Geothermal Structure of the Hatchobaru Geothermal Field derived from Detailed Gravity and Resistivity Surveys

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Abstract

The geothermal reservoir in the Hatchobaru geothermal field has a typical fractured-type structure associated with fault systems. The components of the fault system are clarified or estimated mainly on the basis of geoscientific surveys, but some faults are confirmed by drillings. However, while the geothennal structure around the production and reinjection wells is well determined the structure at levels deeper than the present drilling depth, and also in the surrounding area where the number of drilled wells is small, is not detailed enough to assist in choosing drilling targets. Therefore, the clarification of the structure for the drilling of future supplementary wells is considered to be quite important to maintain a stable power output of 110MW at both power plants: the Hatchobam No.1 and No.2 units

This paper will discuss the features of the geothennal structure estimated according to the detailed gravity and resistivity surveys. The probabilities of geothermal development at deeper depths in and around the Hatchobaru geothermal field will be also discussed

1.0 INTRODUCTION

Located in central Kyushu, Japan, the Hatchobam *Geothermal* Power Plant is operated by the Kyushu Electric Power Company (KEPCO). The Hatchobaru No.1 unit (55MW) started commercial operations in 1977 and some years later, in 1990, the Hatchobaru N0.2 unit (55MW) was Commissioned Since then, the Hatchobaru Geothermal Power Plant remains the largest geothermal power station in Japan with a total installed capacity of 110MW.

Since it is very *important* for maintaining the power plants to estimate the features of the geothermal structure, Gravity and Resistivity surveys have been applied several times in the Hatchobaru geothermal field, and have proved to be effective not only for understanding the geothermal structure, but also for the selection of promising drilling targets. However, the separate data from these surveys were not compiled because of the differences in the survey conditions at different times. Therefore, analyses of these surveys were carried out using data compiled from previous records.

2.0 GRAVITY STRUCTURE

According to a gravity survey carried out in a 20km^2 area including the Hatchobaru geothermal field before the commencement of Hatchobaru N0.2 unit, NW-SE trending faults were considered to be the most *important* for geothermal development in the Hatchobaru area This consideration proved to be a good calculation for the whole geothermal *structure* of the Hatchobam area. Especially, since the production zone of the Hatchobaru No.1 unit is located along the NW-SE trending Komatsuike sub-fault, it was *appropriate* to estimate the importance of a NW-SE trending fault in the eastern part of Hatchobaru area. However, since the start of commercial operations in the Hatchobaru N0.2 unit in June 1990, it has become apparent, according to drilling data, *that* the production zone of the Hakhobaru area includes not only NW-SE trending faults, but also NE-SW trending faults.

For that reason, a detailed gravity *survey* with station intervals of about 150m-250m was *carried* out in the Hatchobaru area in August 1992. This analysis uses data from this *survey* in addition to previously recorded data from a 34km^2 area.

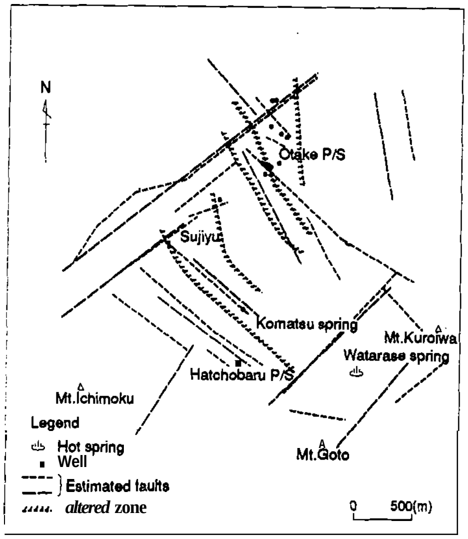

Figure 1: Geothermal structure estimated from gravity survey carried out in 1968

2.1 BOUGUER ANOMALY MAP

Four **Bouguer** anomaly maps were prepared using four correction **factors**: $\rho=2.20$, **2.25**, 2.30, **2.40g/cm^3**. **Since** the optimum correction density, **estimated from geographical** *features*, G-H correlation maps, **and the** core samples collected from wells, was $\rho=2.25$, **the Bouguer anomaly** *map* **shown in** Figure 2 is based on that **value.** **According** to a wide area gravity **distribution**, the **Hatchobaru** ***geothermal*** **field** is **situated** in a **high-gravity** anomaly **zone. The** NW-SE **lineament** in the eastern part of **the** Hatchobaru area is considered to be a large-scale fault dipping toward the **Inomuta** low-gravity anomaly zone, located in **the** northeastern part of the **Hatchobaru** area This detailed gravity survey **has** proved not only **that there** is a wide **area** gravity **structure**. **as** mentioned above, **but also** that **the** Hatchobaru area is **located** in a low-gravity anomaly zone ***situated*** in the middle of a high-gravity anomaly **zone.** This low-gravity anomaly zone (**Hatchobaru** low-gravity anomaly zone) around the production area trends E-W **and** then extends to the northern **part** of the **high-gravity** anomaly zone near **Mt. Ryoshi** (Mt. **Ryoshi high-gravity** anomaly zone). **Corresponding** to the E-W trending low-resistivity line **that** *can* be **recognized** from the resistivity **distribution** *map*, this E-W trending lineament is expected to be a promising target

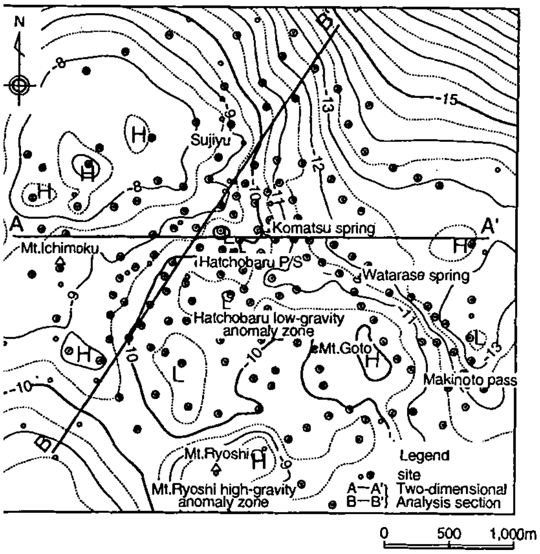

Figure 2: Gravity anomaly map ($\rho=2.25g/cm^3$) ; c.l.=0.5mgal

2.2 RESIDUAL GRAVITY MAP AND SECOND DERIVATIVE MAP

A residual gravity map and a second derivative *map* were made to **extract** the anomaly zones from the shallow to the deep parts of the structure. Figure 3, a residual **gravity** *map* that shows the structure of the **gravity** basement and the zone above it, is obtained **by** subtracting the **regional** *map* **from the** Bouguer anomaly *map*. **Figure 4** is a second derivative map using the Rosenbach system **with** a **sampling** grid space of **S=500m.**

2.2.1 RESIDUAL GRAVITY MAP

The high-gravity anomaly zone near Mt. Goto trends E-W and then extends in a NW-SE direction to Sujiyu. Corresponding to an upheaval zone **that** can be **recognized** from the resistivity basement *map*, **this NW-SE** trending high-gravity anomaly zone is considered to be the **product** of the upheaval of a small basement area The low-gravity anomaly zone in the ***eastern*** part of this **high-gravity** anomaly line extends very clearly in a NW-SE direction from Makinoto Pass to **Komatsu** spring, **and** according to geological ***studies***, **corresponds** very well **with** the Komatsuike fault, which **dips** eastward. The gravity transition zone that extends in a NE direction from Makinoto Pass to Watarase spring is very narrow, indicating remarkable **changes** in **the subsurface** density distribution. ***An*** E-W **trending** low-gravity anomaly zone **can be** recognized in the **high-gravity** anomaly zone located from **Mt.** Goto to **Sujiyu**. **Corresponding** to the E-W **trending** low-gravity anomaly **zone that** can be **recognized** from the Bouguer anomaly *map* **and the** second derivative map, this E-W trending **low-gravity anomaly zone is** considered to be **indicating the presence** of low **density** layers. The **E-W trending lineament in the northern** part of **Mt. Ryoshi** can be recognized both **from** the **Bouguer** anomaly map, **and also from this map.**

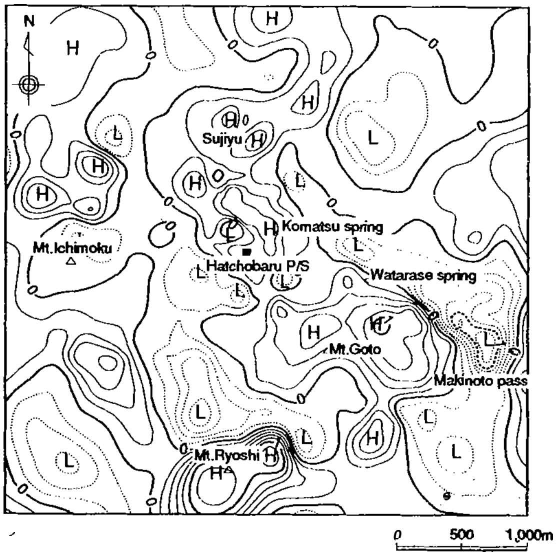

Figure 3: Residual map ; c.l.=0.2mgal

2.2.2 SECOND DERIVATIVE MAP

If the range of gravity anomalies extracted from a second derivative *map* with a sampling grid space of S=500m is about 1-2 times the size of the grid space, the subsurface anomalies are shown to be at a depth of between 500m and 1000m. The negative anomaly zone northeast of Mt. Goto clearly trends in a NW direction from Makinoto pass to Komatsu spring, and then extends in a western direction from Watarase spring. These trends agree very well with the results of the residual gravity *map*. Therefore, the existence of a NE-SW trending fault is estimated around the production zone of the Hatchobaru No.1 unit. This fault is crossed by the *NW-SE* trending Komatsuike fault in *the* area between the Hatchobaru power station and Mt. Goto. If the NW-SE trending fault in the eastern part of the Hatchobaru geothermal field is the *Original* source of geothermal water, the estimated NE-SW trending fault or fracture intersecting it is considered to be the flow path of the geothermal fluid. Watarase spring, the *geyser*, and the other manifestations probably indicate the area where these two faults intersect.

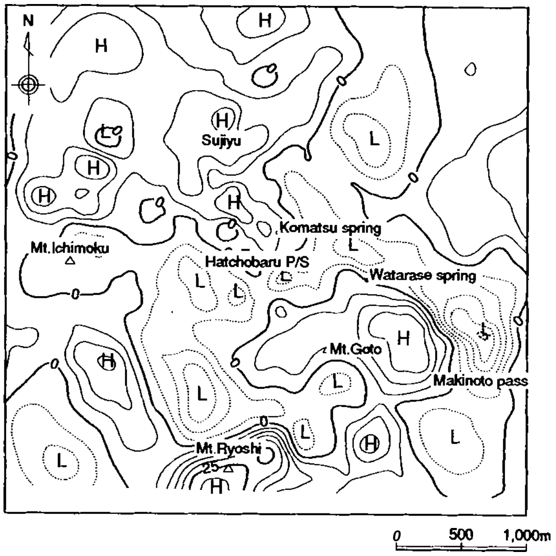

Figure 4: Second derivative map (S=500m) Residual map ; c.I.=0.2mgal

2.3 TWO-DIMENSIONAL ANALYSIS

It is difficult to distinguish the density layers of the Usa formation and of the basement rocks in 2D modeling because of the very small difference in density between them. Therefore, if these *two* layers together are considered to be the gravity basement, the model structure above it consists of four density layers as follows :

(1) Kuju volcanic group (density; 2.314g/cm^3)
(2) upper and middle formations of the Hohi volcanic *group* (density ;2.069g/cm^3)
(3) lower formations of the Hohi volcanic *group* (density; 2.392g/cm^3)
(4) lowest formation if the Hohi volcanic *group* (density ;2.603g/cm^3)

It is appropriate to estimate that the actual densities of these layers are lower than those actually measured from the core samples of the HT-4 well. Consequently, the densities used for 2D modeling are as follows ;

(a) the first layer 2.25g/cm^3 (Kuju volcanic group)
(b) the second layer 2.00g/cm^3 (upper, middle, and lower formations of the Hohi volcanic group)
(c) the third layer 2.50g/cm^3 (lowest formation of the Hohi volcanic group)
(d) the gravity basement 2.70g/cm^3 (Usa formation and pre-tertiary rocks as the gravity basement)

This section analysis is conducted for the two sections, A-A' (E-W direction) and B-B' (NE-SW direction), whose locations are shown in Figure 2. The 2D section is obtained by making the observed values, which are calculated on the basis of a simplified subsurface structure, fit the Bouguer values after fixing the control point at the gravity basement, confirmed from the existing well.

2.3.1 A-A' SECTION (E-W DIRECTION)

The gravity basement is uplifted from Mt. Ichimoku in the west to Mt. Kuroiwa in the *east*, and even more so in the area to the east of Watarase spring, where the top of the gravity basement is about 200m-300m higher (Figure 5). This result agrees with the low-gravity anomaly zone, which *can* be recognized on the residual gravity *map* and the second derivative *map* and extends in a *NW-SE* direction from Makinoto Pass. The uplift of the gravity basement to the west of Watarase spring is smaller than that to the *east* of Watarase spring. In other words, the fractures along the Komatsuike sub-fault cannot be clearly recognized from 2D analysis. Therefore, these are not considered to extend too deep.

2.3.2 B-B' SECTION (NE-SW DIRECTION)

The top of the gravity basement becomes sharply deeper north of Otake (Figure 6). This result fits the core samples data obtained from the DY6 well, confirming the presence of the Taio formation (corresponding to the Usa formation) at an elevation of -1,450m. It is worth noting that there is a small subsidence zone south of the Komatsu River. This subsidence zone corresponds to Hatchobaru low-gravity anomaly zone. The subsidence zone and the fractures around it, especially the Hatchobaru fault, the Komatsuike fault and the Komatsuike sub-fault are considered to be the most important targets for geothermal development in the Hatchobaru geothermal field. The southern part of the Hatchobaru fault is therefore expected to be a promising target.

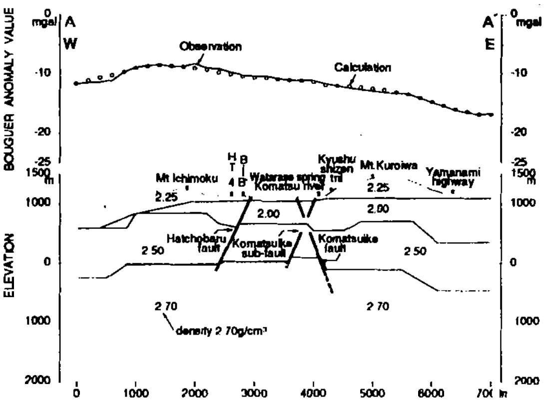

Figure 5: Two-dimensional density analysis for section A-A'

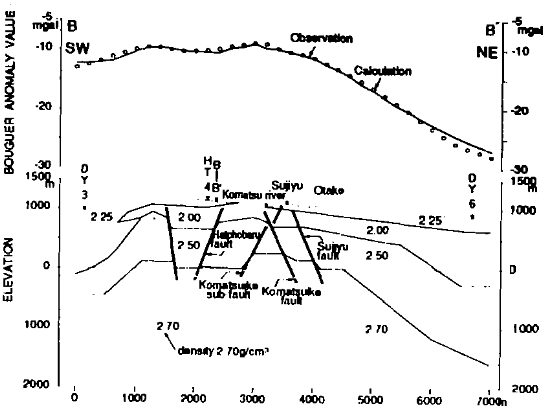

Figure 6: Two-dimensional density analysis for section B-B'

3.0 RESISTIVITY STRUCTURE

The resistivity structure of the Hatchobaru geothermal field generally exhibits an H pattern (high-low-high) like most geothermal fields in the world. This pattern consists of the first layer (resistive overburden: ranging from 200 ohm-m to 500 ohm-m), the second layer (low resistivity layer: ranging from 5 ohm-m to 20 ohm-m) and the third layer (electrical basement: ranging from 50 ohm-m to 200 ohm-m). The thickness of the layers obtained from the one dimensional analysis ranges from 100m to 200m for the first layer, and from 400m to 800m for the second layer. In the geological structure, the first layer corresponds to the Kuju volcanic group, the second layer to the altered zone in the upper and middle formations of the Hohi volcanic group, and the third layer to the lower formation of the Hohi volcanic group and Usa formation. If there is a fault in a geothermal reservoir, the horizontal changes in resistivity distribution (electrical discontinuity) are remarkably clear. Figure 7 shows the distribution of electrical discontinuity recognized from the resistivity maps and the feed zone confirmed by drilling. Some locations of this electrical discontinuity fit the locations of recognized faults as flow paths for geothermal fluid, and are considered to be the best drilling targets for production and reinjection wells. These results show that the low-resistivity zones' indicate altered zones in the faults and fractures along them made by geothermal fluid flow. If the same results are obtained from one-dimensional analysis, then the choice of good drilling targets is greatly facilitated. This is one of the reasons why the geothermal reservoir in the Hatchobaru area is considered to have a typical fracture-type structure associated with fault systems, and MT and CSAMT survey with station intervals of about 200m was carried out in this field. In addition to Occam's onedimensional analysis, a two-dimensional analysis was carried out to obtain more detailed information about the resistivity structure, and the probabilities of geothermal development at deeper depth in and around the Hatchobaru area were reexamined.

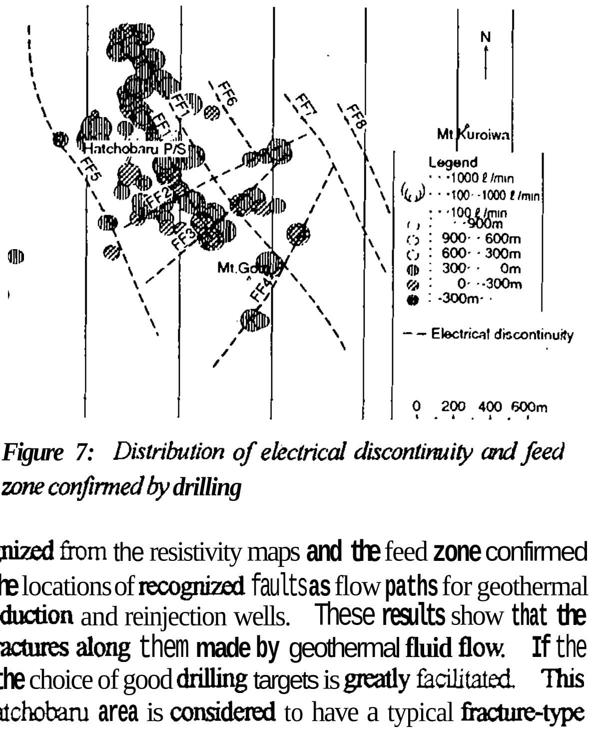

Figure 7: Distribution of electrical discontinuity and feed zone confirmed by drilling

31 OCCAM'S ONE-DIMENSIONAL ANALYSIS

In order to obtain the layer resistivity structure for an understanding of the geothermal structure in the Hatchobaru area, Occam's onedimensional inversion was carried out at all MT and CSAMT stations. Two Resistivity maps at elevation levels of 0m and -1000m made from the results are shown in Figure 8 and Figure 9.

3.1.1 RESISTIVITY MAP AT 0m ELEVATION

Considering that the depth of the production wells is about 1,500m and that the elevation of the Hatchobaru geothermal field is about 1,100m, Figure 8 shows the distribution of resistivity in the production zone and a little above. This elevation layers correspond closely to the lower formations of the Hohi volcanic group and the Usa formation A high-resistivity zone of more than 40 ohm-m is recognized in the center of the Hatchobaru area These trends agree with the high-gravity anomaly zone that can be recognized from the residual gravity map. The Komatsuike fault is located in the eastern part, and the Hatchobaru fault in the western part of this high-gravity anomaly zone. The main fracture zones in the Hatchobaru area are located along these faults. Since the resistivity around Watarase spring is shown to be lower than 30 ohm-m this low-resistivity zone is expected to indicate the locations of the fracture zones and the geothed water. The low-resistivity zone. located in the western part of the high-resistivity zone in the center of the Hatchoh area. trends in a NE-SE direction. This low-resistivity zone corresponds to the Hatchobaru fault.

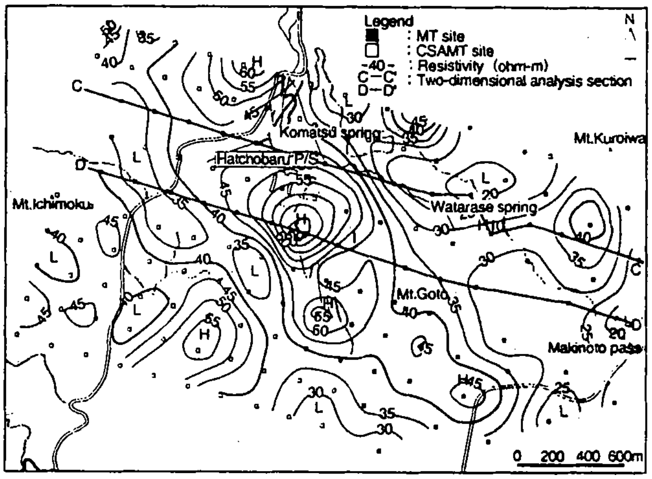

Figure 8: Resistivity map in elevation level at 0m

3.1.2 RESISTIVITY MAP AT -1000m ELEVATION

Figure 9 shows the resistivity distribution at -1000m elevation which corresponds to the Usa formation and the basement rocks. The resistivity around Watarase spring is the lowest (lower than 40 ohm-m) in the Hatchobaru area. When this is compared with the resistivity map at 0m elevation. the low-resistivity zone is estimated to uplift from east of Watarase spring to Watarase spring. since the center of the low-resistivity zone is located more to the east than shown on the resistivity map at 0m elevation. The result indicates the probability of the existence of a geothermal reservoir at deeper depth in the eastern part of Watarase spring. The low-resistivity of the shallow part is considered to' indicate the altered zone and the other manifestations. The low-resistivity of the deep part is considered to indicate the original source of geothermal water.

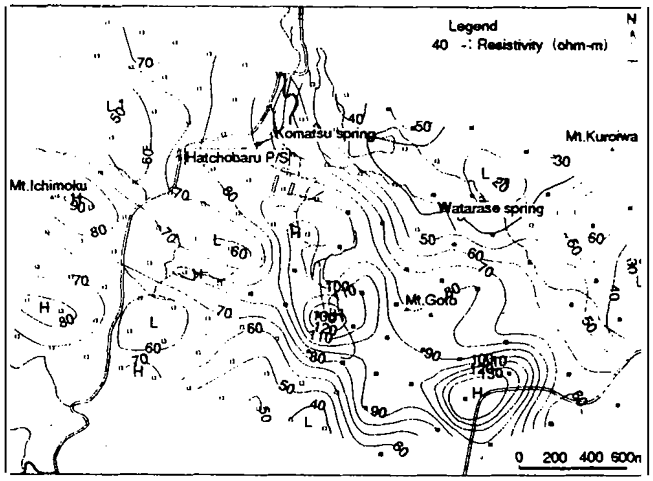

Figure 9: Resistivity map in elevation level at -1000m

A low-resistivity zone is recognized around Mt. Ryoshi. This results agrees with the results of the gravity distribution. Therefore. since the presence of an E-W trending fault is estimated from these results, the deep northern part of Mt. Ryoshi is expected to be a promising target.

Figure 10 and Figure 11 show the results of a two-dimensional analysis for Section C-C' and Section D-D', the location of which were shown previously in Figure 8. According to *our* analysis, the production area of the Hatchobaru geothermal field is clearly located in the high-resistivity zone, corresponding to the NW-SE trending upheaval zone recognized in the gravity distribution. Since the fracture zones are located along horizontal changes (electrical *discontinuity)* in resistivity distribution (Figure 7), electrical discontinuity can be a good indicator of promising targets. Figure 11 is characterized by a resistivity basement in the eastern part of the Hatchobaru area dipping toward the east, which agrees with the gravity basement and the low-resistivity zone (lower than 10ohm-m) recognized in the eastern and western parts in depths from shallow to deep in the Hatchobaru area. Especially, the low-resistivity zone located in the eastern part of the Hatchobaru area is larger than in the western part, and extends into the production zone. As a result, it is appropriate to estimate that the original source of geothed water in the Hatchobaru area is supplied from the eastern part of the Hatchobaru area dipping eastward, rather than from deeper depths along the Komatsuike sub-fault, located north and north-*east* of Mt. Goto, including the production area of Hatchobaru No.1 unit. From the results of the gravity and resistivity distribution, the NW-SE trending Komatsuike sub-fault is considered to be a secondary reservoir. The original sources of geothermal water from deeper depths in the eastern part of the Hatchobaru area flow along a NE-SW flow path to the production area.

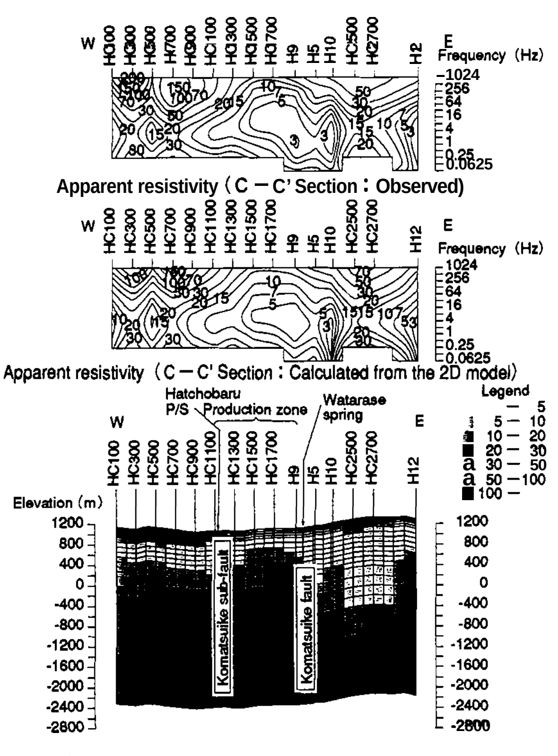

Figure 10: Two-dimensional resistivity analysis for section C-C'

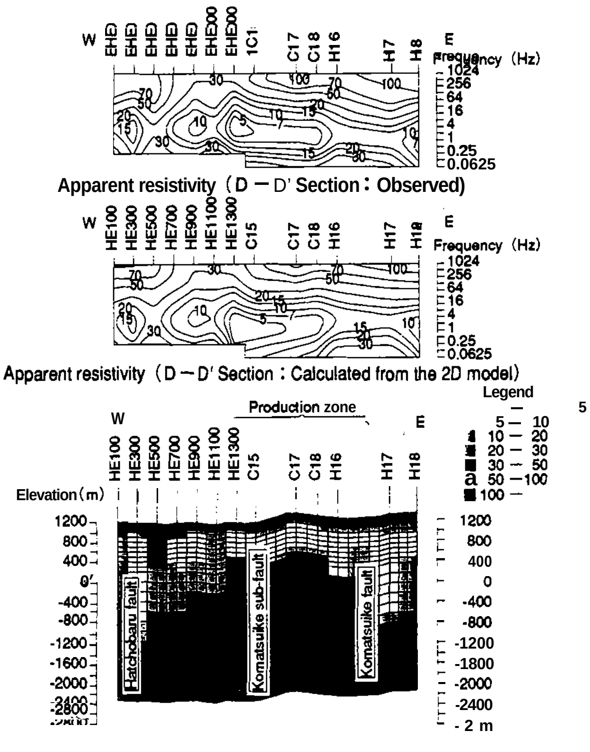

Figure 11: Two-dimensional resistivity analysis for section D-D'

4.0 GEOTHERMAL STRUCTURE AND DEVELOPMENT AT DEEPER DEPTHS IN THE HATCHOBARU GEOTHERMAL FIELD

As mentioned above, the geothermal structure in the Hatchobaru geothermal field has a typical fractured-type *structure* associated with fault systems. The main NW-SE trending faults are the Komatsuike fault, Komatsuike sub-fault and Hatchobaru fault. The Komatsuike fault dips eastward, while the Komatsuike sub-fault and Hatchobaru fault dip westward. The present main reservoir in the Hatchobaru geothermal field is along the Komatsuike sub-fault, which is exploited by the Hatchobaru No.1 unit and part of the N0.2 unit The Hatchobaru hult is of a different nature from the Komatsuike sub-fault (Geothermal water extracted from the Hatchobaru fault indicates acidity.), but the reservoir has been confirmed by the drilling of production and investigation wells. The Komatsuike fault hasn't been reached by drilling, but geothed water of high *temperature* and pressure is confirmed by a production well that has been *drilled* near that fault.

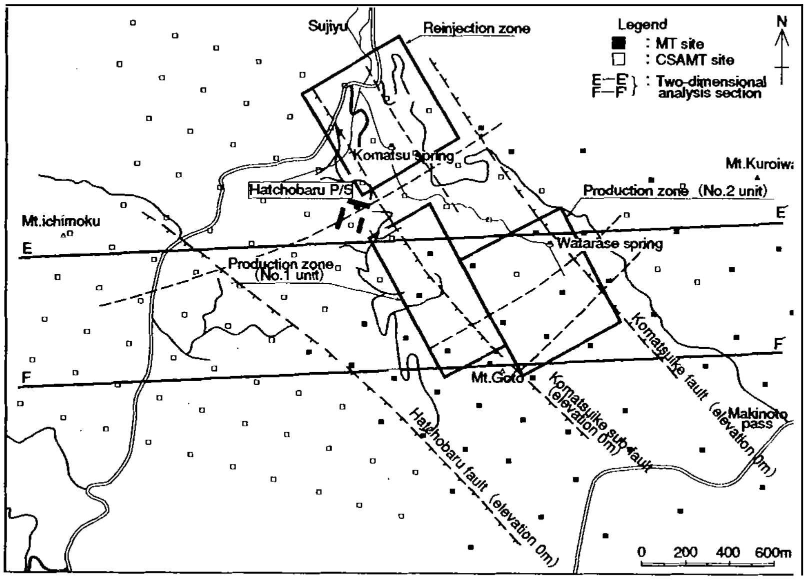

Figure 12: Location ofthe production, injectionzone and the faults

As shown in Figure 12, twodimension density and resistivity analysis for section E-E and section F-F' were made, in order to discuss the probabilities of geothermal development at deeper depths in and around the Hatchobaru geothed field Figure 13 and Figure 14 show the results of twodimension density and resistivity analysis for section E-E' and section F-F'. The low-resistivity zone that can be recognized from the twodimension resistivity analysis almost corresponds to the second layer of the low-density zone and to a part of the third layer that *can* be recognized from the two-dimensional density analysis. These faults are located along horizontal changes (electrical discontinuity) in resistivity distribution, and the low-resistivity zone extends deep along a part of the faults. As a result, the geothermal *structure* is considered to be clear

Considering that the faults have been successful geothermal targets in the Hatchobaru area, the places where electrical discontinuity extends around and *at* deeper depths of the low-resistivity zone are *also* considered to be promising drilling targets. Therefore, the low-resistivity zones located along the Komatsuike hult in section E-E and located along the Hatchobaru hult in section F-F' are estimated to be promising targets. Specifically, these *faults can* be considered to be quite important geothermal *features* of the Hatchobaru geothermal structure.

However, around the areas of the Komatsuike sub-fault that have been developed until now, the upheaval of the high-resistivity basement can be recognized, and the low-resistivity zone is not as remarkably clear as along other faults. As a result, part of the geothermal water flowing along the Komatsuike or the Hatchobaru fault is considered to be flowing to the Komatsuike sub-fault and to be stored there.

From the features of gravity and resistivity distributions, it is appropriate to estimate that the original source of geothermal water in the Hatchobaru area is supplied from the eastward dipping eastern part of the Komatsuike sub-fault and the deeper depth of Mt. Ryoshi rather than from deeper zones along that sub-fault.

Therefore, the deeper zone of the Komatsuike fault in the eastern part of the Hatchobaru area, the deeper zone of the Hatchobaru fault in the southern part of the Hatchobaru area, and the area around the low-resistivity zone located near Mt. Ryoshi in the south-eastern patt of Hatchobaru fault are expected to be promising targets for supplementary wells to be drilled for maintaining the power plants.

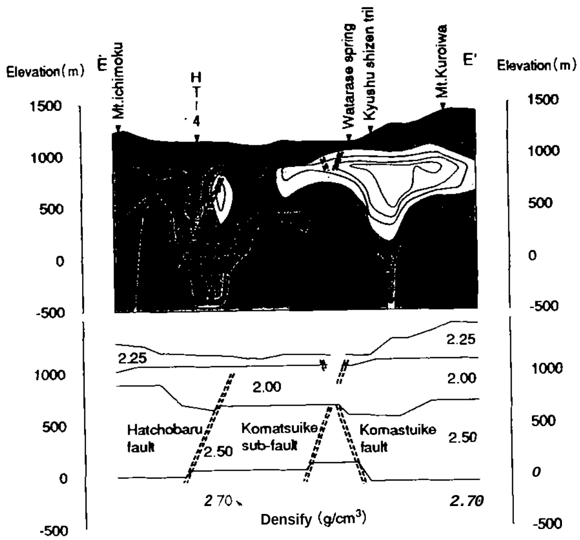

Figure 12: Two-dimensional resistivity and gravity analysis for section E-E'

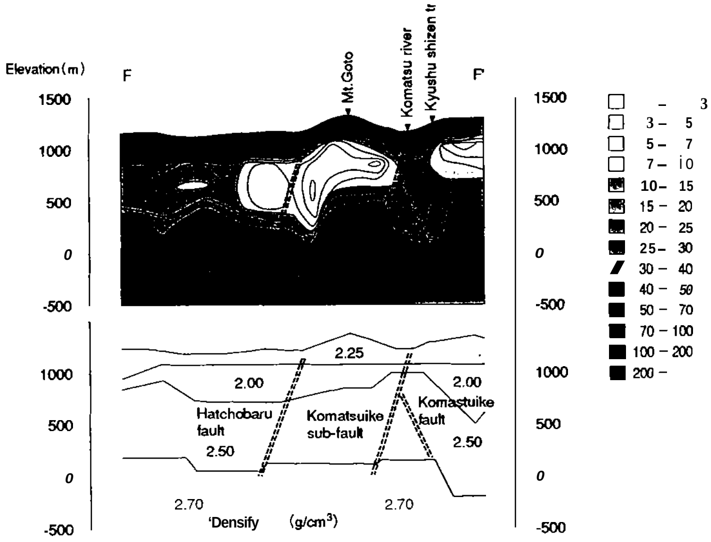

Figure 13: Two-dimensional resistivity and gravity analysis for section F-F'

5.0 CONCLUSIONS

Since gravity surveys have been evaluated to be a suitable geophysical exploration method to delineate basements over a wide area, gravity surveys generally have been carried out for such purposes. This time, because the results of the detailed gravity survey and resistivity survey agreed very well with the location of the feed zone confirmed by drillings, it was discovered that a detailed gravity survey could also be used to effectively delineate the distribution of fractures and the detailed shape of a basement.

It is hoped that promising drilling targets can be precisely determined by carrying out gravity and resistivity surveys, and that these results will be verified in other areas.

Acknowledgments

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