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MONITORING OF A GEOTHERMAL RESERVOIR UTILIZING MICROEARTHQUAKES

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ABSTRACT

Microearthquake observation was conducted in a geothermal field and hypocenters were determined by the seismic network data, revealing the extent of the geothermal reservoir. Compared with hypocenter distributions in the past, the region of high seismic activity had migrated. This temporal change is due to variations in the amount of re-injection fluid and the elongation of the fracture zone. Microearthquake observation is one of the more practical ways to monitor reservoirs in a geothermal field.

INTRODUCTION

Earthquakes (Acoustic Emissions) occur more frequently in geothermal areas than in surrounding areas. Occasionally, more than 100 seismic events are observed in a single day, with such high seismicity being termed a ‘seismic swarm.’ Earthquakes are monitored not only for the assessment of the circumstances, but also for the exploration of geothermal resources (e.g. Batini et al., 1995). Some are so small in magnitude that they are undetectable by humans. Thus, they are called microearthquakes.

The reasons for the high seismicity in geothermal fields are that the highly fractured zones, where the geothermal reservoir forms, are well developed and that the seismo-tectonic strength of the fractured rocks is extremely weak. Earthquakes occur as a result of the increase in the differential stress field in the tectonic regions, and it is considered that the effective differential stress increases according to a rise in pore pressure due to the flow of geothermal fluid.

Since microearthquakes are thought to happen in the fractured zone of a geothermal field, hypocenters of the microearthquakes in a fractured geothermal reservoir indicate the location of the reservoir, and geophysical parameters such as permeability can be estimated from the analysis of the focal mechanism of the microearthquakes. Other exploration methods using microearthquake data are also being carried out in geothermal exploration. A 3-dimensional analysis of the seismic velocity structure estimates the configuration of a geothermal reservoir (e.g. Foulger et al., 1997) and the distribution of the fractured zones is estimated by the analysis of scattered waves. Sugihara et al. (1998) demonstrated the `micro`-structure of a fractured fault and discussed the slip vector of earthquakes along with the `macro`-structure of the fractured zone.

In this paper, we will present the hypocenter distribution in the Kakkonda geothermal field as an example of reservoir monitoring utilizing microearthquakes.

GEOLOGICAL AND GEOPHYSICAL BACKGROUND

Kakkonda Geothermal Field

Kakkonda is located in the Kakkonda Gorge approximately 40km NW of Morioka City (Figure 1). The Kakkonda geothermal field is one of the most active, predominantly liquid geothermal fields in Japan. Many geological, geochemical, and geophysical surveys have been carried out there since the early 1950s with hopes of geothermal exploitation. The Kakkonda Geothermal Power Plant (Unit 1) was constructed in 1974 with a 50MW generator and a new plant, Unit 2 with a 30 MW generator, commenced operations in March 1996. The Kakkonda River runs through the field from NW to SE and is fed by several tributaries. The Akidorizawa Stream, the Matsuzawa Stream, and the Kita-Shirosawa Stream are on the left (north) bank of the river and the Kurotakizawa Stream and the Minami-Shirosawa Stream are on the right (south) bank.

Numerous wells (investigative, production and re-injection wells) have been drilled in the field. The investigative wells are for the exploration of geothermal resources, while the geothermal power plants manage the production and re-injection wells. The wells provide a wealth of information on the geological structure of the field, while detailed analysis of such well data yields the structure of the highly fractured zones. (Doi et al., 1988).

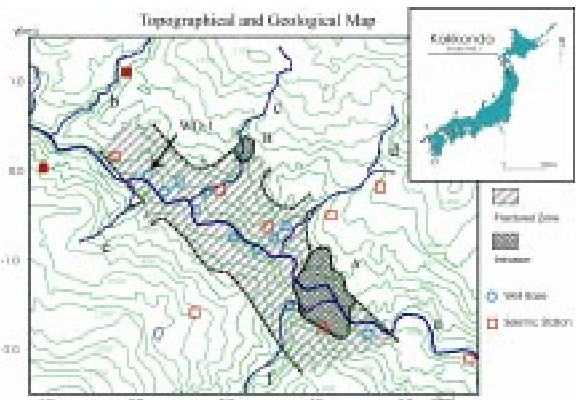

Figure 1 *Map showing the topography of the Kakkonda geothermal field. Topographic contours are drawn at 50m interval. x and y are the Cartesian coordinates based at 39 50'N and 140 50'E. Circles and squares show well bases and seismic stations, respectively. Exposures of two intrusions, the Torigoenotaki dacite (A) and the Matsuzawa dacite (B), and the fractured zone estimated from the well data are also shown after Doi et al.(1988). Two seismometers were added to the network for the project conducted by NEDO shown as filled squares. Names of river and streams are as follows;Kakkonda River (a), Akidorizawa Stream (b), Matsuzawa Stream (c), Kita-Shirosawa Stream (d), Kurotakizawa Stream (e) and Minami-Shirosawa Stream.(f).*

Figure 1 shows the fractured zone at about 100m b.s.l. (below sea level). This fractured zone is considered to be both channels where geothermal fluid has invaded and reservoirs where the fluid is sprouting, and has enlarged to a width of about 1km in the NW-SE direction in the central region of the Kakkonda geothermal field. The microearthquakes were distributed to the extent of this fractured zone. It is worthwhile to note that the fractured zone is quite wide, laying predominantly in the NW-SE direction.

A seismic network with 8 seismometers was operated by the Geological Survey of Japan (GSJ) until 1993 when NEDO acquired and improved the network for a new project, the Deep-seated Geothermal Resources Survey Project. Monitoring of microearthquakes with 10 seismometers was begun in December 1994 to determine the extent of the deep-seated reservoir.

Microearthquakes and AE

There are many common features between microearthquakes and AE (Acoustic Emissions) that seem to suggest the same geophysical phenomena. However, for observation purposes, seismometers that detect the velocity of the ground motion with the characteristic frequency of a few Hz are used in microearthquake observation. Seismometers with accelerometers are used to detect elastic waves with higher frequencies during AE observation. In recent years, a broadband seismograph that employs an acceleration sensor is growing in popularity, making the difference between microearthquake and AE observations unclear. In this paper, the phenomenon that causes a dislocation at the fault and emanates an elastic wave

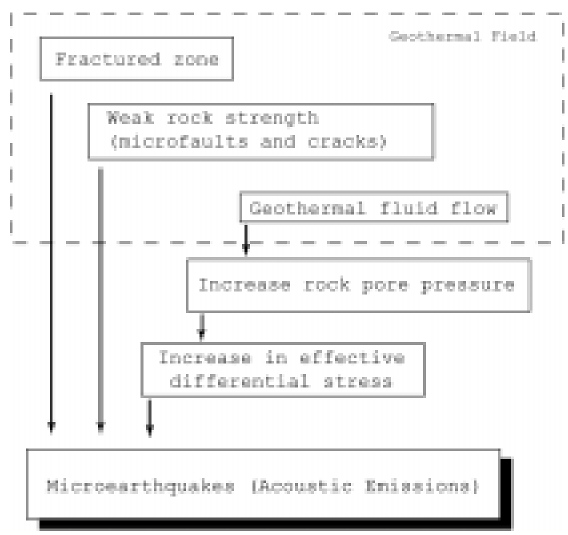

Figure 2 *Conceptual model of the occurrence of the microearthquakes at the geothermal field*

is classified as a microearthquake.

Figure 2 shows the possible causes of microearthquakes in a geothermal field.

HYPOCENTERS

Hypocenters in 1988

Hypocenters are crucial information in the geophysical exploration of the geothermal reservoir as they pinpoint the location of the reservoir. Epicenter distribution in 1988 is show in Figure 3. More than 6000 microearthquakes were observed in 1988, with 5027 of those events judged to be originating in the Kakkonda area.

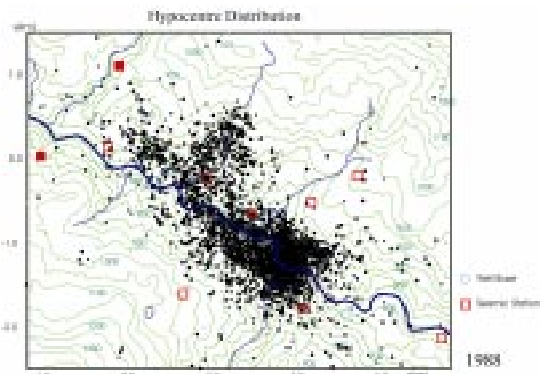

Figure 3 *Hypocenter distribution in 1988. The seismic data were collected by the 8 seismic stations shown as open squares in Figure 1.*

Many of the microearthquakes occurred in the eastern region of the geothermal field, where the re-injection wells are concentrated (recognized as the re-injection region). Most of the events at the re-injection region were caused by seismic swarms, exceeding 100 events daily. There were at least 5 seismic swarms in 1988, with the most active happening on October 15 when more than 2000 events were detected and 1687 events were located.

Although the fractured zone extends mainly along the Kakkonda River, it also seems to branch along the Matsuzawa Stream and the Kita-Shirosawa Stream (Fig.1). The two tributaries flow primarily NE-SW and intersect perpendicularly with the Kakkonda River which flows NW-SE.

Microearthquakes are not observed along the Kita-Shirosawa Stream, where a highly fractured zone is indicated by the well data. This implies that microearthquakes do not occur in the entire region where the tectono-physical strength of the rock is weak and that the fractures are highly developed. Another geological and / or geophysical condition is required to explain the occurrence of microearthquakes. Fluid flow should increase the pore pressure, decrease the effective differential stress around the fractured rocks and trigger the microearthquakes.

The activity of earthquakes decreases abruptly near the Torigoenotaki intrusive rock in the eastern region of the field. Microearthquakes seldom occur outside the periphery of the Kakkonda geothermal field and do not represent the characteristics of a seismic swarm, but are classified as foreshock, main shock, and aftershock activities. The difference in their destructive intensities is recognizable between the characteristics of rocks encountered from inside and outside of the geothermal field.

Cross Section of Hypocenters

Figure 4 shows a cross section of the hypocenters along the NW-SE axis in 1988. Clear boundaries separate the seismic and aseismic regions in the SE region (right) where fewer earthquakes occurred.

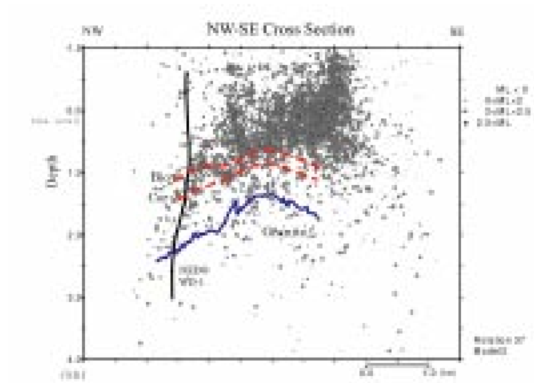

Figure 4 *Cross section of the hypocenter along the northwest-southeast axis. The first occurrence of metamorphic minerals such as biotite (Bio) and cordierite (Cor) are shown as broken lines (after Doi et al., 1998). The investigation well, WD-1, and the top margin of the Kakkonda granite are also shown.*

Shallow earthquakes were dominant in the SE region where the re-injection wells are concentrated and hot water is re-injected into the ground. On the contrary, earthquakes deeper than 1km b.s.l. occurred on the NW (left) margin where the production zone is developed. Very deep earthquakes originate in the production zone and are associated with deep-seated geothermal resources, the target of NEDO's project. The number of earthquakes decreases rapidly at depths of 1-2km b.s.l. The rapid decrease at these depths is possibly associated with the heat of the new-granitic pluton, termed Kakkonda granite (Tosha et al., 1998).

Hypocenters after 1994

Figure 5 shows the hypocenters in the years from 1994 to 1998. As the microearthquake system commenced operations in December 1994, the minimal data from 1994 was combined with that of 1995 (Fig. 5a). As shown in Figure 5, the number of earthquakes increased after 1996, although there were several lapses in observation due to failures of the network system in 1995. The seismic zone spread mainly to the south in 1996 and 1997, with the seismic activity increasing over the entire field in 1998.

the Matsuzawa Stream and the other is located to the west of the Matsuzawa cluster (in the region of the extension of the Kurotakizawa Stream). The former was recognised in the hypocenter distribution map in 1988 (Fig. 3) but was limited to the northern region

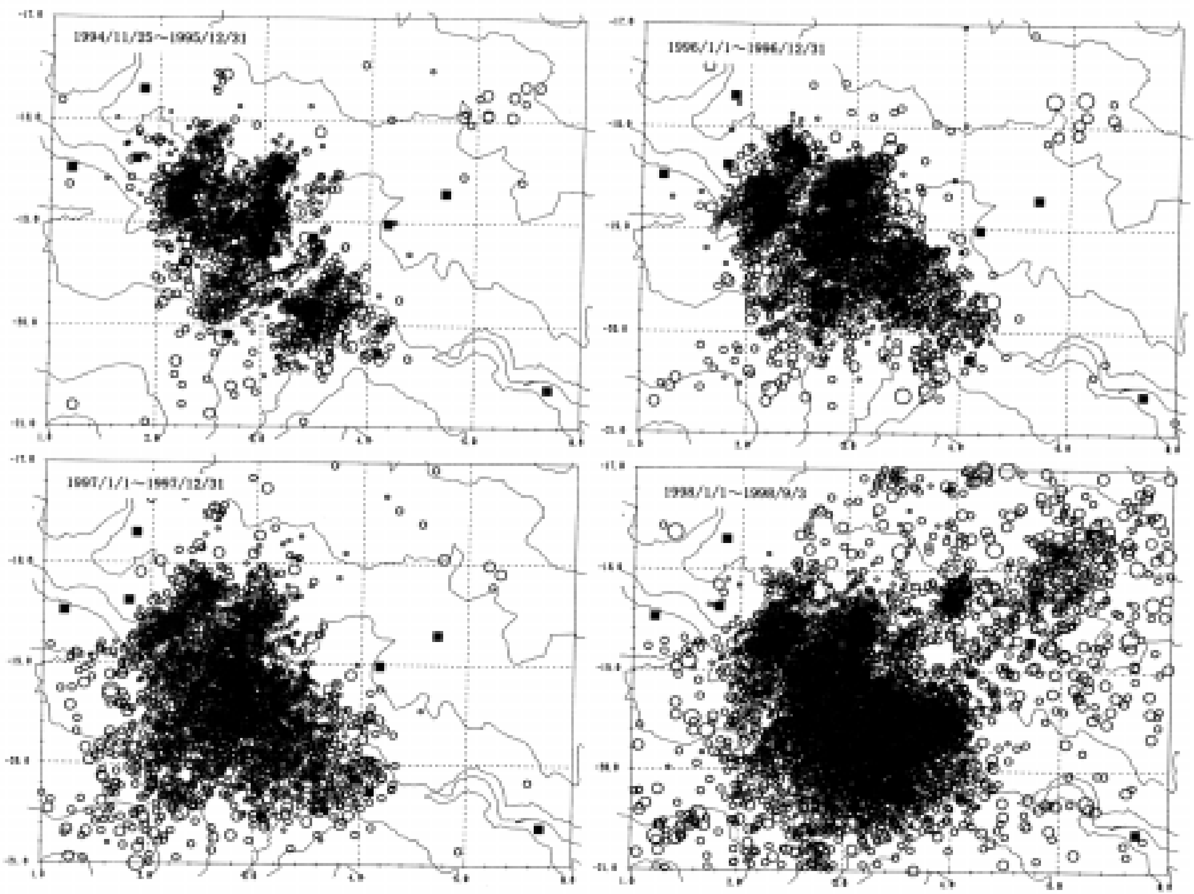

Figure 5 *Hypocenter distributions after 1994.*

In the 1998 observations, a major earthquake (M6.1) transpired near the field and the distribution of hypocenters through September 3 is displayed in the data. The number of earthquakes in 1998 was extremely high when compared with that of other years. Some earthquakes in 1998, however, resulted from the major shock on September 3. Figure 6 shows the daily and the cumulative frequencies of the microearthquakes at Kakkonda. A lot of events happened in 1998 and the cumulative number of event increased significantly about a half year before the major earthquake (about March in 1998). Therefore, the hypocenter distribution in 1997 shall be used in this discussion.

DISCUSSION

Two or more clusters of earthquakes extending in the NE-SW direction are seen in the hypocenter distributions in Figure 5. One of the clusters extends along

of the geothermal field. It should be noted that the cluster along the Matsuzawa Stream extended to the south in the hypocenter map of 1997.

The cluster of hypocenters in the western region of the geothermal field was observed around the exploration well, WD-1, that was drilled for NEDO's project (Fig. 1). These events occurred at relatively shal-

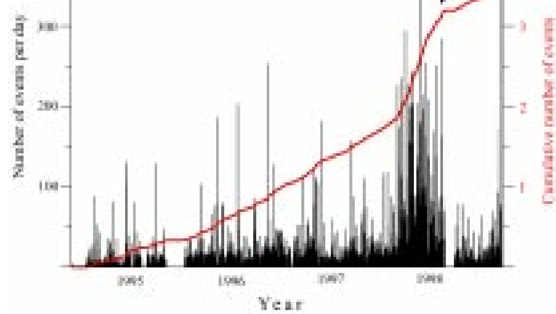

Figure 6 Number of events per day and the cumu-

low depths. Deep microearthquakes were observed around WD-1 in 1988 but none were found at shallow depths (Fig. 4). The deeper earthquakes were associated with the deeper geothermal resources that were the target of the "Deep-seated Geothermal Resources Survey Project" conducted by NEDO. The production wells for the deeper resources in the Kakkonda geothermal field were drilled in the western region of the geothermal field near WD-1. The increase in the seismicity here is interpreted as resulting from an increase in the upflows caused by the exploration of deep geothermal resources.

On the one hand, seismic activity declined remarkably in 1997 in the re-injection area (the eastern region of the field) that was active in 1988. There were at least 5 seismic swarms occurring in the re-injection area in 1988, though no swarms occurred after 1994 and the overall number of earthquakes decreased. Thus, the production area is a region where seismicity in 1997 was active as compared with that in 1988 and the re-injection area is a region where seismicity decreased.

It is thought that microearthquakes happen when the effective differential stress decreases in the area where destructive intensity is weak. The decrease in the differential stress is due to the increase in the pore pressure, whereas the pore pressure is possibly controlled by the flow of geothermal fluid. Therefore, microearthquake activity indicates the development of the fractured zone and the circulation of the geothermal fluid.

The deeper fluid has a higher enthalpy and less water concentration. Though the quantity of steam for achieving the measure of power generation in the geothermal power plant was the same as in 1988, the amount of geothermal fluid re-injection decreased in 1997. The seismicity of microearthquakes moderated owing to the decrease in the quantity of the fluid re-injected. The increase in the seismic activity in the western region of the field can be explained as the expansion of the geothermal reservoir in view of the microearthquake activities.

Hypocenter distribution indicates the outline of the geothermal reservoir as a cloud and further analysis, such as the collapsing method (Jones and Stewart, 1997), is necessary to represent the detailed structures of the cloud. The accuracy of hypocenter determination deteriorates for deeper earthquakes.

In the monitoring of microearthquakes, the larger the seismic network, the better the resolution of the hypocenters. The extension of the network is the most effective way to increase the location precision, and to obtain improved understanding, of the hypocenters. Nonetheless, the installation of additional seismometers outside of the present seismic network is ordinarily limited by various reasons. For example, the geothermal fields are situated in mountainous areas with steep cliffs making installation of the seismometer and transmission cables impractical. Furthermore, there are animal and plant sanctuaries where the installation of seismometers is prohibited.

In order to improve the precision of the hypocenters, an extra seismometer was installed for 2 weeks in 1997 at the Matsukawa geothermal field, located about 4km northwest of Kakkonda. It is, however, impossible for such seismometers to be connected by cable to transfer the seismic data to the recording center of the seismic network. The seismometer was asynchronous with the seismic network in Kakkonda and the waveforms of the earthquakes were recorded.

More than 30 seismic forms were recorded during the observation at Matsukawa and the hypocenters of 13 events, which happened at Kakkonda, were recalculated using the seismic data. The microearthquakes were relocated and the accuracy of the hypocenter estimation was improved. Seismometers that are located distant from the seismic network are useful in analyzing the hypocenters of deep earthquakes and in improving the accuracy of the hypocenter estimation. The results of the additional seismometers for the Kakkonda field will be presented in a future paper (Tosha et al., 2000).

CONCLUSIVE REMARKS

Microearthquakes (or Acoustic Emissions) were used to monitor the geothermal reservoir in the Kakkonda geothermal field. Several geophysical mechanisms postulate why the earthquakes arise so frequently in the geothermal field, while the circulation of geothermal fluid is theorized to be one of the possible causes triggering the earthquakes. Hypocenter distribution clearly indicates the extent of the geothermal reservoir and the precise determination of the hypocenters is anticipated for deep geothermal resources surveys utilizing microearthquakes.

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