Interpretation of Gravity and Gamma-Ray Spectrometry Data in Low Temperature Hydrothermal Systems, Southeastern Part of Fukuoka, Japan

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A b s t r a c t

The Hakata hot springs area is located in Fukuoka City, which is in the southwestern part of Japan. Gamma-ray and gravity surveys were conducted to understand the relationship between the low-temperature hydrothermal systems and geophysical data of the area. The depth of the reservoir basement, which was derived from gravity data, gradually deepens toward the east; it includes some steep depth gradients in the Hakata hot springs area. High intensities of gamma-rays were detected around these gradients. In addition, higher hot spring temperatures and flow rates can be observed in this area. These results indicate that some part of the level of the basement where the hot springs are concentrated is a part of the Kego Fault and is similar to the fracture zone created by past activities of the fault. Moreover, these steep depth gradients act as a path for hot spring water from the deeper side of the granitic body to the surface.

Key words: gravity, gamma-ray, Hakata hot springs, Kego Fault, hydro-thermal system.

1. INTRODUCTION

Fukuoka City, which has the largest population on Kyushu Island, is situated in the southwestern part of Japan (Fig. 1). The Hakata hot springs area is one of the low- to moderate-temperature hot spring areas on the southeastern end of Fukuoka and is associated with an active fault (Kego Fault). Some 11 wells were drilled in the late 1960s to access the hot springs (Table 1). The wells reach depths of 150 m and produce hot spring temperatures of 27°C to 50°C (Matsushita *et al.* 1971). The hot spring temperatures are relatively high compared to the other hot springs in the city, but no deeper geothermal resource is expected to be discovered (Karakida *et al.* 1994).

Fig. 1. Location of the Hakata hot springs area, southwestern part of Japan; modified from HERP (2013). NW-SE trending normal and left-lateral strike-slip faults are developed throughout the area.

Table 1

Characteristics of hot spring wells in the Hakata hot spring area
(Matsushita *et al.* 1971)

Well ID	AB	S1	S2	SE	MI	KK	A	TK-A	T-F	SI	FU
Depth [m]	72	70	100	78	100	150	100	150	150	130	100
Temperature [°C]	49.0	43.0	37.5	46.0	31.0	42.0	27.0	46.0	34.3	33.1	43.0
Flow rate [kg/s]	1.7	0.9	2.0	0.8	0.4	1.8	0.3	2.0	0.7	—	2.0
Borehole geology	○					○					

A strong earthquake ($M_{\text{JMA}} 7.0$) occurred offshore to the west of Fukuoka Prefecture on 20 March 2005. The distribution of hypocenters and seismogenic stress as defined by aftershocks suggested that the 2005 West Offshore Fukuoka Prefecture earthquake occurred on the fault that runs in the NW extension of the Kego Fault (Shimizu *et al.* 2006). The results of gravity gradient interpretation techniques (Saibi *et al.* 2008) showed that the Hakata hot springs area was strongly connected with the NW-SE active fault system that is named the Kego Fault. MEXT (2013) reported the precise location of the Kego Fault based on the comprehensive survey of the active fault in Fukuoka city, passing through this study area (Fig. 2).

Most active urban faults are covered by unconsolidated Quaternary sediments. Dense buildings and other facilities constructed in the study area prevented the use of electromagnetic and seismic methods. There are some geophysical approaches, however, that can detect the fractures and faults in urban areas (Sultan *et al.* 2012, Xu *et al.* 2015). A gravity survey is one of the effective methods for the detection of a fault structure related to a path of hot water (Abdelzaher *et al.* 2011, Represas *et al.* 2013). Additionally, a gamma-ray survey is an efficient method for fracture identification. Subsurface fractures previously have been associated with elevated uranium concentrations due to the movement of uranium in subsurface hot water circulation (McCay *et al.* 2014). The results of a gamma-ray survey in geothermal and hot spring areas (Mogi and Okada 1990a, b) suggested that the high gamma-ray intensities of ^{214}Bi and ^{208}Tl are strongly related to the presence of an upflow of hot water.

The over pumping of hot spring water is causing a shortage of hot spring resources. To avoid such an exhaustion of a hot spring, it is necessary to understand the underground structure and hydrothermal system. Several surveys have been conducted in the Hakata hot spring area. Yamashita *et al.* (1965) used an electrical resistivity method for the groundwater survey in this area. The low resistivity zone was detected at a depth of more than 30 m.

1: Reclaimed land 2: Qurtanary sand dune deposit 3: Quartanary alluvium 4: Aso-4 pyroclastic flow deposit 5: Quartanary gravel and sand 6: Qurtanary Paleo-sand dune deposit 7: Neogene Basalt 8: Paleogene sandstone and mudstone 9: Paleogene sandstone and conglomerate 10: Paleogene sandstone, mudstone, conglomerate and coal 11: Cretaceous granite 12: Cretaceous plutonic rock 13: Paleozonic metamorphic rock

— Kego Fault (MEXT, 2013) Study area

Fig. 2. Geological map of the study area and its surroundings. Modified from GSI AIST (2014). The red line and the black rectangle show the location of the Kego Fault (MEXT 2013) and study area, respectively.

Matsushita *et al.* (1971) interpreted this low resistivity zone as a hot spring reservoir based on the observation of a stratigraphic column. The flow path of the hot spring water and the reservoir structure, however have been little investigated. In addition, few geophysical studies have attempted to understand low-temperature hydrothermal systems such as this hot spring area. This study was carried out to understand the relationship between the hot

spring water flow in the low-temperature hydrothermal system and the geophysical survey results (gravity and gamma-ray surveys).

2. GEOLOGICAL SETTINGS

Northern Fukuoka is located in the W-E compression field caused by the subduction of the Philippine Sea Plate under the Eurasian Plate (Shimizu *et al.* 2006). There are therefore many NW-SE trending active faults in the northern part of Fukuoka Prefecture (Fig. 1). The Headquarters for Earthquake Research and Promotion (HERP 2007) reported that the Kego Fault is a NW-SE-trending left-lateral strike-slip fault with an overall length of 27 km. According to Kimura *et al.* (2013), the strike-slip basin structure is characterized by west-to-south westward tilting and bounded by the Kego Fault on its southwest side. This basin of the basement is covered by Middle Pleistocene to Holocene deposits.

Figure 2 shows the geological map of Fukuoka city (GSJ AIST 2014). The geological setting in Fukuoka is comprised of Sangun metamorphic rocks (Paleozoic), Late Mesozoic granitic rocks, Paleogene sandstone, Neogene basaltic rocks, and Quaternary sediments (Karakida *et al.* 1994). In this map, the gravitational basement, which is high in density, is considered Mesozoic granitic rocks.

3. GAMMA-RAY SPECTROMETRY

The gamma-ray survey was carried out using the portable multi-channel spectrum analyzer E-560A and a NaI (Tl) scintillation detector (made by NAIG Co. Ltd., Japan) at 214 points. The diameter and height of detector is 4 inches. The detector unit was set on the ground; the analyzer measures 1024 channels between 0.03 and 3.00 MeV. The spacing between stations varies between 50 and 100 m, depending on the accessibility. Three radioactive elements, ^{40}K , ^{214}Bi (1.76 MeV), and ^{208}Tl (2.61 MeV), were detected as an indicator of upflows of hot water. A data processing method based on Mogi and Jinguuji (1993) was used; it included the error estimation of observation. The intensity of each element was defined as the net count in 300 s.

Aswathanarayana (1985) pointed out that the net count is affected by surface geology and meteorological conditions. The two net count ratios, $^{214}\text{Bi}/^{40}\text{K}$ and $^{208}\text{Tl}/^{40}\text{K}$, were therefore adopted for the index of gamma-ray intensity. These indexes are shown in Figs. 3 and 4, classified into the following four categories using an average (m) and a standard deviation (SD).

Cat. 1 (high) > m + SD > Cat. 2 > m > Cat. 3 > m – SD > Cat. 4 (low)

Fig. 3. Distribution of the $^{214}\text{Bi}/^{40}\text{K}$ ratio. The coordinates in Figs. 3-6 are Japan Plane Rectangular Coordinate System II. Two high $^{214}\text{Bi}/^{40}\text{K}$ intensity areas (A and B) were detected along the Kego Fault. Mean: 0.16, Standard deviation: 0.04. Cat. 1 > 0.2 > Cat. 2 > 0.16 > Cat. 3 > 0.12 > Cat. 4.

Two high $^{214}\text{Bi}/^{40}\text{K}$ and $^{208}\text{Tl}/^{40}\text{K}$ intensity areas, which correspond to the Kego Fault, were identified. The northwestern high intensity area was located in and around the hot spring wells. These results indicated that ^{222}Rn and ^{220}Rn , the parent elements of ^{214}Bi and ^{208}Tl , respectively, come to the surface together with hot water. The difference between these two elements is their half-life, as the half-life of ^{208}Tl (3 min) is shorter than that of ^{214}Bi (19.9 min). ^{208}Tl is accumulated rapidly at the location where hot water nears the surface.

Although there is no hot spring well in the southeastern area where the high intensity ^{214}Bi and ^{208}Tl are detected, it is possible that hot water is moving up towards the surface in that area.

Fig. 4. Distribution of the $^{208}\text{Tl}/^{40}\text{K}$ ratio. Two high $^{208}\text{Tl}/^{40}\text{K}$ intensity areas (A and B) were detected along the Kego Fault. Mean: 0.08, Standard Deviation: 0.02. Cat. 1 > 0.1 > Cat. 2 > 0.08 > Cat. 3 > 0.06 > Cat. 4.

4. GRAVITY DATA

The gravity survey was carried out using Scintrex CG-3, CG-3M, and CG-5 gravimeters. The intervals of the survey points were set as several tens to two hundred meters. The measured gravity data was reduced to complete the Bouguer anomaly, applying the necessary corrections such as height, tidal, free-air, Bouguer, and terrain conditions. The assumed density of 2470 kg/m^3 was determined by an objective Bayesian approach (Murata 1993) for the Bouguer and terrain corrections.

The complete Bouguer anomaly map is depicted in Fig. 5. The Bouguer anomalies are all positive, ranging from 14.1 to 17.4 mgal, decreasing in the southeastern regions of the map area (Fig. 5). The regional anomaly, caused

Fig. 5. Bouguer anomaly with an assumed density of 2470 kg/m^3 . Red circles show the location of the gravity station.

Fig. 6. Residual Bouguer anomaly map. The regional anomaly calculated by first-order polynomial fitting was removed from Fig. 5.

by the deep granite structure, was isolated using the first-order polynomial trend.

Figure 6 clearly indicates a low Bouguer anomaly extension that has a NW-SE direction and coincides with the Kego Fault, as was further confirmed by a trenching survey (Shimoyama *et al.* 2005). The Kego Fault (MEXT 2013) is on the western edge of the low Bouguer anomaly (Fig. 6).

In addition, the location of this low Bouguer anomaly is consistent with a depression of basement rock based on the stratigraphic column (Kimura *et al.* 2013). Most wells are on the northwestern edge of this low anomaly and the surrounding area. Moreover, a high-low-high pattern can be found from the southwest part to the northeast part of the study area. Cretaceous granite and Pleistocene pyroclastic flow deposits correspond to these high Bouguer anomalies.

5. GRAVITY MODELING AND DISCUSSION

According to the geological map (Karakida *et al.* 1994) and the stratigraphic column (Matsushita *et al.* 1971) shown in Fig. 7, it is possible that the survey area can be approximated by two geological layers: Quaternary sediments and Cretaceous granitic basement rock. In order to determine the depth and detailed shape of the basement rock, including fault structure, 3-D gravity modeling was conducted. Distribution of the basement rock was approximated as an aggregation of rectangular prisms whose horizontal dimensions are the same as those of the input residual Bouguer anomaly grid (Cordell and Henderson 1968, Rao *et al.* 1999). The grid adjusted the depth of the basement rock and the prismatic cells that formed a three dimensional (3D) model. This was done to minimize the difference between the obtained gravity data and the model's output. The thicknesses of the prisms represent the depth, from surface to the basement, and a constant density contrast of -400 kg/m^3 was assigned to all prisms. That is, the density of the Quaternary sediments was set at 2200 kg/m^3 , while that of the basement rock was 2600 kg/m^3 (GSEAK 1981). Since gravity modeling is non-unique, the depth of granite in the two hot spring wells (Fig. 7) was used to constrain the model. The horizontal size of the cells was set as 50 m and a westward coordinate was set at 41 degrees.

The outcome of the 3D gravity basement analysis can be seen in Fig. 8. Panel (a) shows the depression with a NW-SE trend on the eastern side of the Kego Fault. On the eastern side of the depression, a continuous steep gradient in the level of the gravity basement was detected. The depth of the basement is reducing to the west, including some steep gradients in the level of basements on the western side of the Kego Fault. These depth gradients have a strike of NW-SE and the most eastern step corresponds with the Kego

Fig. 7. Stratigraphic column of two wells (well ID: KK and AB) in the Hakata hot spring area (Matsushita *et al.* 1971). The depth of granite in these wells was used to constrain the three-dimensional gravity modeling.

Fig. 8. (a) Gravity basement in meters above sea level with density contrast of 400 kg/m^3 . Black rectangle shows the area of panels (b) and (c). (b) Focused map of the Hakata hot springs in comparison with the distribution of hot spring temperatures based on Table 1. (c) Focused map of the Hakata hot springs in comparison with the distribution of the hot spring flow rates [kg/s] based on Table 1. The black line and black rectangle show the location of the Kego Fault (MEXT 2013) and the hot spring wells with well ID, respectively. The coordinate is turning westward at 41 degrees.

Fault. Almost all the hot spring wells are located near these steep depth gradients. Additionally, most of the high-intensity gamma-ray results agree with the depth gradients in the gravity basement.

Figures 8b and c show a comparison of the distributions of hot spring temperatures and flow rates, respectively, based on the hot spring wells data (Table 1). Figure 8b indicates that the high-temperature area is located on and to the west of the Kego Fault. This high-temperature area coincides with high gamma-ray intensities and the steps or steep depth gradients of the gravity basement. In contrast, the hot spring temperature decreases toward eastern side of the Kego Fault. Figure 8c shows that the high flow rate area is located in the western part of the Kego Fault. This high flow rate of hot water can be observed in almost the same location as the high-temperature area; it corresponds to the small depression of the gravity basement. The high gamma-ray intensities correspond to high flow rate area. In comparison with the distribution of the hot spring temperatures, the extent of the high

Fig. 9. Profile of line AB in Fig. 8a. The hot water flows up to the near surface through the fault structure. The density of the granite is assumed to be 2600 kg/m^3 and that of the sediments to be 2200 kg/m^3 . The main flow path of the hot spring is considered a part of the Kego Fault. KK, SE, S2, MI, and A indicate the hot springs well IDs, which are located near the profile.

flow rate area is narrow. Considering these results, it can be presumed that the hot spring water is coming from deeper part of the high flow rate area and flows toward the eastern and southern areas laterally through the Kego Fault.

Figure 9 shows a cross-section of A-B in Fig. 8a. The depth of basement gradually deepens toward the east; it includes steep depth variations in the Hakata hot springs area. High gamma-ray intensities (^{214}Bi and ^{208}Tl) were detected around these areas. Furthermore, the high-temperature hot springs and high flow rates were observed above these steps.

Results of the electrical resistivity observations (Yamashita *et al.* 1965) indicated that a low resistivity zone (less than 10 Ohm-m) was detected at a depth of more than 30 m in the Hakata hot springs area. Matsushita *et al.* (1971) interpreted this low resistivity zone as a hot spring reservoir by using the stratigraphic column of the hot spring wells.

Taking these results into account, a portion of the steep difference in the level of the gravity basement where the hot springs are concentrated is a part of the Kego Fault. This is similar to a fracture zone created by past activities of the fault. Moreover, the fracture zone around these steep depth gradients acts as a path for hot spring water to travel from the deeper side of the granitic body. It is therefore thought that the hot spring water comes up through this fracture zone from a deeper side in the high flow rate area and then flows toward the east and southeast at a shallow depth.

6. CONCLUSION

This paper presented the analysis of gamma-ray and gravity surveys over the Hakata hot springs area. Two high-intensity gamma-ray areas ($^{214}\text{Bi}/^{40}\text{K}$ and $^{208}\text{Tl}/^{40}\text{K}$) that coincide with the Kego Fault were detected. The northwestern high-intensity area is located in and around the high temperature and high flow rate area. The distribution of the 3D gravity basement depths enabled the delineation of the interface between the basement rocks and the sediments. In addition, some steep depth gradients of the gravity basement, including the Kego Fault, were detected. We have reported that the results of gamma-ray and gravity surveys indicated that the differences in the level of the basement where the hot spring wells concentrate correspond to a part of the Kego Fault. Fracture zones were created by the past activities of the fault; these enable hot spring water to come up to the surface from the deeper side of the granitic body. It can be presumed that the hot spring water flows laterally to the east and south through the shallow part of the Kego Fault in relation to the distributions of hot spring temperatures and high flow rates. Although there is no hot spring well in the southeastern area where similar underground structures were detected, it is possible that hot water is moving up toward the surface from those structures.

These geophysical survey methods are likely to remain appropriate in the future, as they were quick and cost-effective ways to evaluate the hydro-thermal system of this hot springs area. These methods allowed not only an

understanding of the underground structure of low-temperature hydrothermal systems, but also an assessment of the sustainability of hot spring usage. To understand the sustainability of hot spring usage more fully, a further study that would involve geothermal modeling and numerical simulation of hydrothermal systems should be conducted.

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