1 was too small to be detected by the spinner.

Candidates of high permeable fractures were picked up from well OGC-3 by examining FMI and UBI images. Their distribution indicates that high permeable fractures exist below the artificial reservoirs (Figure 6).

Table 1. Main results of circulation tests at the Ogachi HDR test site.

Year	Experiment	Injection (OGC-1)			Production (OGC-2)		
		Flow Rate (l/min)	Wellhead Pressure (MPa)	Total Water Volume (x 1000 m^3)	Flow Rate (l/min)	Temperature (°C)	Recovery
1993	22 days Circulation	750 1200	17 19	21	12 30	109	2
1994	5 months Circulation	500 750	13 16	140	50 65	160	10
1995	1 month Circulation	500 750	7 9	24	125 150	170	25

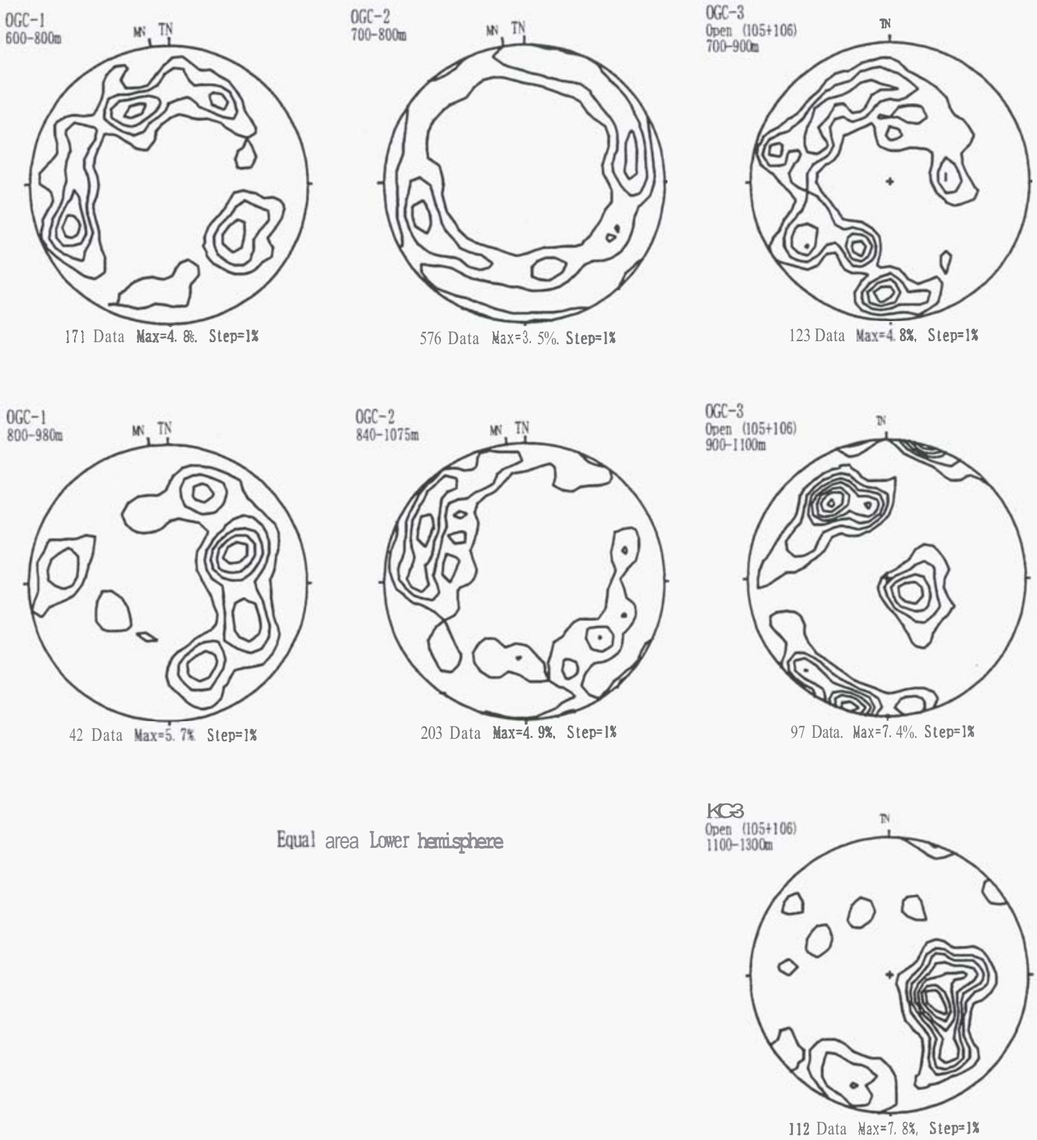


Figure **4.** Natural fracture distribution in the Ogachi reservoir revealed by BHTV, FMI and UBI survey.

5. GEOLOGICAL IMPLICATIONS

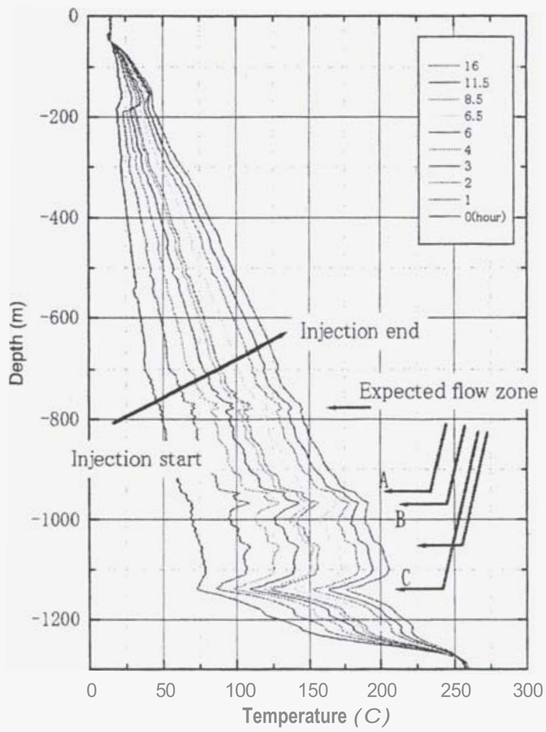
In the upper reservoir key natural fi-actures such as dykes and thick hydrothermal veins trend E-W, coinciding with eastward reservoir propagation (Ito and Kitano, **2000).** The maximum principal stress direction **of** E-W also favours this direction. The NNE propagation of the lower reservoir should be closely associated with the dominant natural fracture direction at the corresponding depth.

The low water recovery rate using **OGC-1** as an injection and ***OGC-2*** as a production may be attributed to that high permeable fractures exist deeper than the bottom hole **of** well OGC-2 (Figure *6)*. **A** majority of injected water may flow into these permeable fractures and/or a major fault –500 m to the west of the Ogachi site.

Some aspects gained fi-om the Ogachi experiments that seem to be considered for the future HDR development are **as** follows:

1) Many **AE** events occurred in the Ogachi reservoir where thermal conduction prevails. Few **AE** events occurred where zones of major mud loss, **i.e.** high permeable zones, exist. The low water recovery during the circulation tests may be associated with those high permeable zones that reside beneath the artificial reservoir.

2) If a majority of injected water that seems to have flowed into the high permeable zones were recovered by connecting them to a production well, the Ogachi site would become a much productive place.



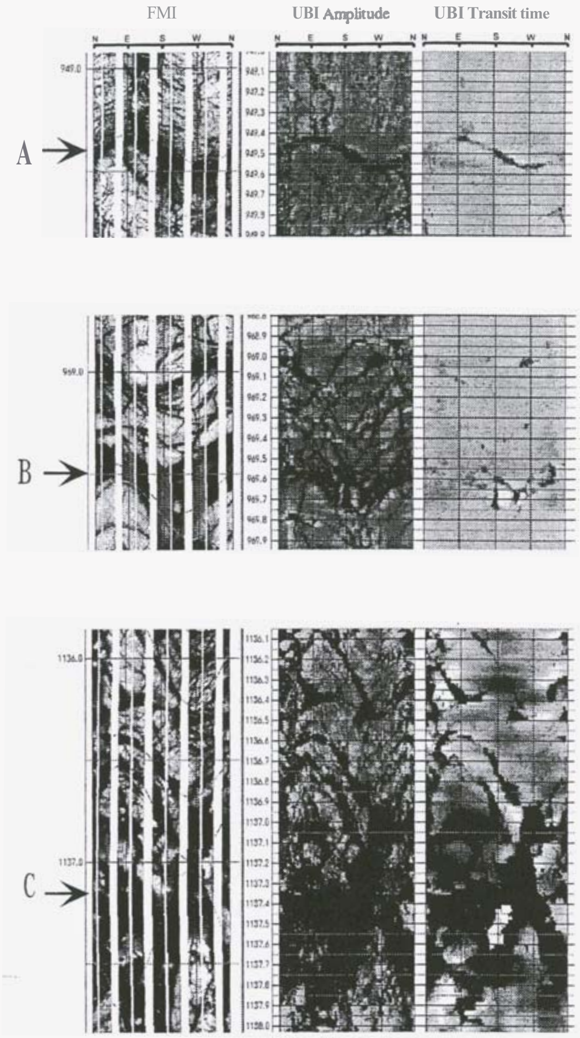


Figure 5. Flowing points detected by optical fiber thermometer and corresponding permeable fractures in well OGC-3.

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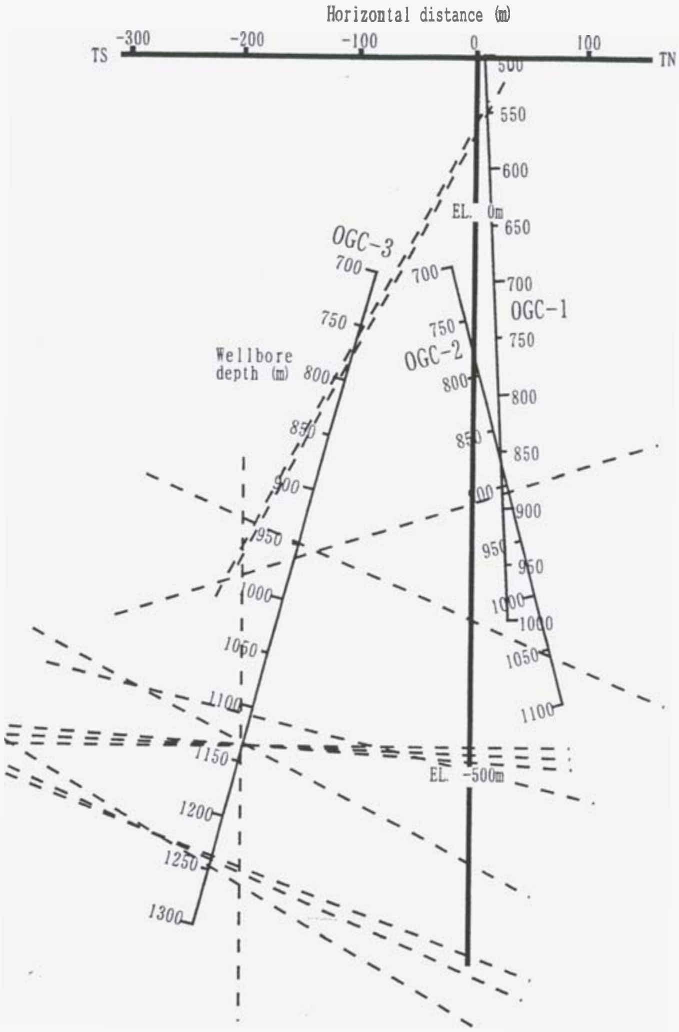

Figure 6. Distribution of highly permeable fractures (dashed lines) plotted in cross sectional view.

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