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STRUCTURAL INTERPRETATION OF THE KAKKONDA DEEP GEOTHERMAL RESERVOIR

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ABSTRACT

The Kakkonda geothermal field is known as a unique field such that a new reservoir was found at about 2500 m in depth after the shallow reservoir ranging from 1000 m to 1500 m had been produced for about eight years. The shallow reservoir is composed of sedimentary rock with igneous rock intrusions, while the deep reservoir is a fractured thin zone located at the top of a large granite intrusion. Between the two, there exist thermally metamorphosed zones.

This study aims at integrated interpretation of the top structural surface of the deep reservoir. The data used include well data, microearthquakes, and several metamorphic minerals. Microearthquakes, which are continuously observed at surface, reflect the structural surface of the granite intrusion of the deep reservoir. The metamorphic minerals such as biotite and cordierite caused by strong heat conduction out of the granite also give an image of the structure. Based on the spacings of acoustic emission data, images of the structural surface are extracted statistically. The degree of uncertainty is evaluated. The isograds of the metamorphic mineral distributions are reproduced by a regional heat conduction model.

INTRODUCTION

The Kakkonda geothermal field in Japan has been reported on various aspects through its development history over twenty years (see Hanano, 1995, for a list of main references). The field has been developed in two stages. In the first stage a power plant of 50 MWe capacity was installed in 1978 to utilize the shallow reservoir which ranges from 1000 m to 1500 m in depth. The second stage started in 1989 to develop the deeper zone in order to sustain the first power plant and to start the second plant of 30 MWe. The deeper reservoir ranges from 1500 m to 3000 m.

A good geological description of the field is given by Doi et al. (1995) and Kato et al. (1993, 1995). Although the shallow and deep reservoirs are hydraulically connected (Arihara et al. 1995), they show remarkable differences in characteristics.

A conceptual model as shown in Fig. 1 shows various features of the field. The shallow reservoir is composed of Tertiary formations. The deep reservoir contains Tertiary formations, Pre-tertiary formations and neo-granitic intrusion. Temperature jumps from 250 °C in the shallow reservoir to 300 °C at around 1500 m. The shallow reservoir is characterized by highly permeable rock and slightly alkaline fluid, while the deep reservoir is tight and contains acidic fluid.

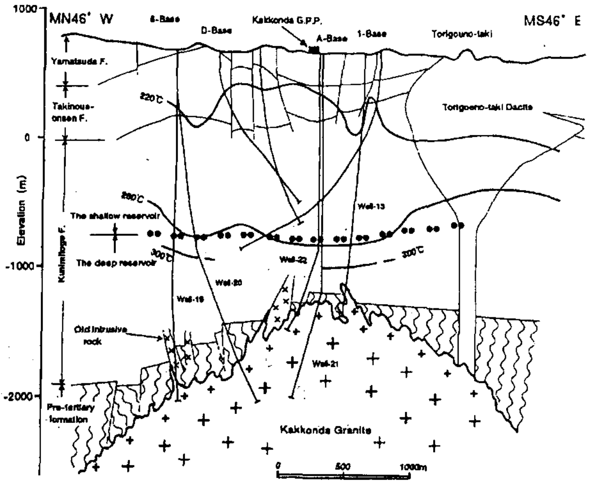


Fig. 1. Geological cross-section of the Kakkonda geothermal field (after Kato and Sato, 1995).

As interpreted by Doi et al., fractures are main sources of permeability in both reservoirs, but are created from different origins. Permeable fractures which develop over the whole interval in the shallow reservoir are formed by regional stresses and magma intrusion. In the deep reservoir, fractures are induced by thermal effects and more regional stresses. Five wells drilled into the deep reservoir confirmed a fractured zone at the boundary between the Pre-tertiary formation and the neo-granite rock.

Rocks are thermally metamorphosed in the lower part of the shallow reservoir and above the neo-granite rock in the deep reservoir, where several metamorphic minerals including biotite and cordierite are detected. As the metamorphism is estimated to be caused by heat from the neo-granite body (Kato and Doi, 1993), the degree of the metamorphism is a function of the distance from the top surface of the neo-granite rock, and a specific mineral is metamorphosed only within a certain range. An isograd of a mineral is defined as a three-dimensional surface connecting the shallowest depths where the metamorphism of that mineral is detected. Kato and Sato (1995) presented contour maps of the biotite, cordierite, anthophyllite and andalusite isograds, and indicated similarity of shapes between the isograds and the top surface of the neo-granite. Isograds of the metamorphosed minerals are considered useful for interpreting the structure of the neo-granite rock.

MICROEARTHQUAKES

Microearthquakes are common phenomena in geothermal reservoirs where pressure distributions are strongly disturbed by changes in high flow rates of production and injection (Ito and Sugihara; 1988, Sigihara, 1993). In the Kakkonda field, microearthquakes are continuously monitored by eight seismometers installed in 50 m deep holes and on surface rock at the average distance of about 500 m (Tosha et al. 1993).

Microearthquakes observed in 1988 are plotted in Fig. 2(a), epicenters, and in Fig. 2(b), hypocenters projected onto a cross-section in the northwest-southeast direction. Similar observations were repeated in other years. Although hypocenters are widely spread particularly to the southeastern region, most of microearthquakes are confined within a certain boundary. Tosha et al. showed that the area of high epicenters density coincides with the areal extent of the fractured zone in the shallow reservoir. Comparing a geological cross-section and a vertical hypocenters distribution as Fig. 2(b), Tosha et al. pointed out that less microearthquakes occur in the neo-granite rock.

Sugihara (1993) also specified correlation between microearthquakes and fracture distributions as (1) the epicenter distribution in the shallow reservoir roughly agrees with the extent of the fractured zone, (2) the epicenters in the deep reservoir are not uniformly distributed over the areal extent but swarm at flank zones, and (3) hypocenters linearly slope down at the northwest side as seen in Fig. 2(b).

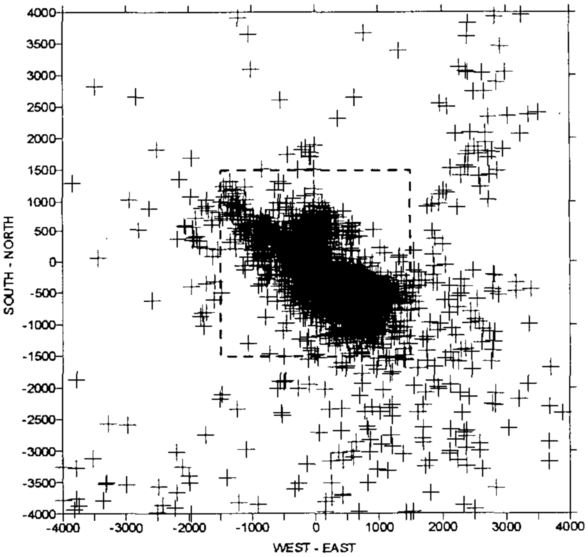


Fig. 2(a) Epicenter distribution observed in 1988. (Tosha et al. 1995)

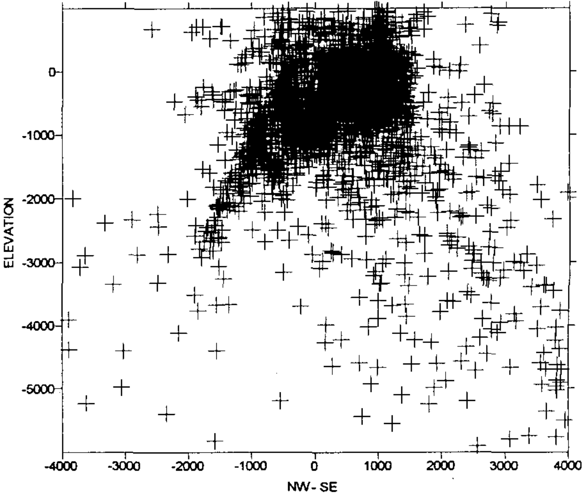


Fig. 2(b) Hypocenters projected on NW-SE cross-section.

Sugihara further demonstrated that the lower boundary of the high density zone of hypocenters agrees with the top surface of the neo-granite rock, and stated that microearthquakes are useful information for interpreting a geological structure.

STRUCTURAL INTERPRETATION

As the fractured zone in the deep reservoir exists at the top surface of the neo-granite rock, it is highly desired to know the precise structural top surface of the neo-granite pluton. Four wells have been drilled into the neo-granite and confirmed the top depths. Another well was drilled to the neiborhood and provides a good estimation. Based on the well data, Kato and Sato (1995) drew a contour map for the top surface of the main neo-granite body, as shown in Fig. 3. The isograds of certain metamorphic minerals can be also used to estimate the top depths of neo-granite, as they reflect the structure of the neo-granite rock. As seen in Fig. 3, the structural contour map based only on well data tends to show a general shape of smooth surface, because of sparsity of the well data.

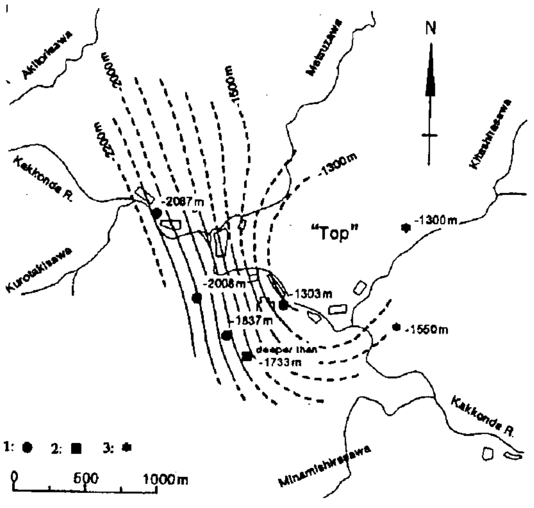
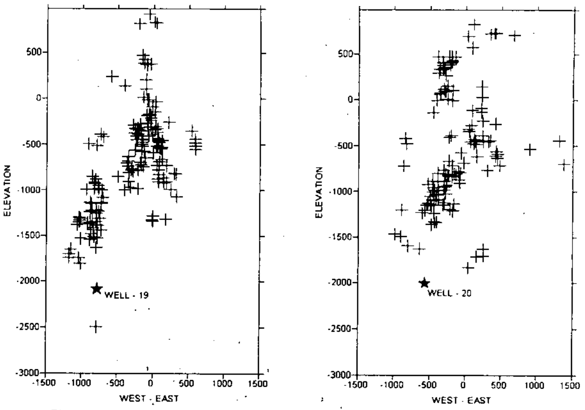


Fig. 3. General shape of the neo-granite rock.
1: Top of neo-granite, 2: Bottom of Well-13, 3: Estimated by isograds. (Kato and Sato, 1995)

On the other hand, the microearthquake data cover the reservoir area rather uniformly, and therefore give information at zones away from the wells, although errors in depth are as large as 200 - 300 m or even larger. In this study, a three-dimensional surface was statistically extracted from the microearthquake hypocenters, based on the assumption that relative positions of hypocenters are relaible, and that distribution of the hypocenters reflects the structure of neo-granite. This surface was used as an external trend or soft data which provides a shape in kriging the well data. Several surfaces obtained from the spatial density of the hypocenters were applied for this purpose.

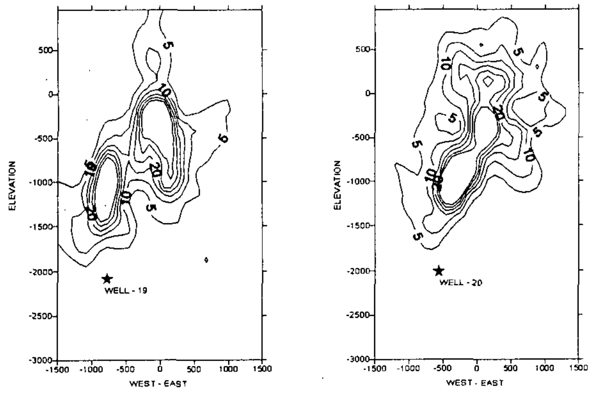
Different approaches are thought to be applicable to define a lower boundary of hypocenter distribution which is parallel to the top surface of neo-granite rock. To assess the boundary of a geological body, Pawlowsky et al. (1993) used indicator kriging in two steps, the first for the purpose of extrapolating control points outside the body, the second to obtain a weighting function which expresses the uncertainty attached to estimations obtained in the boundary region. In the present work, the bottom surface of the hypocenter distribution was estimated by two statistical steps, the first for evaluating distributions of hypocenters density, the second to define the bottom surface of a constant density.

Figs. 4(a) and (b) show hypocenters within the cross-sectional slab of 100 m thickness including Well-19 and Well-20, respectively. In both cross-sections, the zone of microearthquakes is above the well datum which shows the top surface of neo-granite. Density distribution of hypocenters was determined by counting number of hypocenters within a spherical window placed at each hypocenter in the three-dimensional space. The radius of 200 m was found appropriate for the window. Based on this three-dimensional density distribution, a variogram to



(a) Crosssection through Well-19
(b) Crosssection through Well-20

Fig. 4 Crosssectional view of hypocenters contained in 100m thick crosssectional slabs.



(a) Crosssection through Well-19 (b) Crosssection through Well-20

Fig. 5 Density distribution for hypocenters shown in Fig. 4

show spatial correlation was calculated, and applied to draw density contour maps. Contour maps were obtained for 30 cross-sectional slabs in the 3000 m x 3000 m region as shown in Fig. 2(a). Figs. 5(a) and(b) are density distributions for the hypocenters in the cross-sectional slabs corresponding to Figs. 4(a) and 4(b).

Next, the lower-side boundaries of all the contour maps were used to estimate the shape of the top surface of the neo-granite rock. Selecting the density contour of 5, a variogram to describe continuity of depth values versus horizontal lag distance was calculated. With this variogram, 30 x 30 data of the density 5 were kriged to obtain a lower surface of hypocenters as shown Fig. 6. Compared with the structural top surface based only on the well data as shown in Fig. 3, the obtained surface is quite rough, and has several local highs and lows. This surface was introduced as soft data in collocated-cokriging the well data of the structural top of neo-granite. Fig. 7 is the final surface obtained by this process.

The same procedure was applied to the data of density contours 10, and resulted in Fig. 8. A clear difference is seen along the south boundary. In Fig. 7 there appears an anticlinal high which is not seen in Fig. 8. This was caused by different areal extents of the surfaces extracted from the hypocenter densities. Obviously, the degree of uncertainty is high at the southwest and northeast regions, because almost no hypocenter was observed as seen in Fig. 2(a).

Fig. 9 shows top structural surfaces of the neo-granite rock in the NW-SE direction for three cases.

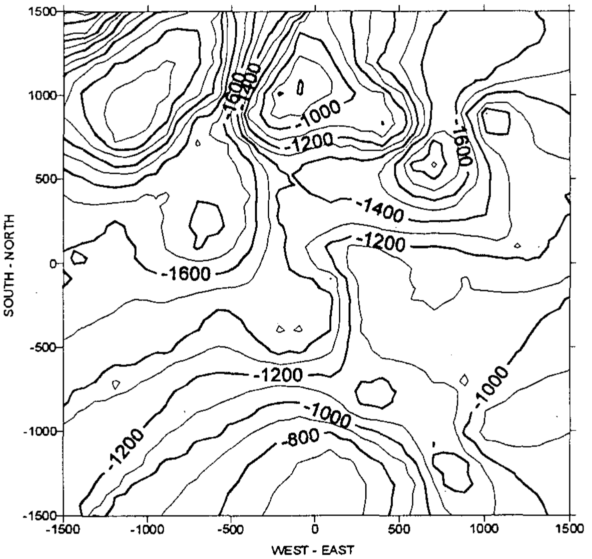


Fig. 6 Lower surface of the hypocenter zone of density 5 or higher.

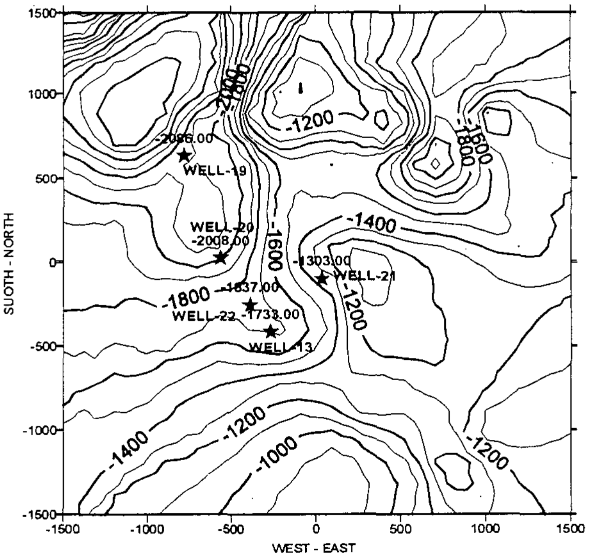


Fig. 7 Top structural surface of the neo-granite rock interpreted by the hypocenter zone of density 5 or higher.

Note similar trends in the middle region and large differences at the north-west side.

Using the geological structure of neo-granite as obtained above, model calculations were carried out to examine the hypothesis that the metamorphism is caused by heat from the neo-granite body. Calculations were simply for steady state heat conduction between the neo-granite rock and the

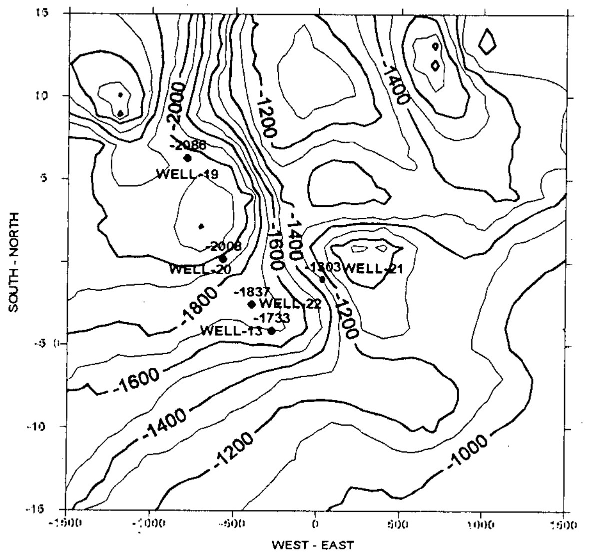


Fig. 8 Top structural surface of the neo-granite rock interpreted by the hypocenter zone of density 10 or higher.

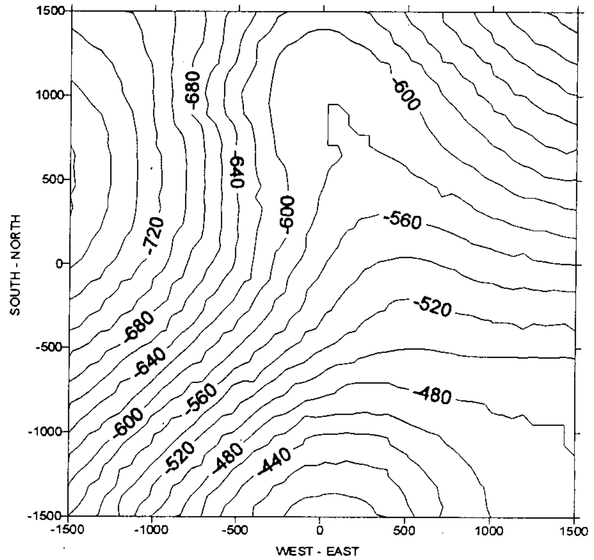


Fig. 10 400 °C isotherm calculated by steady heat flow from the neo-granite rock to the ground surface.

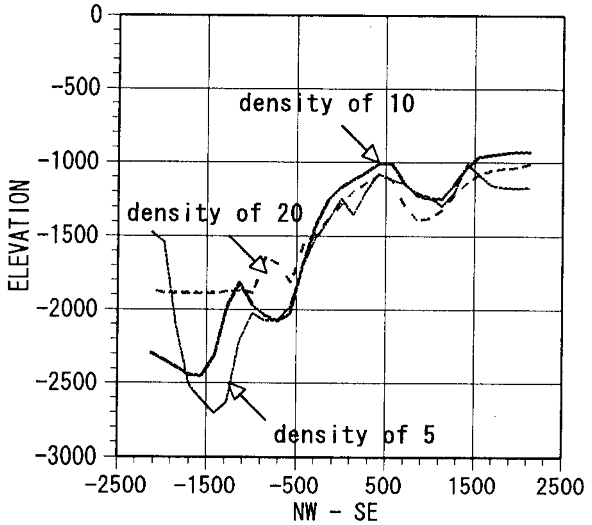


Fig. 9 Crosssectional view of top structural surfaces of neo-granite rock interpreted by different densities of hypocenters

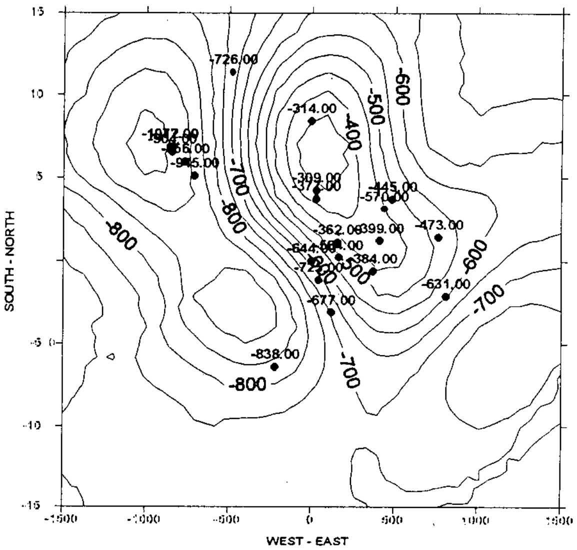


Fig. 11 Biotite isograd based on the well data.

ground surface. As the boundary conditions, temperatures at the top surface of neo-granite and the ground were set to be 700 °C and 15 °C, respectively.The ground surface level was set at 700 m and to be flat.

Assuming Fig. 7 for the top structural surface of neo-granite, an isothermal surface of 400 °C was obtained as Fig. 10. 400 °C is supposed to be minimum temperature for metamorphosing biotite.

The calculated isothermal surface does not show local highs and lows which exist in the top structural surface of Fig. 7. As the heat front propagates up through rock, the rough shape of the top structural surface of the neo-granite rock tends to be dissipated and not retained in the calculated isothermal surface.

Fig. 11 is an isograd map of biotite obtained by kriging the well data. Although an anticlinal and a synclinal shapes in isograd distribution were drawn, this isograd surface is much smoother than that of neo-granite given by Fig. 7 or 8. Comparing Figs. 10 and 11, the calculated isothermal surface differ much from the isograds in southern half of the study region, because the anticlinal structute at south in Fig. 7 strongly influences the calculated temperature field. Existence of this structure is highly uncertain, however.

CONCLUSIONS

(1) Bottom surfaces of the zone of microearthquake hypocenters were extracted statistically based on the hypocenter density.

(2) Top structural surfaces of the neo-granite rock were obtained by integrating the well data and the bottom surfaces of the hypocenter zone. The contour maps show rougher surfaces than that of the well data only.

(3) Isothermal surfaces calculated by a conduction model are smooth, and do not reflect ragged details of the top structural surface of the neo-granite. This result is consistent with smooth isograd surfaces of thermally metamorphosed minerals.

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