DEVELOPMENT OF PERMEABLE FRACTURES IN GEOTHERMAL SYSTEMS IN THE JAPANESE ISLANDS

-Two Contrasting Types of Geothermal Reservoirs-

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ABSTRACT: Permeable fractures developed in geothermal reservoirs are controlled by their tectonic environment and geologic structure. Accumulated surface investigations and subsurface borehole data in exploited geothermal fields suggest that development of permeable fractures are classified into two types in the Japanese Islands. A geologic framework of a geothermal reservoir is characterized by a high-angle normal fault system in central and southern Kyushu, and by fracture networks in Tohoku (northeast Honshu). The type of fractures is probably related to the regional and local stress fields, and the geologic development of their host rocks.

KEY WORDS: Fault, Fracture, Geothermal Reservoir, Japanese Islands, Kyushu, Stress Field, Tectonics, Tohoku

INTRODUCTION

The outline of fracture-type geothermal reservoirs is becoming clear in the Japanese Islands. The exploitation of the Kirishima geothermal field delineated a reservoir controlled by a high-angle normal fault system in southern Kyushu (Kodama and Nakajima, 1988; Gokou et al., 1988; Taguchi, 1992). This high angle structure is similar to the Hatchobaru-Otake geothermal system in central Kyushu (Fujino and Yamasaki, 1984). Both systems are located in the region where normal and strike-slip faults arc predominant. On the contrary reservoir structures controlled by a large high-angle fault have not been found in the northern part of Tohoku, where the Kakkonda, Matsukawa and Sumikawa-Ohnuma geothermal systems are exploited (Sasada et al., 1994). In this paper, I will describe these contrasting reservoir structures based on their present tectonic environment and their geologic structure.

REGIONAL TECTONIC SETTING

The major geothermal fields exploited for power generation are located on the volcanic front of the Japanese Islands, where the Pacific and Philippine Sea plates are subducting under the Eurasian plate (Fig. 1). Earthquake\ frequently occur along the convergent plate boundaries, and their hypocenters are mostly distributed in the Wadachi-Benioff zone and in the upper crust of the island arc (e.g.

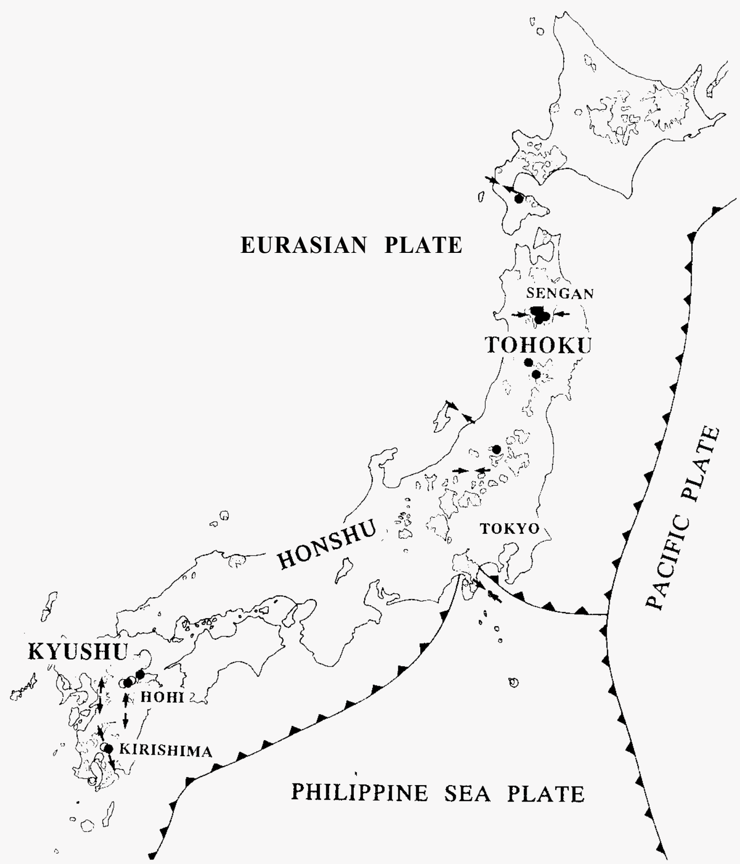

Fig. 1 Geothermal exploitation sites and Stress fields in the Japanese Islands
Solid circle. geothermal power station, open circle: exploitation site where a power station will be constructed near future. Arrow: Stress field determined by focal mechanisms of shallow earthquakes (Ishida, 1991). Outward directed arrow: T-axis, inward directed arrow: P-axis. Dotted area: Quaternary volcanic rocks.

Hasegawa et al., 1991). The stress fields in the upper crust were estimated from the focal mechanisms of the earthquakes as follows; T-axis trends N-S to NNW-SSE in central and southern Kyushu, whereas P-axis E-W in Tohoku (Ichikawa, 1971; Okada and Ando, 1979; Ishida, 1991). An active geologic structure is also a good indicator for present stress fields. The active faults are mostly normal and lateral in Southwest Japan including Kyushu, whereas reverse in Tohoku. This configuration of the active faults is consistent to the stress field determined from the focal mechanisms of the shallow earthquakes (Okada and Ando, 1979).

GEOLOGIC AND TECTONIC SETTING OF THE GEOTHERMAL AREAS AND RESERVOIR STRUCTURES IN KYUSHU

Exploration and exploitation sites

The exploitation sites of the geothermal resources in Kyushu are located in the Hohi graben (Kuju-Beppu graben), around the Kirishima volcanic complex, and around the Ata caldera (Fig. 2). The Hatchobaru and Otake power stations, small power plants at Beppu and Takenoyu, and two exploitation sites of Takigami and Oguni are all located in the Hohi graben in central Kyushu, whereas the Ogiri exploitation site, the Shiratori exploration field, and a small power plant for Kirishima-Kokusai Hotel are located around the Kirishima volcanic complex, and the Yamakawa exploitation site around the Ata caldera in southern Kyushu (Fig.2).

The Hohi graben and the Hatchobaru-Otake geothermal system

The calc-alkaline volcanic rocks of Pliocene and Quaternary ages were distributed with the average thickness of 2.5 km in the Hohi graben (Kamata, 1989; Nakada and Kamata, 1991), where the Bouguer anomaly is regionally negative (Komazawa and Kamata, 1985). The southern margin of the graben is represented by a steep gravity gradient, and bounded by a ENE-trending right-lateral fault. Many E-W trending normal faults are also running in the graben, most of them moved in Quaternary (Okada and Ando, 1979; Ikeda, 1979). The Hohi graben is a volcano-tectonic depression (Kamata, 1989; Tamanyu, 1993), and one of the tectonic control mechanisms is a pull-apart caused by an oblique subduction of the Philippine Sea plate (Kido, 1993; Tsukuda, 1993).

Crustal earthquakes occur mostly shallower than 20 km depth in Kyushu (Kakuta et al., 1992), and the fault plane solutions of the shallow earthquakes in the Hohi graben are normal fault type and strike slip fault type of N-S extentional axis (Fig. 2)(Sudo, 1993). These focal mechanisms are consistent to the distribution of active faults.

The normal and lateral faults are expected to develop in the Hatchobaru-Otake geothermal system from the regional geology and the present stress field in the Hohi graben as described above. Actually, the Hatchobaru-Otake geothermal reservoirs are located in the horst and graben structure controlled by NW-trending normal faults. The normal fault systems with horst and graben play an important role on the formation of the geothermal reservoir, based on the exploration data (Fujino, and Yamasaki, 1984).

The geological succession of the Hatchobaru-Otake geothermal system is divided into the following four groups in descending chronologic order; Kuju and Hohi volcanic rocks of Quaternary ages, Tertiary volcanic rocks and pre-Tertiary basement. The Kuju volcanic rocks, consisting of hornblende andesite lava, formed dome-shaped volcanoes at the ages from 0.5 Ma to 0.1 Ma B.P. The present geothermal activity is probably related to the crystallized magma reservoirs beneath the volcanoes (Fujino, personal commun.).

The geologic structure is characterized by NW-trending normal fault systems with high angles. The exploited reservoir lies at the southwestern border of the horst (Fujino and Yamasaki, 1984). In addition to the NW-trending faults, a few NE-trending faults are located nearby. Characteristics of iso-thermal lines and borehole geology suggest that the NW-trending faults control fluid flow and reservoir structure.

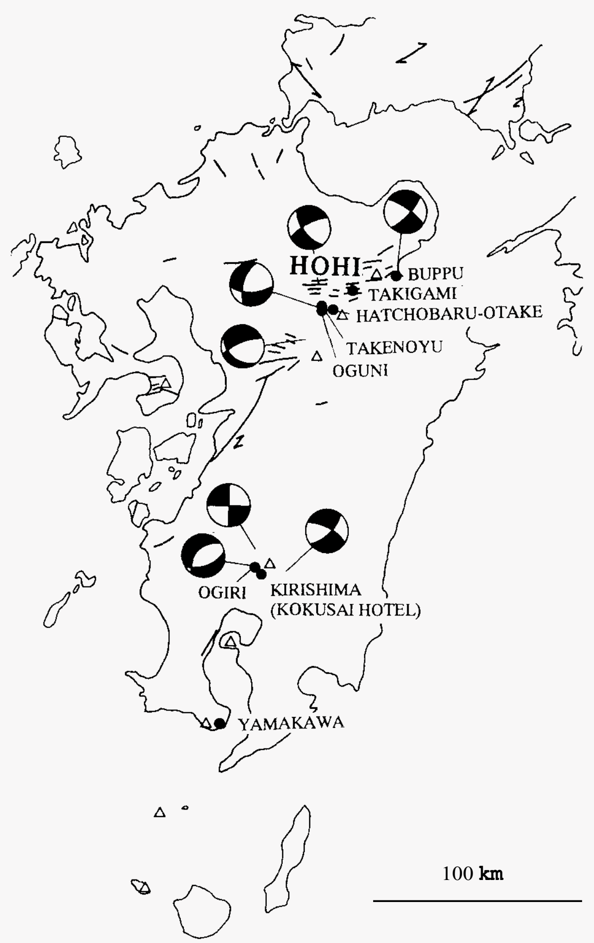

Fig. 2 Tectonic environment of geothermal areas in Kyushu
Solid circle: geothermal power stations(working and under construction). Open triangle: active volcano. Solid line: active fault after Kinugasa et al. (1992). Focal mechanism of crustal earthquakes is based on Kagiyama (1991) and Sudo (1993).

The Kirishima geothermal area

The present fault activity is less in the Kirishima area than the Hohi graben, but hydrothermal activity forming NE-trending vein-type deposits and NE-trending geothermal reservoirs have been present since Pliocene (Taguchi, 1992). Recent investigation of the microearthquakes in Kirishima, southern Kyushu shows that normal faults with NW-trending T-axis, and strike-slip faults with ENE-trending P-axis (Fig. 2)(Kagiyama, 1991). Both of the structures of vein-type deposits of Pliocene and Pleistocene ages and present geothermal reservoir can be interpreted as pull apart structures related to the subduction of the Philippine Sea plate (Taguchi, 1992)

Ogiri geothermal exploitation site is located on the western flank of the Kirishima volcano. Recent development revealed the subsurface structure, especially along the Gin'yu fault, which is a main reservoir of the Ogiri geothermal system (Kodama and Nakajima, 1988; Gokou et al., 1988). The Gin'yu fault runs in the direction ENE-WSW and dips steeply NW. The borehole data indicates that the fault zone is 150m wide. The cuttings recovered from the hole show that rocks in the fault zone are highly altered and quartz, wairakite and adularia are common minerals (Gokou et al., 1988).

GEOLOGIC AND TECTONIC SETTING OF THE GEOTHERMAL AREAS AND RESERVOIR STRUCTURES IN NORTHERN TOHOKU

Exploration and exploitation sites in the Sengan area

The Sengan is one of the largest geothermal areas including several active volcanoes and geothermal exploration and exploitation sites of Matsukawa, Kakkonda and Sumikawa-Ohnuma (Fig.3). Matsu-kawa **is** the only geothermal exploitation site utilizing a vapor-dominated resource. The Kakkonda is located in the large subsurface high-temperature anomaly to the southwest of Iwate-san volcano. The Sumikawa-Ohnuma geothermal system is located in the northeast of Akita-yake-yama volcano, where intense hydrothermal manifestations are distributed.

Geologic and tectonic setting

The Sengan area is widely covered with the Quaternary volcanic rocks. The geothermal reservoirs are mostly developed in the Tertiary formations of volcanic rocks and marine sediments. The lowest members of submarine volcanics and sediments formed when the Sea of Japan was opening in the middle of Miocene. The Tertiary formations are highly deformed so that folding and faulting structures are common. The NS-trending and NNW-trending faults are running in the Sumikawa-Ohnuma and Kakkonda geothermal systems respectively.

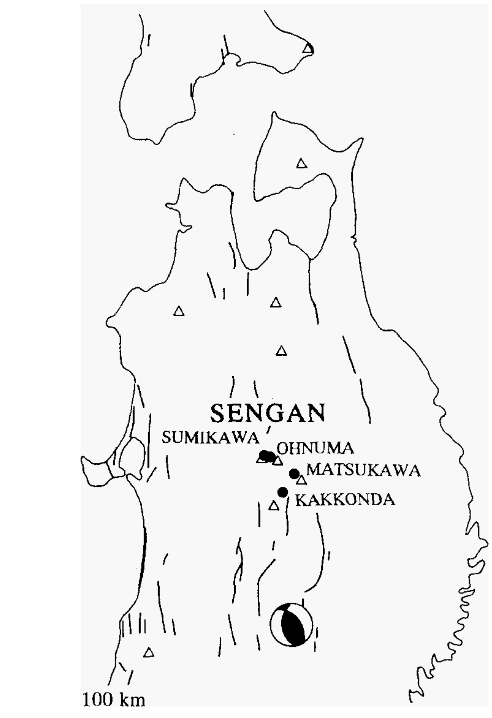

Fig. 3 Tectonic environment of geothermal areas in northern Tohoku Solid circle: geothermal power stations (working and under construction). **Open** triangle: active volcano. Solid line: active fault after Kinugasa et al. (1992). Focal mechanism of crustal earthquakes is based on Shimazaki et al. (1978).

Focal depths of crustal microearthquakes are shallower than 15 km in Tohoku (Takagi et al., 1977). Their focal mechanisms commonly show reverse-type nodal planes striking northerly and P-axis trending to the west (Fig. 3) (Okada and Ando, 1979). Recent seismic observations shows that under the tectonic stress field of horizontal compression beneath the volcanic arc, stress concentration will arise around the regions where the base of the brittle seismic zone is locally elevated (Hasegawa et al., 1991).

Kakkonda

The geothermal reservoir is situated in the Tertiary and pre-Tertiary formations and the intrusive rocks including a very young granitic pluton. The Tertiary formations consist of dacitic-andesitic pyroclastic rocks, andesite lava, shale and sandstone The pre-Tertiary formations consist of slate, sandstone and andesitic-dacitic tuffs. The thermally metamorphosed rocks of the Tertiary and pre-Tertiary formations are distributed around the granite. The microearthquake activity appears to correspond to the reservoir where geothermal fluids are circulating. The bottom of microearthquake swarm seems to be located in the uppermost part of the granitic pluton.

The latest fracture systems observed on the surface outcrops arc NE-, E-W trending veins and faults with lateral and normal displacement, both of which were formed by the stress field with horizontal NW-SE minimum principal stress axis (Koshiya et al., 1993). Investigation of subsurface geology indicates that the fractures are related to folding structure of the Tertiary formations (Sato, 1982; Ide, 1985; Doi et al., 1988). The fractures are also controlled by intrusive bodies (Doi et al., 1988). The shallow reservoir is expressed by NW-trending fracture zone. It extends 3.6 km long and 1.0 km wide and 1.4 km deep (Doi et al., 1988). Any high-angle major faults like the Gin'yu fault have not been found in the Kakkonda system. Recent drilling revealed the deep fracture system around the granitic intrusive body at the levels of 1,950 to 2,770 m deep from the surface (Kato and Doi, 1993). Intensive survey of the deep geothermal system is now being conducted using a 4,000 m hole by NEDO (Sasada et al., 1993).

The subsurface temperature in the geothermal system changes from 230 "C to 300 "C abruptly at the depth of about 1,500 m. The geothermal reservoir could be divided into the shallow and deep ones at the boundary of the steep temperature gradient. This discontinuity does not suggest major high-angle fractures connecting them. The permeable fractures in the deep reservoir have been found in the pre-Tertiary formations, and at the upper margin of the pluton. Their deep structure has not been characterized yet. Low angle reverse faults and fractures could be expected in the deep levels if the stress field is compressional. Fractures could also be controlled by a structure of the granitic pluton.

Geological studies show several types of fracture system reflecting the complicated geologic history of the Kakkonda geothermal system. They are normal, lateral and reverse faults with several directions, several fracture systems related to anticline and syncline structures of Miocene formations, and joint systems oblique to the bedding (Ide, 1985; Koshiya et al., 1993). The Tohoku region underwent different types of stress fields since Miocene. The Several types of fractures and faults corresponding to different types of stress fields may contribute to the fluid circulation in the Kakkonda system.

Sumikawa-Ohnuma

The subsurface geologic formations consist of Tertiary dacitic pyroclastics, marine sediments, andesite lava, granodioritic intrusives. They are covered with Quaternary andesite lava and lacustrine sediments in paleo-caldera at Akita-yakeyama volcano. The subsurface temperature recorded at the depth of 2,000 m exceeds 300°C . The geothermal heat sources are probably lying beneath the Yakeyama-Hachimantai volcanic chain located to the south of the developing area (Sakai et al., 1993).

The conceptual model of the geothermal system was described by Kubota (1985). The characteristic feature of the reservoir is the presence of a steam cap (vapor dominant part) at the top of water dominated reservoir. Quaternary formations of andesite lava and lacustrine sediments have an important role for making the steam cap of the reservoir. Storage consists of open fractures like cavities as observed in ore veins. During drilling work, lost circulation occurs frequently at high temperature zone suggesting the area is fairly fractured. However, fractures are self-sealed with vein materials in low temperature zones.

The geothermal fluids are controlled by fractures in the host rocks. The geothermal fluids are mostly stored in the fractures of the Tertiary formations, and any significant difference among the rock facies have not been detected for development of the geothermal reservoir (Sakai et al., 1993).

FRACTURE SYSTEMS IN GEOTHERMAL RESERVOIRS

Fractures form in shear and hydraulic processes in geothermal systems. The reduction of effective stress by increment of pore pressures results shear-type fractures and hydraulic fractures (Phillips, 1972). The increment of hydropressure of fluid dilatation by heating is one of the important factors for formation of fracture especially in geothermal systems.

Two contrasting types of geothermal reservoir were described above. The Hatchobaru-Otake geothermal system is characterized by high-angle normal faults, whereas the Kakkonda by fracture networks. The Ogiri geothermal reservoir is similar to the Hatchobaru, and the Sumikawa is similar to the Kakkonda.

The regional stress fields of the upper crust in central and southern Kyushu differ from those of the Sengan in Tohoku. The NS- and NNW-trending T-axis, and normal and strike-slip fault systems in central and southern Kyushu are probably caused by oblique subduction of the Philippine Sea plate (Tsukuda, 1993), whereas the regional stress field in Tohoku is compression with EW-trending P-axis.

Since geothermal reservoirs develop in shallow zones, the fracture formation could be more closely related to a local stress field, especially for a geothermal system developed in a mountainous area with great altitudinal differences (Hast, 1973; Scheidegger, 1977). The fracture systems in the shallow part of the Kakkonda geothermal system could be affected by topography, because it is located in a steep canyon.

The fracture system of Kakkonda consists of several types, some of which are related to geologic history of the Tertiary formations. The faults and joints formed in the previous time are weak planes to be fractured by the present geothermal condition. The reactivation of the faults could only occur when fluid pressure exceed the lithostatic load (Sibson et al., 1988). Host rocks of some Japanese geothermal systems underwent a long geologic history and the faults and joints predate the present geothermal activity. Some pervious faults and flexure structures could be related to reactivation by increment of pore pressures in heating geothermal systems.

CONCLUSION

Two contrasting types of geothermal reservoir are recognized in Japanese Islands. One is a high-angle Hatchobaru-type, the other is a network Kakkonda-type. The fracture types are related to their stress fields and their geologic developments.

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