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 are 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, Mitsuoka, 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). Earthquakes frequently occur along the convergent plate boundaries, and their hypocenters are mostly distributed in the Wadati-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).

Trends in Kyushu

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

Exploration and exploitation sites

The exploration 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 Hohi graben is located at the southwestern border of the horst (Fujino and Yamasaki, 1984). In addition to the NW-trending normal faults, a few NE-trending faults are located nearby. Characteristics of isothermal lines and borehole geology suggest that the NW-trending faults control fluid flow and reservoir structure.

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 has 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 NE-trending P-axis (Fig. 2), have developed. Both of the structures of vein-type deposits of Pliocene and Pleistocene age are present in the geothermal reservoir. The present geological structure is probably related to the crystallized magma reservoir beneath the volcanoes (Fujino, personal communication).

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

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

Exploration and exploitation sites in the Sengan area

The Sengan area is one of the largest geothermal areas including several active volcanoes and geothermal exploration and exploitation sites of Mutsukawa, Kakkonda and Sumikawa-Ohnuma (Fig. 3). The Sengan area is the only geothermal exploration 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 NW-trending faults are running in the Sumikawa-Ohnuma and Kakkonda geothermal systems respectively.
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 show 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 pyroclastics, marine sediments, andesite lava, and lacustrine sediments in the Tertiary and pre-Tertiary formations. The geothermal reservoir is situated in the Tertiary and pre-Tertiary formations and the intrusive rocks including a very young granitic pluton. 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 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 hydroprosper 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 P-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; Schiedegger, 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.

References


* in Japanese and English abstract.