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SEISMIC ACTIVITY IN THE KAKKONDA GEOTHERMAL SYSTEM CHARACTERIZED BY THE QUATERNARY KAKKONDA GRANITE, JAPAN

Nobuo Doi[1], Satoshi Shigehara[1], Ken Ikeuchi[1], Osamu Kato[1], Masaki Takahashi[1],
Takao Ominato[3], Kazuo Koide[2] and Toshiyuki Tosha[2]
[1]Japan Metals and Chemicals Co. Ltd.
[2]New Energy and Industrial Technology Development Organization (NEDO)
[3]Institute of Earthquake Research, Tokyo University

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ABSTRACT
The seismic activity in the water-dominated Kakkonda geothermal system has been examined in relation to permeability. The microearthquakes occur only in the hydrothermal convection zone. The zone of hypocenters coincides with the permeable zone higher than $8\times10^{-12}m^3$ in permeability-thickness product (kh) value. The seismic activity in the Kakkonda geothermal system became active in association with the magma and/or magmatic water intrusion below Iwate Volcano, 13 km east of the field, and around the Mitsuishi-yama Volcano in February 1998. The microearthquakes in the Kakkonda geothermal system occurred along fractures in NE-SW and NW-SE direction, and occurred above the extended body of the Kakkonda Granite, the heat source of the geothermal system. The Kakkonda Granite underlies not only the exploited field but also the Mitsuishi-yama Volcano with acidic hydrothermal alteration and gas emission zones.

1. INTRODUCTION

The NEDO (New Energy and Industrial Technology Development Organization) began the Deep Geothermal Resources Survey program in FY-1992 to delineate the deep geothermal structure related to the Kakkonda Granite. A core part of the program was to drill the deepest well (WD-1) in Japan,. Seismic monitoring began in December, 1994 with ten seismometers (Takahashi et al., 1995; Uchida et al., 1996)?

Several thousand microearthquake events occur in the Kakkonda field each year (e.g. Ito and Sugihara,1988; Sugihara and Tosha,1988). The occurrence and mechanism of microearthquake events have been studied in relation to fracture distribution, metamorphic aureole, neo-granitic pluton (Kakkonda Granite), formation temperature, regional stress field and pore pressure movement. The microearthquakes occur horizontally and vertically in the densely fractured zone (Tosha et al.,1993,1998) and above the Kakkonda Granite, probably controlled by the highly metamorphosed cordierite zone (Tosha et al., 1993, 1998). The microearthquakes diminish in depth around a temperature contour of approximately 350ºC (Uchida et al., 1996).

In this paper, we describe the hypocenter distribution and lower depth of the seismic zone with the concrete permeability-thickness product (kh) value. We also show the fracture distribution and the extended shape of the Kakkonda Granite using the hypocenter distribution associated with the volcanic activity of Iwate Volcano.

2. SEISMIC ACTIVITY IN HIGH PERMEABLE ZONE

2.1 Kakkonda geothermal system

The Kakkonda field is located in the Sengan Hachimantai) geothermal area, one of the most active volcanic-geothermal areas in Japan (Fig.1). The field shows a temperature of >300ºCat ~1500m, suggesting an active heat source at depth. Deep geothermal wells including NEDO's WD-1 well confirmed the Kakkonda Granite as a heat source of the geothermal system (see Geothermics special issue, 1998). The Kakkonda Granite was intersected at depths 1300 to 2800 m b.g.l. *(*below ground level*, ed.)* by eleven wells over an area of 1.5 km (EW) by 1.3 km (NS) (Fig.2). Based on geological constraints, e.g. distribution of the granite itself and some metamorphic mineral isograds, the granite is a stock about 5 km ×8 km at 2.2 km below sea level (Doi et al.,1998; Fig.1).

At depths shallower than 3100 m in WD-1 there is a zone of hydrothermal convection at less than 380ºC with the boundary between the lower conduction zone. (Ikeuchi et al., 1998; Fig.3), and with a potential reservoir for steam production from permeable fractures near the upper margin of the Kakkonda Granite.

2.2 Microearthquake distribution in the zone of hydrothermal convection

Figure 4 shows the permeability-thickness product (kh) values of wells relative to elevation in the Kakkonda field. The kh values were obtained by production and injection tests using 49 exploration, production and re-injection wells. The kh values determined by injection tests are higher than those from production test because the lower injection fluid-temperature resulted in contraction of reservoir rocks. The kh value in the shallow reservoir at 0–500 m depth b.g.l. (e.g. Hanano,1995) decreases with depths and is higher than that of the deep geothermal reservoir by one magnitude or more. The kh value of the upper part of the Kakkonda Granite at –1800 m to –2200 m is less than 8×10^{-12} m^3.

The microearthquakes in 1988 occurred above the Kakkonda Granite. The number decreased rapidly at depths approximately 300-500 m above the granite (Tosha et al,1998). The microearthquakes from 1994 to 1999 also occurred above the Granite (Fig.8). So, the kh value at the zone of hypocenters and its lower limit in the field is thought to be higher than 8×10^{-12} m^3. The permeability may control the velocity of hydrothermal convection, and the formation temperature resulted in the restricted distribution of microearthquakes.

3. FRACTURE DISTRIBUTION AND THE SHAPE OF THE KAKKONDA GRANITE

The seismic activity in 1994 to 1999 in the Kakkonda field is shown in Figures 5 and 6. These figures show the restricted seismic activity in the geothermal reservoir of the field. It is divided into three periods of activity; December 1994 to July 1996, August 1996 to January 1998 and February 1998 to March 1999.

3.1 Seismic activity in December 1994 to July 1996

The seismic activity in this period (Fig.5) is an usual state of number in the Kakkonda field as shown by Tosha et al. (1998). The hypocenter distribution clearly shows an en echelon arrangement of microearthquake swarms trending NNE-SSW along the Kakkonda river which flows in a NW to SE direction (Fig.6).

3.2 Seismic activity in August,1996 to March,1999

The seismic activity in this period changed gradually in number and hypocenter distribution. Figures 5 and 6 show the increase of microearthquakes in the SW region during August 1996 to January 1998.

The seismic activity remarkably increased in February 1998 in the NE and SW regions. The microearthquakes in NE region occurred near the Mitsuishi-yama Volcano (Figs.5 and 6). This activated seismicity is caused from magma and/or magmatic water intrusion under the Iwate Volcano (elevation, 2038m), 13 km east of the field, and around the Mitsuishi-yama Volcano (e.g. Tanaka et al., 1998). The upheaval of the ground in the Kakkonda field was observed in 1998 by levelling (Doi et al.,1999) and DISAR (Differential Interferometric Synthetic Aperture Radar) using the satellite JERS-1 (Earth Observation Research Center of National Space Development Agency of Japan and School of Science of Nagoya niversity,1999; Geographical Survey Institute,1999). The seismicity decreased after the earthquake of September 3, 1998 (M6.1), and became gradually high again at the end of the period of observation.

The microearthquakes occurred along fractures in NE-SW and NW-SE directions in the 4.5 km wide zone between Akitori-zawa and Omatsukura-zawa. The zone occupies a portion of the fractured zone from the Akita-komagatake Volcano to the Matsukawa geothermal field (Fig.1).

3.3 Estimation of extended shape of the Kakkonda Granite

Microearthquakes occur above the Kakkonda Granite in the exploited field (Figs.7 and 8) delineate the shape of the granite at east area of the field *(either* eastern end of the field*, or,* east of the field*; ed)*. The estimated shape of the granite extends 3 km toward the east and has a diameter of about 5 km. The shape of the granite is concordant with that estimated from geological constrains (Fig.1). The Kakkonda Granite underlies not only the exploited field but also the east area near the Mitsuishi-yama Volcano with wide acidic hydrothermal alteration and gas emission zones.

4. CONCLUSION

The microearthquakes in the Kakkonda field occur in the permeable zone higher than 8×10^{-12} m^3. The seismic activity became active in the geothermal system along the NE-SW and NW-SE trending fracture in February, 1998 associated with the magma and/or magmatic water intrusion below the Iwate Volcano and around the Mitsuishi-yama Volcano. The microearthquakes occur above the Kakkonda Granite, the heat source of the geothermal system, in the exploited field and delineate the extended shape of the granite at east of the field *(either* eastern end of the field*, or,* east of the field*; ed.)*. The estimated shape of the granite is concordant with that from geological constraints. The granite underlies the Mitsuishi-yama Volcano with wide acidic hydrothermal alteration and gas emission zones.

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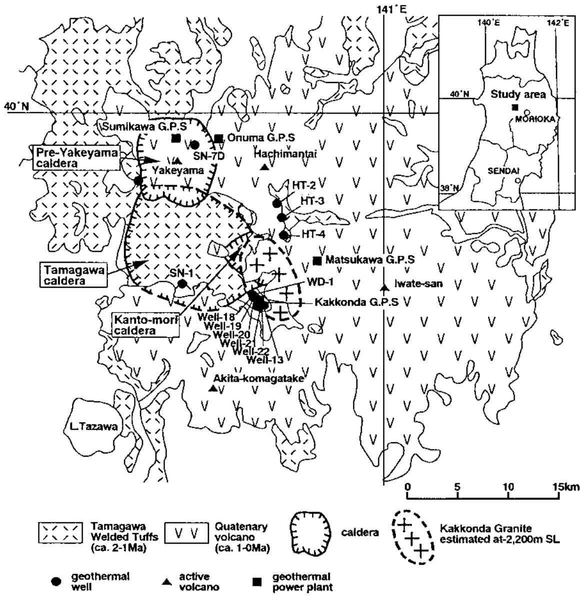

Figure 1. Geological map of the Sengan (Hachimantai) volcanic-geothermal area (Doi et al.,1998). The distribution of the Kakkonda granite at –2200 m a.s.l. is estimated from geological constrains.

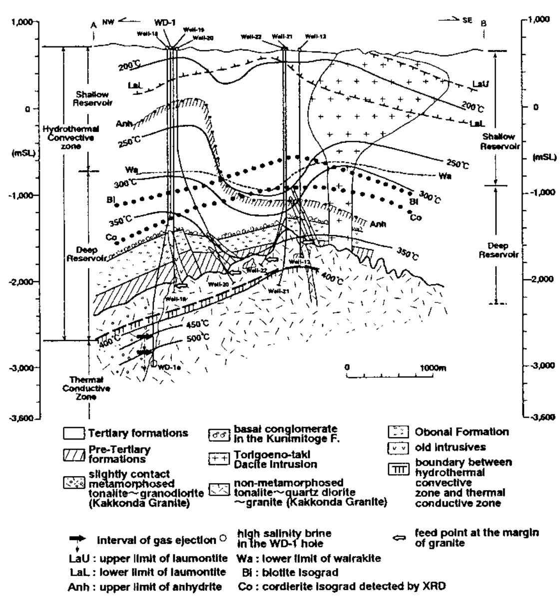

Figure 2. Schematic geothermal model of the Kakkonda geothermal system along the Kakkonda river in a NW-SE direction (Doi et al.,1998). Some data off the cross-section, such as well trajectory and temperature, were projected to the section.

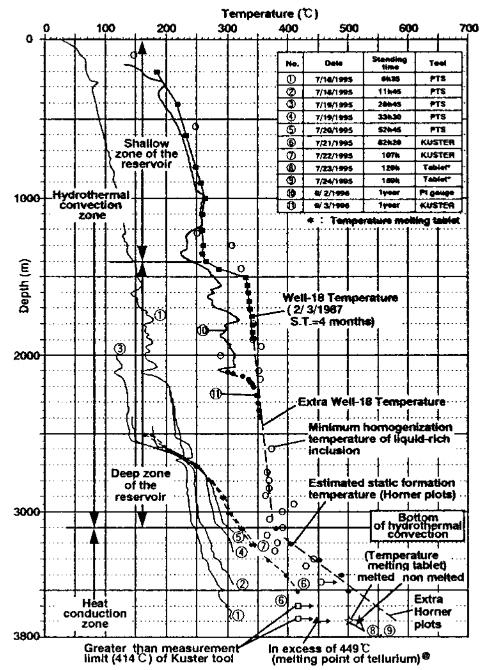

Figure 3. Thermal structure of the Kakkonda geothermal system determined by logging data of WD-1a (Ikeuchi et al.,1998).

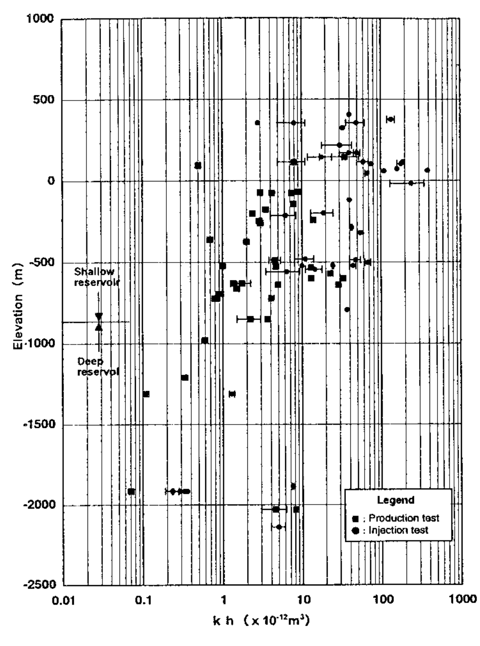

Figure 4. Elevation vs. permeability-thickness product (kh) plot in the Kakkonda geothermal system. The kh values of 49 wells are determined by the production and injection test.

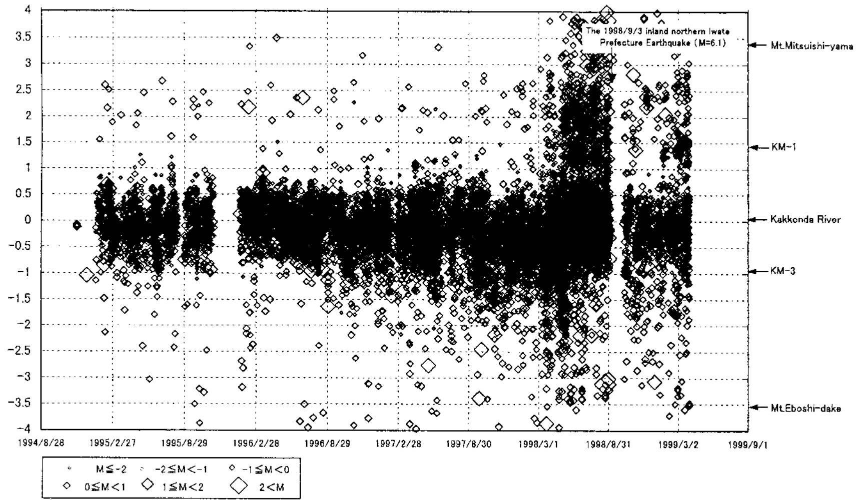

Figure 5. Space-time plots of the microearthquake in the Kakkonda geothermal system shown from SE direction. The seismic activity is divided in three periods; November, 1994 to July, 1996, August, 1996 to January, 1998 and February, 1998 to March, 1999.

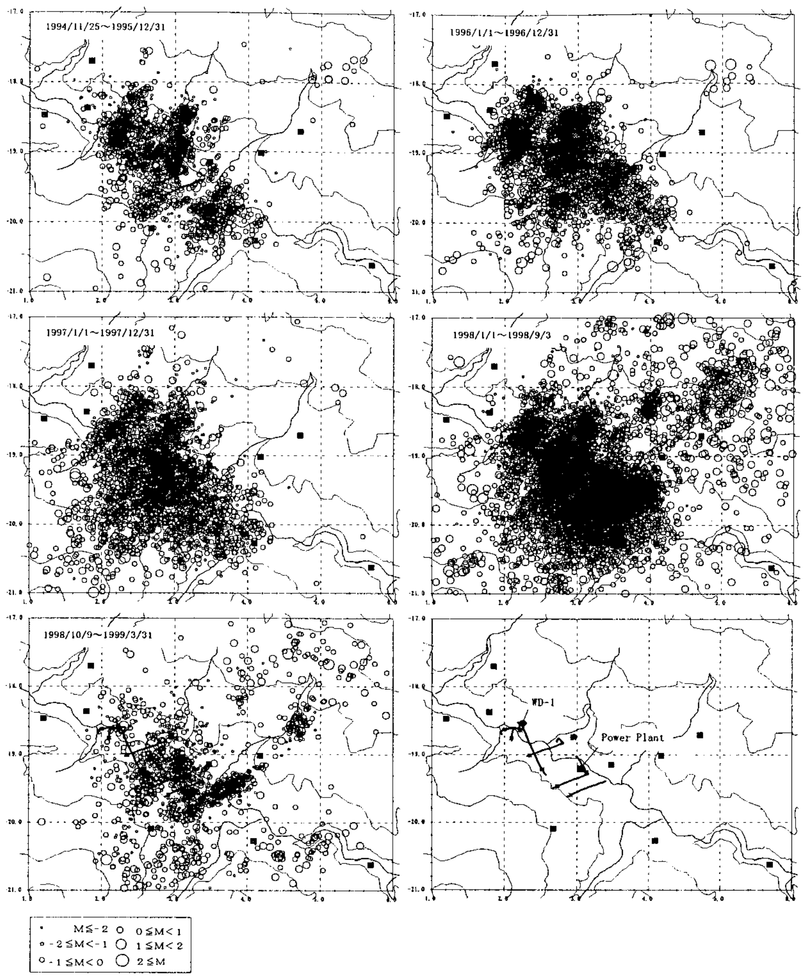

Figure 6. Hypocenter distribution of the microearthquakes in November, 1994 to March, 1999. Hypocenter is calculate by MEPAS (Micro-earthquake Data Processing and Analysis System; Miyazaki et al.,1995) using the velocity model by NEDO (1996).

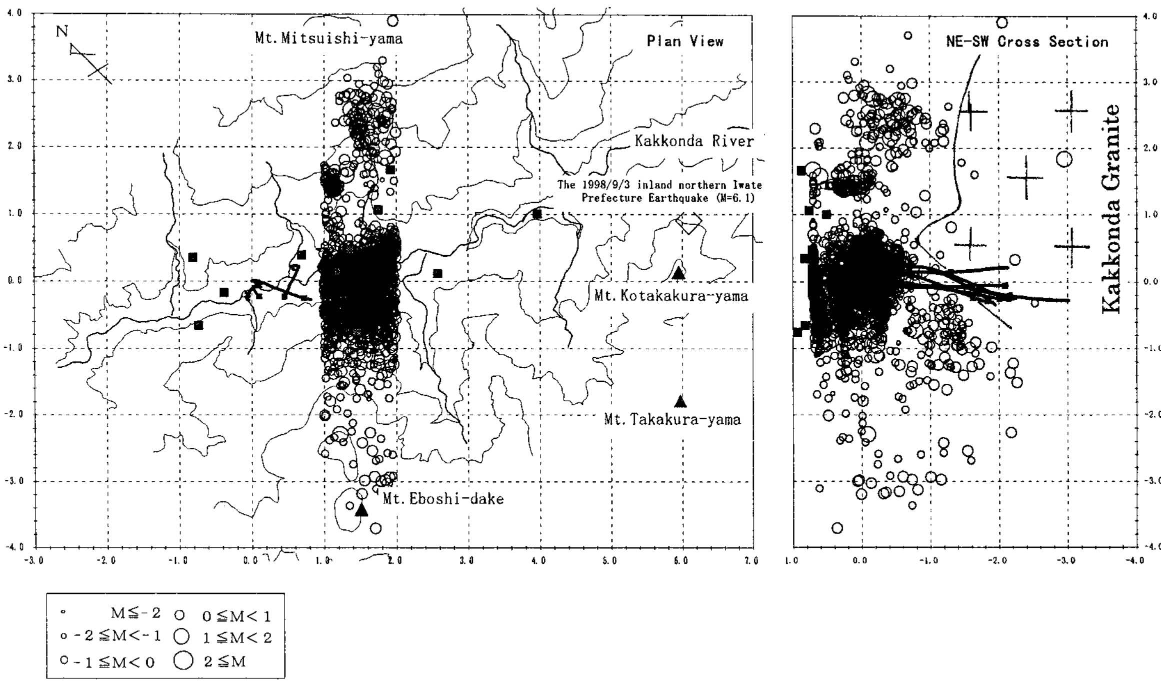

Figure 7. Selected hypocenter distribution in March 1 to September 3, 1998 to show the lower limit of the distribution. The Kakkonda Granite underlie the microearthquakes at the exploited and the east area. The estimated shape of the granite is concordant with that shown in Fig. 1.

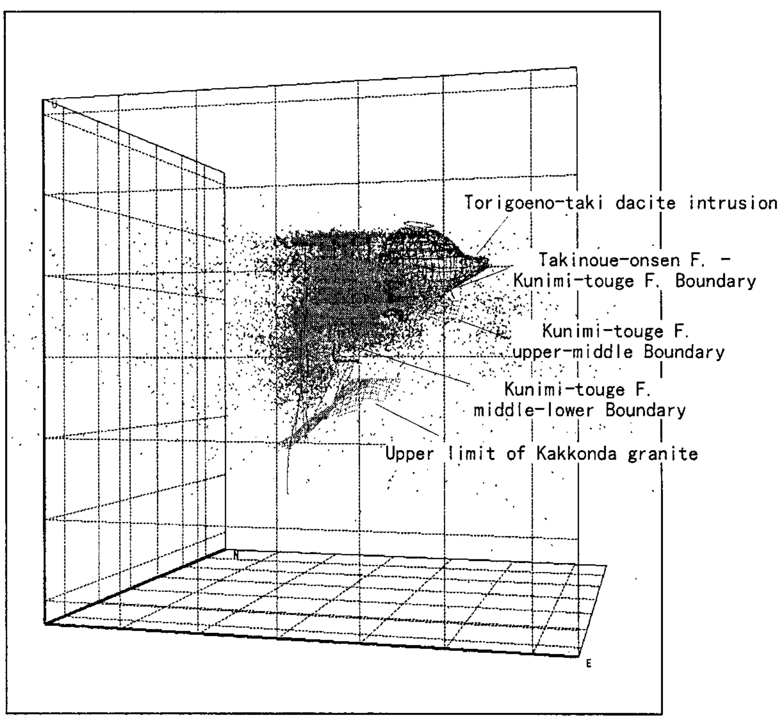

Figure 8. "Bird-eye" view of hypocenter distribution in December, 1994 to September 3, 1998 from the SSE direction. The microearthquakes occurred above the Kakkonda Granite.