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3D Temperature Modeling over Kyushu Island (SW Japan) and Its Characterization from Geologic Structures

Naoyuki Tadakuma, Katsuaki Koike and Hisahumi Asaue

Graduate School of Science and Technology, Kumamoto University, Kurokami 2-39-1, Kumamoto 860-8555, Japan

koike@gpo.kumamoto-u.ac.jp, asaue@kumamoto-u.ac.jp

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ABSTRACT

Three dimensional (3D) temperature distributions down to deep depths are important for exploration and assessment of geothermal resources. With the rapid development of computer capability and the increase of open sources of geoscience data, such temperature modeling has been executable for multiple purposes. This study is aimed at developing a method for accurate 3D temperature modeling using an open access database over a wide area by selecting Kyushu Island, southwest Japan as a study area. The modeling was targeted for a rectangular solid covering 280 km (E-W), 330 km (N-S), and 1 km along the depth, and was carried out by a spatial estimation technique, 3DOPT using the temperature data by well-logging at 202 sites and the thermal gradient data at 29 sites. 3DOPT is founded on a mechanical minimization principle similar to spline methods. The resultant 3D model clarified plausible characteristics on the locations of high and low temperature zones: high temperature zones up to shallow depths, which are attributable to convective flows, are highlighted in the geothermal areas and near the active volcanoes. Another interesting feature is the continuous low temperature zone along the largest tectonic line (Usuki-Yatsushiro Line) across Kyushu Island and around the active faults, which signifies that the tectonic line and the faults may form high permeable zones by the large fracturing and derive descending flows of the groundwater down to the deep depths. This interpretation can be confirmed by a combination of the groundwater level modeling by co-kriging: the positions of large decline of the groundwater levels correspond with the decrease zones of temperatures at the 1000 m depth.

1. INTRODUCTION

Temperature is one of the most fundamental physical properties that are effective for understanding geosphere environments. Spatial pattern of temperature at a certain depth can be an indicator of groundwater system or heat flow from a deep-seated heat source. Three dimensional (3D) temperature distributions down to deep depths are also essential from the two viewpoints, (1) exploration and assessment of geothermal resources and (2) characterization of fluid flows associated with geologic structures and geodynamics. There have been many reports noting that ascending and descending flows are partly controlled by fault structures (e.g. Bodvarsson et al., 1982; López and Smith, 1996; Yang et al., 2004) and earthquakes tend to occur at a certain temperature range (e.g. Lippmann et al, 1997). With the rapid development of computer capability for large calculation and the increase of amount and sort of open sources of geoscience data, such 3D temperature modeling has been executable for various areas over the world.

The purpose of this study is to develop a method for accurate 3D temperature modeling over a wide area and to characterize the resultant model from hydrogeologic, fault, and volcanic structures. We selected Kyushu Island, southwest Japan as a study area (Fig. 1), because it is well-known to be rich in geothermal resources. Regional geothermal system of the study area is clarified down to 1 km depth, and its usefulness is validated by the accordance of high and low temperature zones to the active volcanoes and the large faults.

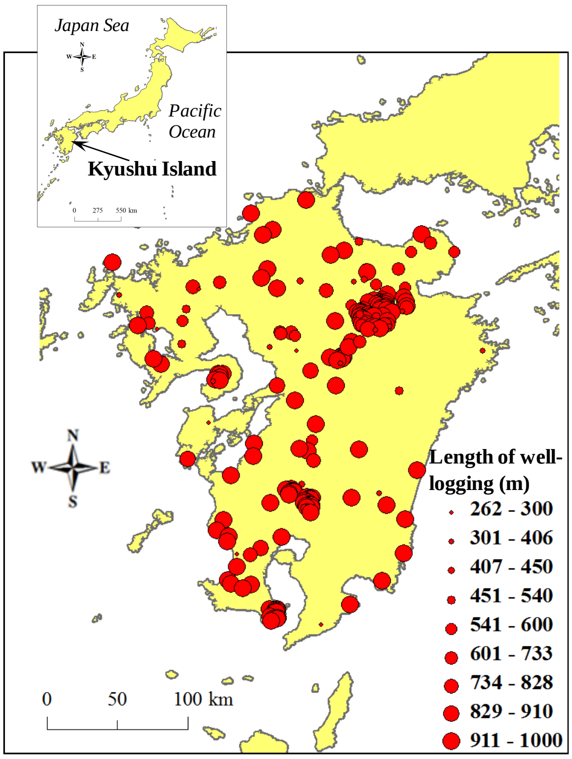


Figure 1: Kyushu Island situated in southwest Japan showing topography, location of wells and length of downhole logs used in the study. Depths range from 262 to 1500 m.

2. TEMPERATURE DATASET

Kyushu Island, southwest Japan, is the third largest Japanese island. It is dominated by metalliferous deposits such as Hishikari gold mine, hot springs, and active volcanoes, because the Daisen-Kirishima volcanic belt is located in the middle of the island. There are several geothermal power stations such as Hatchobaru (110 MW).

We used two open sources of the temperature data by drillholes for geothermal investigations; the well-logging data at 202 sites, which were extracted from the database of well-logging temperature profiles in Japan by Japan Atomic Energy Agency (http://www.jaea.go.jp/04/tono/siryou/welltempdb.html), and the thermal gradient data at 29 sites from the database of geothermal gradient in and around Japan by Tanaka et al. (2004). The bottom depths of the logging data range from 262 to 1500 m. Figure 1 shows the 231 drillhole sites in total with information on the bottom depth: 49 shallow, 173 medium, and 9 deep drillholes in the 200–500 m, 500–1000 m, and 1100–1500 m depth range, respectively.

In general, there are two types of wells in terms of the physics of heat transfer along their depth, whether by conduction or convection. At the conductive site, heat is transmitted from deep places to the surface by conduction and the temperature increases linearly with depth; whereas, at the convective site, heat is transferred by the convection of water and gas. The major characteristics of the convective type are that the rate of temperature increase in the shallow depth is larger than that of the conductive type and the temperature profile has an inflection point. Figure 2 shows two examples of well-logging data with small and large thermal gradients. For both the profiles, the temperature changes along the depth can be approximated by a line. This characteristic signifies that the most well-logging sites are classified into conduction-type and that thermal gradient is constant generally in the study area except for the special sites adjacent to hot springs and active volcanoes.

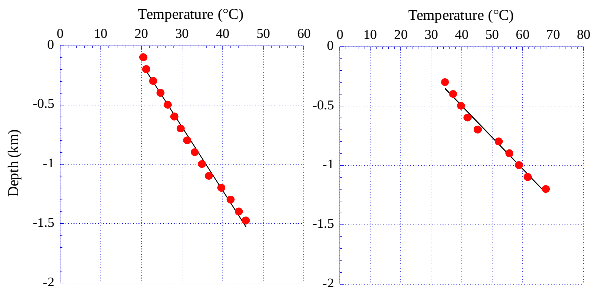


Figure 2: Examples of temperature logging data at two sites with small (left) and large (right) thermal gradients, showing that the data can be approximated by a line at both the sites.

Therefore, we assumed a linear increase of temperature from the surface to the bottom depth at each site of the thermal gradient data. By setting the surface temperature as 20 °C and extrapolating it linearly with the recorded thermal gradient, we made temperature data at 100-m depth interval to the bottom depth at the 29 sites. Number of these data is 263 and finally, 11,804 data in total is used for the 3D temperature modeling.

3. 3D SPATIAL MODELING METHOD OF TEMPERATURE

The drillholes are spread irregularly over the Kyushu Island; borehole depths are variable and the deep wells are strongly localized as shown in Figure 1. The purpose of spatial modeling is to accurately determine certain characteristics at unsampled points and outside the sampled area using regionalized sample data. The temperature modeling was targeted for a wide area covering 280 km (E-W), 330 km (N-S), and 1 km along the depth, and the number of grid (calculation) points were 100 $\times$100 $\times$100 along these directions. The grid interval along the depth direction is set to be small as 10 m, because the temperature data are much closely distributed along the depth than the horizontal direction.

The temperature data reflect the physical properties of various volcanic and sedimentary rocks and hence do not represent a single population. We used the 3DOPT method, which can be applied when developing a complicated distribution model from sample data with obscure spatial correlations and from sample data whose spatial correlations change locally (Koike et al., 1998). This method has been applied successfully in 3D temperature modeling in the Hohi geothermal region over 20 (E–W) × 21 (N–S) km in the central Kyushu (Teng and Koike, 2007). Superimposition of the three spatial models of temperature, flow velocity, and geology to a depth of 3000 m clarified that the geothermal reservoirs are localized near highly fractured fault zones that provide paths for the ascent of thermal fluids from depth.

According to the 3DOPT method, the desired 3D model can be obtained by minimizing the objective function, which is analogous to the minimization principle of mechanical potential energy such as spline methods. The objective function is a linear combination of the functional that evaluates the smoothness of the 3D model and the penalty function, which is the squared summation of residuals between the sample and estimated values.

Let the temperature calculated at a grid point ijk be f_{ijk}. Since the quantity of unknowns (f_{ijk}) is large, the Gauss-Seidel iteration method is used for the solution of minimizing the objective function. For every grid point, the interpolated value at the iteration l is compared to that obtained from the previous iteration l-1, and the difference is calculated. If the highest difference among them is less than a prespecified small amount, ε, the process is said to have converged, and the last set of f_{ijk} constitutes a solution. This criterion can be expressed as

$$\max\left| f_{ijk}^{l} - f_{ijk}^{l-1} \right| < \varepsilon \tag{1}$$

The value of ε was assigned 0.015 for the present study.

4. MODELING RESULTS

4.1 Cross-validation for Temperature Modeling

Before determining the temperature characteristics from the 3DOPT results, it is important to validate the estimation capabilities of the method. To achieve this, we compared measured and calculated temperatures as shown in Figure 3; the 45° line represents perfect estimates. We undertook this cross-validation on two data from relatively high temperature zones and long drillhole length, because accurate estimates are more difficult at depth where fewer field and high temperature data are available. In the cross-validation, the logging data are hidden from the dataset and the temperatures are calculated using the remaining data. The calculated value for the grid point closest to each selected logging point is then compared against the measured temperature. The performance of the 3DOPT method is of a high standard, showing coefficient of determination (R^2 in the figure) close to 1 for both the wells.

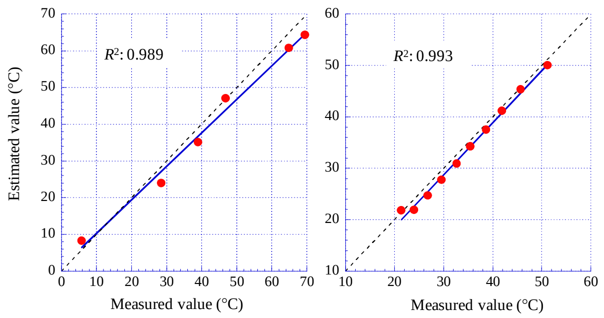


Figure 3: Evaluation of the accuracy of the temperature model by comparison between measured and estimated (3DOPT) temperature data for relatively high temperature (left) and long drillhole length (right).

4.2 Characterization of Temperature Distributions

The computed temperature distributions at the 500 and 900 m depths below the surface are given in Figure 4 and overlaid with the active faults. These figures indicate the presence of high-temperature zones over 60 °C common to the two depths at three active volcano zones (Kusu, Shimabara, and Kirishima) and a granite zone of young age (Tertiary). The temperature distribution at the 500 m depth shows that the two low-temperature zones in the north Kyushu (circled in the top figure) are bounded by the long active faults. Therefore, the active faults are found to affect the temperatures in the shallow depths. At the 900m depth, an NE–SW trending high-temperature belt is conspicuous in the north Kyushu. This belt corresponds generally with the Beppu-Shimabara Graben, an extensive E–W volcano-tectonic depression that has been active since the Neogene (Matsumoto, 1987). This depression can be confirmed to form high temperatures by the 3DOPT modeling.

The six N-S vertical slices passing over the study area (A-A' to F-F') are used to characterize the temperature

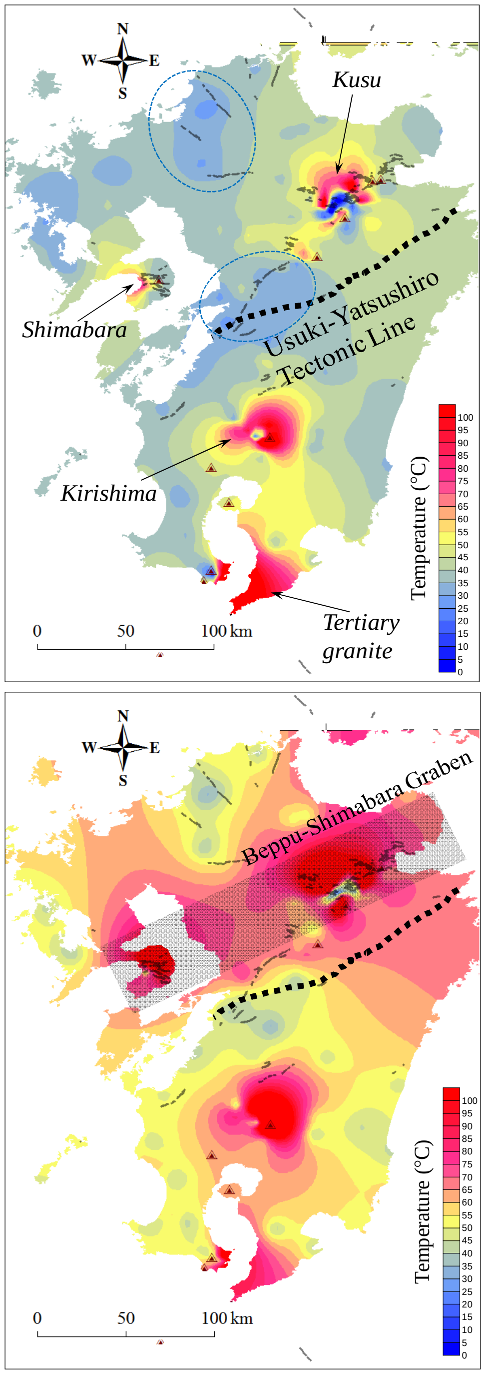
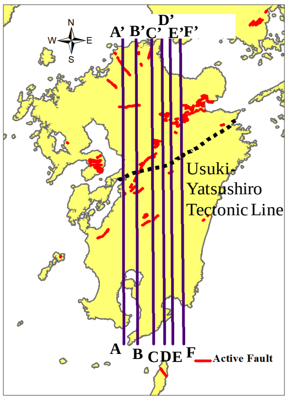


Figure 4: Computed 3-D temperature distribution at 500 (top) and 900 m (bottom) depths. Low-temperature zones bounded by the long active faults are circled in the map of 500 m depth.

distributions as shown in Figure 5. At all the slices, plumes of the high-temperature zones more than 90 °C are remarkable around the active volcanoes, Mt. Sakurajima at A-A', Mt. Kirishima at B-B' and C-C', Mt. Aso at D-D' and E-E', and Mt. Yufudake at F-F'. Another noteworthy feature is the continuous low-temperature zone less than 30 °C along the Usuki-Yatsushiro Tectonic Line (UYTL), which is regarded as an extension of the longest active fault in Japan, the Median Tectonic Line, toward the Kyushu Island from the Shikoku Island. Thus, the 3D temperature model



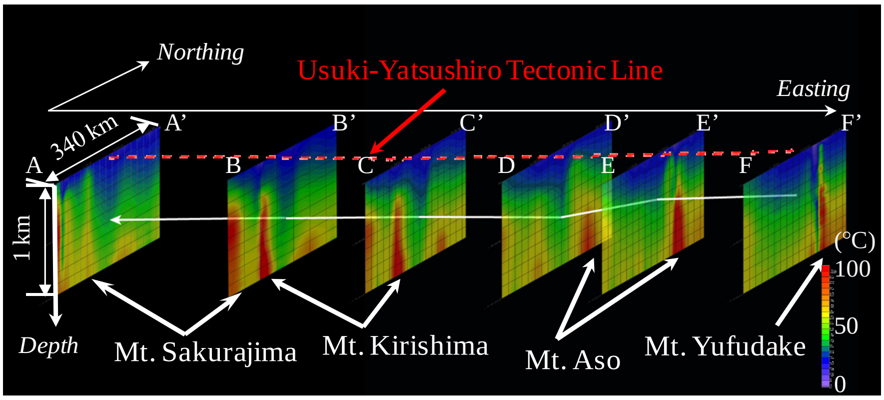


Figure 5: N-S vertical cross-section along sixe lines through the temperature model passing through the Usuki-Yatsushiro Tectonic Line.

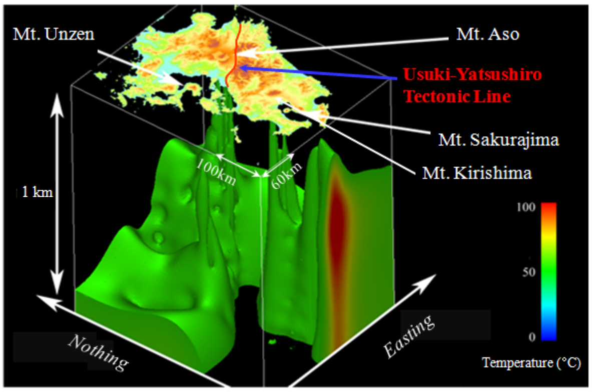


Figure 6: Three-dimensional distribution of the 57 °C surface and its relation to topography (top surface).

clarifies a large effect of UYTL on the decrease of temperatures in the depths shallower than 300 m. In the zones deeper than 300 m, the temperatures decrease largely from the high-temperature zones as clearly seen at the B-B' and C-C', which signifies large circulation of heat and convection of groundwater flows as the result.

Figure 6 represents a superimposition of the topography of Kyushu Island on a volume rendering of relatively high-temperature zones (> 57 °C). This figure clarified that the 57 °C isotherm takes a spike-shaped form around the active volcanoes above-mentioned. From it, the effect of volcanoes on the increase of temperatures is found to be limited spatially. In addition, large depression of the temperatures is clearly appeared along the UYTL. In the western zone, it needs more than 1000 m depth to reach 57 °C. The thermal gradient in the zone is the smallest over the study area. The northern part of the study area is also dominated by low-temperatures generally, but its thermal gradient is larger than that in the UYTL.

5. DISCUSSION

From the 3D temperature model, the temperature depressions around the active faults and the UYTL were confirmed as a common feature over the study area. To identify a possible cause of this depression, we focused on the groundwater level and produced a level map using the data at 1084 sites which were extracted from a search site for the national geotechnical information, "Kunijiban" (http://www.kunijiban.pwri.go.jp/index.html). This is jointly operated by the Ministry of Land, Infrastructure, Transport and Tourism, the Public Works Research Institute and the Port and Airport Research Institute. These data are a mixture of unconfined and confined groundwater levels, but most must be unconfined levels: the data are top groundwater levels at each site. We transformed the data into logarithm, because the data followed approximately a lognormal distribution.

The log-level data had a strong correlation with the topography (elevation of the ground surface at the drilling site), which was confirmed by a high coefficient of determination, 0.995, between the groundwater level and the topography. To improve the estimation accuracy of the level distribution by considering this correlation, we adopted co-kriging method for the level modeling. Let the level data and the elevation data at the *i*-th location are expressed as z_i and y_i, respectively. The groundwater level at a location $\mathbf{u}$, $\hat{z}(\mathbf{u})$, is calculated by:

$$\hat{z}(\mathbf{u}) = \sum_{i=1}^{n} \lambda_i z_i + \sum_{i=1}^{m} w_i y_i$$
$$\sum_{i=1}^{n} \lambda_i = 1, \quad \sum_{i=1}^{m} w_i = 0 \tag{2}$$

where λ_i and w_i are weight coefficients that can be obtained by solving a covariance matrix, and n and m are number of data used for the co-kriging calculation. The covariance matrix is constructed by each semivariogram of the z_i and y_i, and the cross-semivariogram between the z_i and y_i.

The resultant groundwater level map is shown in Figure 7. High accuracy of this map can be confirmed by a cross-validation procedure: a correlation coefficient between the measured and estimated levels is 0.96, which is close to 1. As similar to the temperature distribution, continuous, linear declines of the groundwater levels are appeared.

To compare the groundwater level with the temperature, superimposition of the levels on the temperatures at the 1000 m depth along the three cross-sections A-A’, B-B’, and C-C’ (Fig. 5) are drawn as Figure 8. Interesting characteristic is that the two positions of large decline of the levels correspond with the decrease zones of temperatures along the A-A’. The northern position matches with the location of the UYTL. Such common declines between the levels and temperatures are also existed along the B-B’ and C-C’. Accordingly, there may be a connection from a shallow phenomenon (the top level of groundwater) to a deep phenomenon (the 1000 m depth temperature).

This connection can be interpreted as the effect of UYTL and active faults over the 1000 m depth range by forming the fracture zones around the faults. Hydraulic conductivities in the fracture zones must be higher than the surrounding rocks, which can derive dominant descent flows of cold groundwater from the surface to deep parts. As the result, the temperatures tend to decrease at and around the fracture zones.

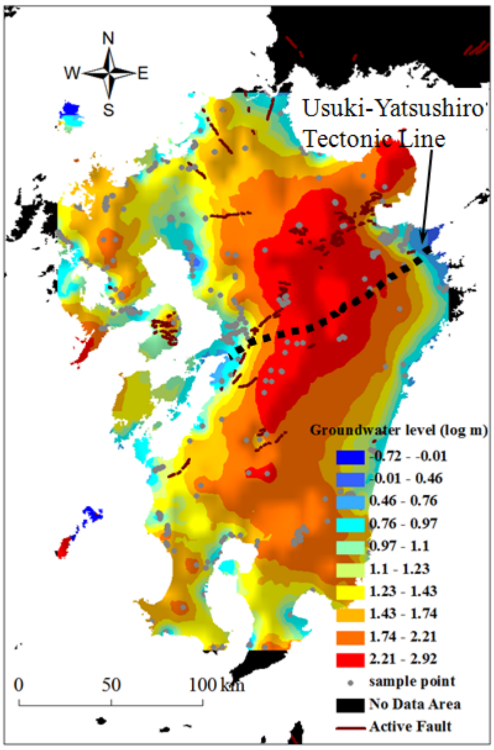


Figure 7: Groundwater level distributions by co-kriging that incorporate the correlation between the groundwater level and the topography into spatial modeling.

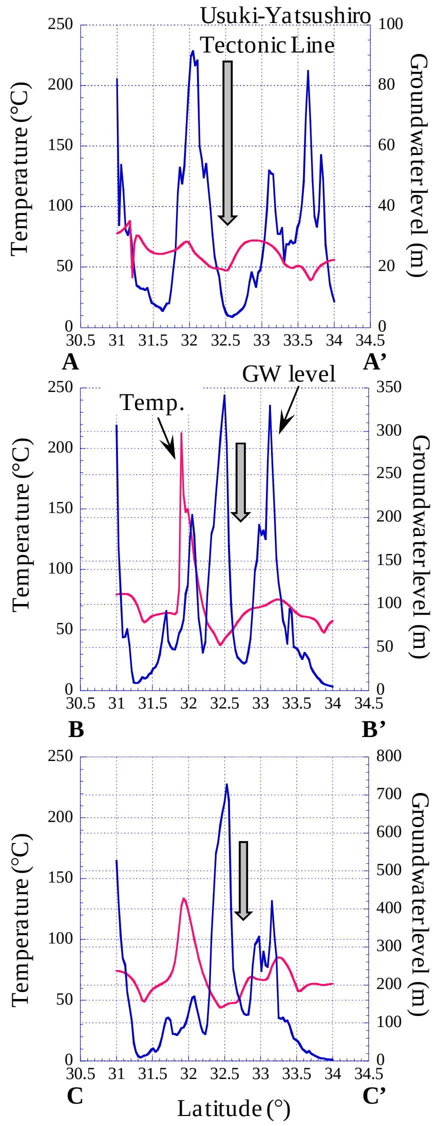


Figure 8: Superimposition of the N–S cross-sections of the temperatures at 1000 m depth onto the groundwater levels.

6. CONCLUSION

In order to develop a method for accurate 3D temperature modeling over a wide area and to characterize the resultant model, we used two spatial modeling techniques, 3DOPT and co-kriging to analyze a set of well-logging data and a set of groundwater level data. By selecting Kyushu Island, southwest Japan, being rich in geothermal resource as a study area, the main results obtained can be summarized as follows.

(1) Using the temperature data at 231 sites, the 3D temperature model was produced over a wide area covering 280 km (E-W), 330 km (N-S), and 1 km along the depth. From the result, the presence of high-temperature zones over 60 °C at the three active volcano zones and a granite zone of young age (Tertiary), the effect of the active faults on the decrease of temperatures in the shallow depths, and an NE–SW trending high-temperature belt, corresponding to the Beppu-Shimabara Graben, were clarified.

(2) A volume rendering technique presented that high-temperature zones take a spike-shaped form around the active volcanoes and the effect of volcanoes on the increase of temperatures is limited spatially. Large depression of the temperatures was appeared along the Usuki-Yatsushiro Tectonic Line in which the thermal gradient is the smallest over the study area.

(3) It was found that the positions of large decline of the groundwater levels correspond with the decrease zones of temperatures at the 1000 m depth. This connection can be interpreted that the hydraulic conductivities in the fracture zones must be higher than the surrounding rocks, which can derive dominant descent flows of cold groundwater to deep parts and decrease the temperatures at deep parts consequently.

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