WHAT CONTROLS DEPTH OF HYPOCENTRES IN KAKKONDA GEOTHERMAL FIELD, JAPAN?

- An attempt to represent microearthquake clouds by earthquake energy density-

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Abstract

Hypocentres for more than 6,000 microearthquakes which occurred in 1988 at Kakkonda geothermal field are located. Errors calculated by a computer program for determining hypocentre are typically 50 m horizontally but more than 100 m vertically if hypocentres are located about 1 km below sea-level. We have to take the errors into account even if the hypocentre solution is represented as a point in a hypocentre distribution map.

The number of microearthquakes decreases rapidly 2 km below sea-level. A conceptual model with probability density and seismic energy distribution is presented to indicate active seismic regions. High seismic energy density region is present in the geothermal field and is concordant with highly fractured region suggested by geological and petrological studies based on well data. The model also shows that a contour map of bottom boundary of high seismic energy region is accord to that of top level of neo-granitic pluton body, inferring that occurrence of microearthquakes in Kakkonda geothermal field is controlled by the neo-granitic rocks in depth.

1.0 INTRODUCTION

Seismic activities have been reported at many geothmal fields (e.g. Batini et al., 1985; Oppenheimer, 1986; Bromley et al., 1987) and have been thought to be one of potential indicator of the geothermal reservoir. The Kakkonda geothermal field in the northern part of the main island of Japan (Honshu Island) is one of the most active geothermal field in Japan and many geological, geochemical and geophysical surveys have been performed there. The Kakkonda Geothermal Power Plant was constructed in 1974 with a 50,000 kW generator and a new plant is starting to operate in March, 1995. Many wells have been drilled and have suggested the deep structure of the field. A seismological approach using microearthquakes is one of the geophysical survey to investigate in the deep structure of the reservoir. We have been observing microearthquakes in the field since 1982 and have succeeded to reveal characteristics of the geothermal field fiom the seismological points of view. Recently several wells have succeeded to penetrate deeper reservoir and reach to granitic rocks, where a fiacture system with high enthalpy fluid exists. The deeper geothermal reservoir with high enthalpy fluid is expected a new geothermal resource and is planned to investigate in the deep-seated geothermal resources survey project by NEDO (New Energy and industrial technology Development Organization). We will present and discuss some of the results in Kakkonda geothermal field, especially on the relationship between the seismic activity and deep structure.

2.0 GEOTHERMAL FIELD

Kakkonda geothermal field is located in the northeastern part of the Honshu Island near Morioka city (Fig. 1) and surrounded by steep mountains. The Kakkonda river goes through fiom northwest to southeast in the field and we can find many signs of the geothermal activities such as steam fumaroles, altered rocks and so on. Most of the strata are composed of Tertiary sedimentary rocks and igneous rocks intrude among the sedimentary strata. Four

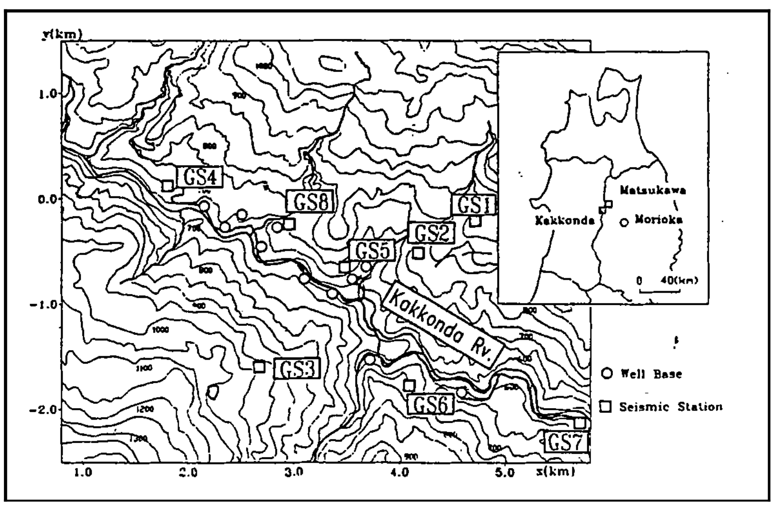
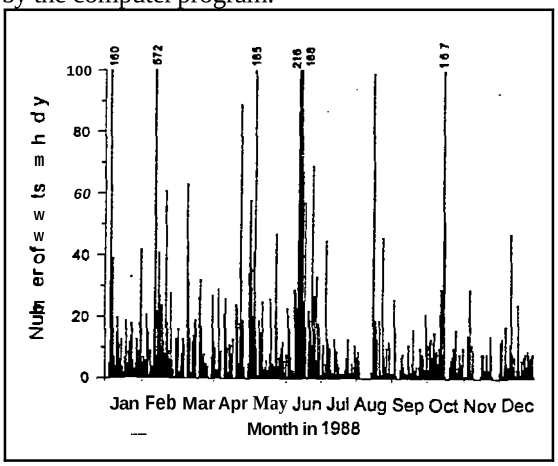


Figure 1. Map showing the location and the topography of the Kakkonda geothermal field. Each topographic contour is drawn every 50 m apart. X and Y are the Cartesian corordinaies based ai the point of 39°50'N and 140°50'E.

in 1982 and **4** others had been added during the next 6 years. Six seismometers out of 8 are set on the bottom of the drilled well beneath about 50 m **from** the surface and the other 2 seismometers are installed in the relatively hard rocks. Seismic signals received at each seismic station are transferred to an observatory with a wire line using an analogue-frequency conversion technique and are recorded onto digital magnetic tapes. The sampling frequency and **data** length for the analoghe-digital conversion are 400 or 500 Hz and 12 bits with **4** bits **gain** code or 16 bits, respectively (Ito and Sugihara, 1987; Tosha et al., 1988). Fig. 2 shows the daily number of the event for **a** year. More than 6,000 microearthquakes occur in Kakkonda and about two-third of them can be located by the computer program.



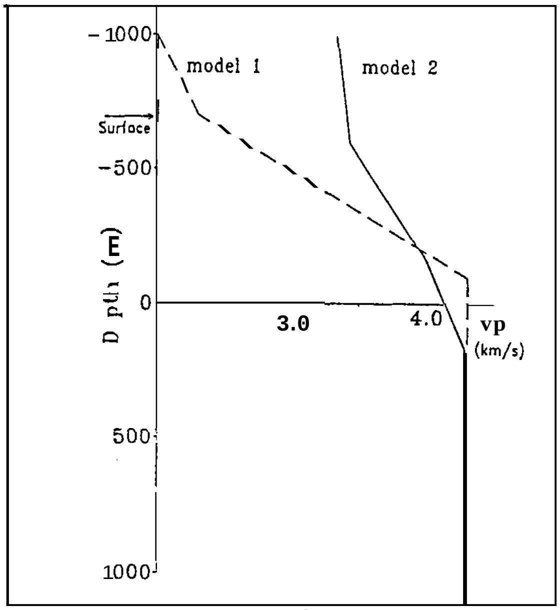


*Figure 3. P-wave velocity models **for** HYPOMH used in this study*

3.2 Velocity Model

It is quite important to make a P-wave velocity structure model for hypocentre solutions in the field. **An** analysis of explosion seismic surveys gives a reliable velocity model. However no reliable explosion seismic **data** was available when we started the study. We recalculate hypocentres using different velocity models in order to estimate the effect of variations in

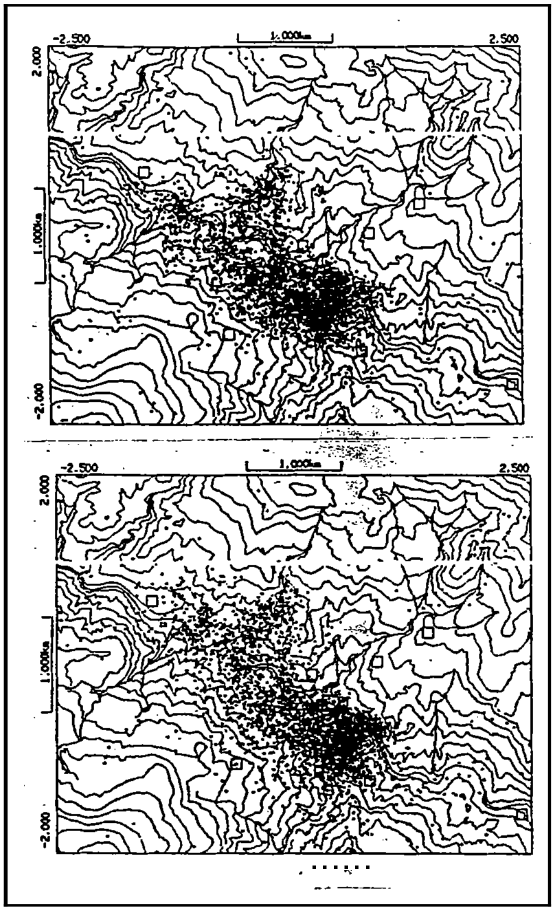
3.0 RESULTS AND DISCUSSIONS

3.1 Computer Program

There are a lot of computer' programs for determining hypocentres. We are using mainly two program packages to obtain hypocentre solutions; one is HYPO71(Lee and Lahr, 1975) and the other is HYPNLI (Hirata and Matsu'ura, 1987). *HYPO71* is one of the most popular software packages which is **installed** in many seismological laboratories. HYPNLI is a program **based** on the Basian statistics which is suitable for determining hypocentres of aftershocks. Both programs are originally designed for large and tectonic earthquakes and are calculated based on a horizontally stratified structure. We have modified program codes suitable for the microearthquake *study* such as input and output routines as default digits for input and output are not enough length. The program HYPNLI is often called HYPOMH. We hereafter denote ***HYPOMH*** instead of HYPNLI. In this paper we present several maps of hypocentre distribution computed by HYPOMH. There are no significant difference between solution maps calculated by

model for HYPOMH though HYPO71 and other hypocentre programs use a step-wise velocity model. The model is quite simple. P-wave velocity ranges from 2.3 km/sec a surface to **4.3** km/sec at 100 above sea-level. The velocity of P-wave **is** constant under 100 m above sea-level.

Ikeuchi et al.(1994) presented a new velocity structure model based on a explosion study made by NEDO in 1993. They showed two kinds of models, two-layers model and four-layers model. However P-wave-velocities of Layer I and Layer **3** in the four-layers model are quite similar with those of Layer 2 and Layer **4,** respectively. We **modified** the two-layers model to a slop velocity model for HYPOMH (MODEL **2** in Fig. 3). There are no significant difference between P-wave velocities in both models under 100 m below sea-level. However, velocity at surface in MODEL **2** is much higher than that in MODEL 1.



gure 4. Hypocentre distribution calculated by HYPOMH usnig (a)MODEL1(top figure) and (b)MODEL2 (bottom figure)

3.3 Hypocentres

Figs. 4(a) and 4(b) show epicentres of more than

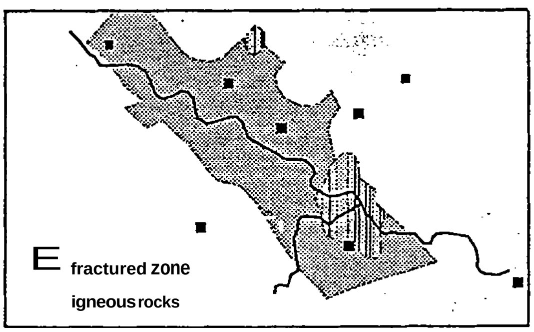
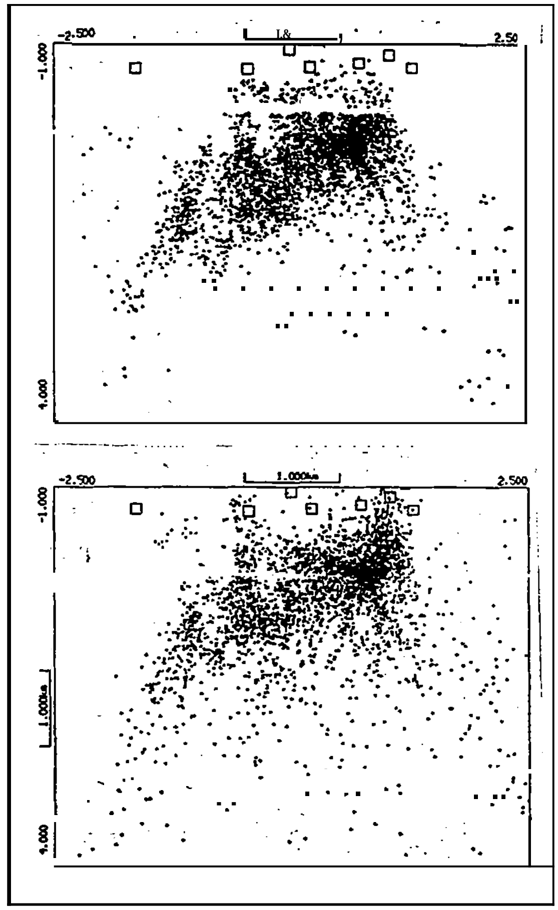


Figure 5. Simplified geological map under 300-900m below sea-level (modified Doi et al., 1988). Closed squares indicate the location of seismometers.

4,000 microearthquakes of the Kakkonda field in 1988. Solutions in Figs. 4a and 4b are calculated based on the velocity MODEL 1 and MODEL 2 in Fig. 3, respectively. There is no significant difference between two figures. As shown in there figures microearthquakes do not occur uniformly but in a restricted area Especially note that the boundary of the area where microearthquakes frequently occur is sharp in the southeast side. There are many investigation, production, and reinjection wells which have been drilled by Japan Metals and Chemicals Co., Ltd. (JMC), the developer in Kakkonda geothermal field, and its related companies. Doi et al.(1988) estimated the distribution of fractured zone at the depth of 100 m above sea-level using the well data. The simplified map for the fractured zone modified after Doi et al.(1988) is shown in Fig. 5. We can infer that microearthquakes in the field happen within the fractured zone.



igure 6. Cross-section of the hypocentres along northwest-southeast axis uding (a)MODEL1 (top figure) and (b)MODEL2 (bottom figure).

The cross-section of the hypocentres along the northwest-southeast axis is shown Figs. 6(a) and 6(b). Clear boundaries which separate the seismic and aseismic regions are also shown at the southeastern area in the figures. As we find epicentres distribute within the restricted region, the cross-section of the solutions also shows that earthquakes occur within the restricted level. And note that the number of the earthquakes decreases rapidly 2 km below sea-level.

3.4 Probability density

A hypocentre solution is represented by a point in **a hypocentre distriiution** map but the solution **contains** several **kinds** of error. In **this** paper we **will** introduce a probability density of seismic energy after Tosha et al. (1995). The true hypocentre is distributed around mean μ with variation **S.** The probability density of the hypocentre for an earthquake p(x) is

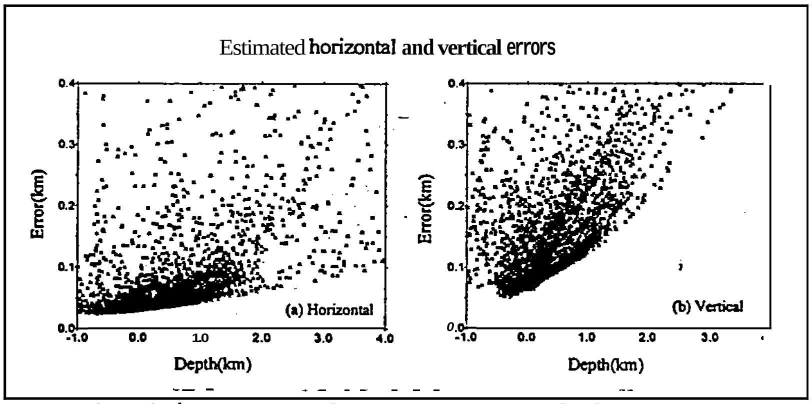
$$p(x) = c \exp\{ -f(x)/2 \}$$

where c is a normalized constant and x denotes a location parameter. f(x) is presented **as** follows;

$$f(x) = (x-\mu)^T S^{-1}(x-\mu)$$

where $(x-\mu)^T$ is the **transverse** matrix of $(x-\mu)$ and S^{-1} is the inverse matrix of **S.**

We can compute the horizontal and vertical error estimations of the located hypocentre σ used by variation matrix **S;**



igure 7. Computed horizontal(a) and vertical(b) errors versus depth

$$\sigma_i = \sqrt{S_{ii}}, \; i=x,y,z$$

Figs. 7(a) and 7(b) show the horizontal and vertical error estimations, respectively. The hypocentres imply horizontal errors at least of 20 m. The error increases when the hypocentre of the earthquake becomes deeper and when the **hypocentre** locates out of the seismic network The vertical **errors** are much larger than the horizontal one. The depth of micro-earthquakes in Kakkonda is **in** average of 1 km below sea-level. The typical horizontally and vertically **errors** of hypocentre solutions are 30 m and 100 m in Kakkonda geothermal field, respectively.

The probability density of seismic energy e(x) is computed by the probability density of hypocentre p(x) multiplied by seismic energy of the earthquake E;

$$e(x) = p(x) * E$$

The seismic energy is estimated by the magnitude of the earthquake. ***An*** equation

$$\log E = 1.5\, Ms + 11.8$$

is well **known** where Ms is the surface wave magnitude. We can use **an** experimental equation between the ***surface*** wave magnitude and the body wave magnitude (mb)

$$mb = 0.63\, Ms + 2.5$$

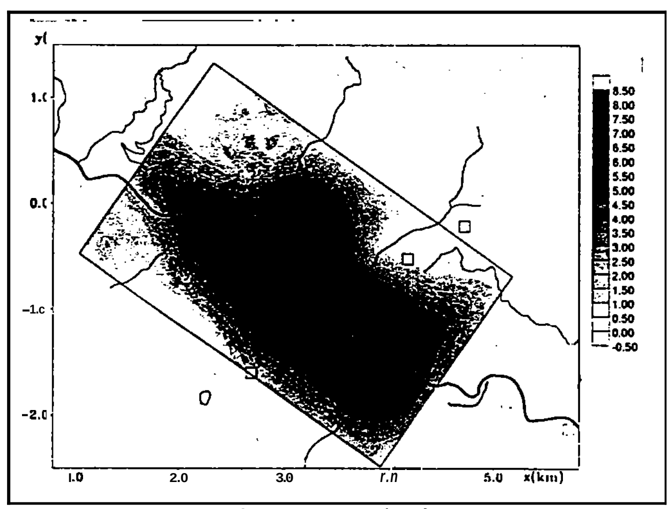
and we get an equation between seismic energy and body wave magnitude **as** follows;

$$\log E = 2.38\, mb + 1.78$$

Fig. 8 shows **a** contour map of seismic energy distriiution for microearthquakes for a year in Kakkonda geothermal field. **High** density region is detected along the Kakkonda river. We can easily separate **thez high** seismic energy region (seismic region) fiom the low seismic energy region (aseismic region).

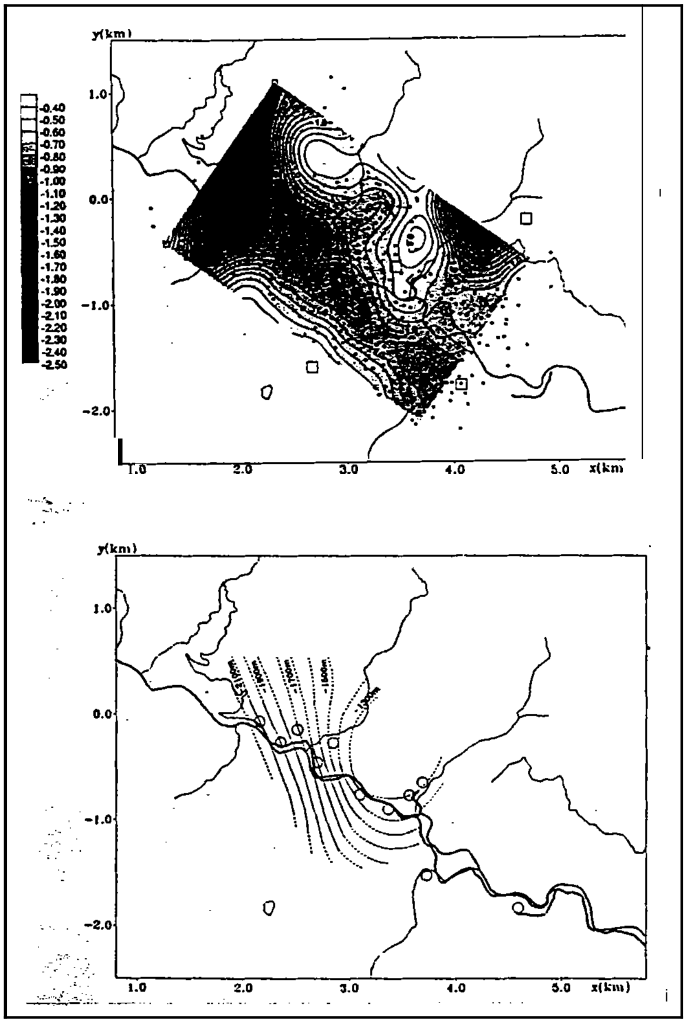
Fig. **9(a)** shows a contour map for the bottom level of the seismic region. The lower boundary becomes shallow in the middle of the analysis area and becomes deeper toward the out side of the area.

There are a lot of wells in the field and recently several wells have succeeded to penetrate the deeper reservoir and reach to granitic rocks, where a fiacture ***system*** with **high** enthalpy fluid exists. The granitic **rocks** are estimated **to** be young and **to** be lying widely under Kakkonda geothermal field. The granitic rock **is** called **as** Neo-Granite or Kakkonda granite. Fig. 9@) is the contour map for the top level of Kakkonda **granite body estimated by well data after Kato and Doi (1993). The contour map for the bottom level of the seismic region is concordant with that for the top level** of Kakkonda granite. Deep microearthquakes in



igure 8. A contour map of seismic energy distribution.

·Kakkonda are considered to be spatially related to the neo-granitic pluton.



energy region. Labels indicate the bottom **depth below sea-level** and **dots** represent **hypocentres of** the earthquakes used m the **analysis. (b;bottom figure) A** *contour map* **for the top level of neo-granitic pluton body** *estimated* **by well data after Kato and Doi (1993).**

4.0 REFERENCE

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