

Three-Dimensional Thermal Structure in the Tohoku District, Japan, Estimated from the Activity Index

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ABSTRACT

The subsurface three-dimensional thermal structure in the Tohoku District, Japan, was estimated from shallow-depth hydrothermal data to evaluate the potential for exploiting next-generation geothermal energy. One of the future targets of geothermal development in Japan is supercritical geothermal reservoirs which are expected to be located immediately beneath the brittle-plastic transition (BPT). The temperature profile of the WD-1a well in Kakkonda encountered a temperature inflection point at 380 °C and depth of 3100 m. The temperature inflection point at 380 °C is considered to indicate the BPT on granitic crust in contraction tectonic fields. The strong correlation between the isothermal depth at 380 °C and the bottom of seismicity clouds is demonstrated in this study. This result indicates the reliability of the subsurface three-dimensional thermal structure in the Tohoku District, Japan, as an important indicator of accessible next-generation geothermal energy underneath the BPT.

1. INTRODUCTION

It is difficult to determine the location and characteristics of underground geothermal resources that cannot be seen, and it takes a large amount of money and time to investigate. This is a major obstacle to the development of geothermal power; hence, a method to quickly and accurately determine the underground structure at the research stage is important.

Suzuki *et al.* (2014) applied a thermal structure estimation method using an activity index in Aomori prefecture in the tohoku district, Japan, and demonstrated its effectiveness. In this study, we applied the method to several geothermal areas in the Tohoku region and evaluated its validity.

The three-dimensional thermal structure was estimated from hot spring data and well data, and an isothermal surface distribution map at 380 °C, which is the brittle-plastic transition depth, was created. The estimated isothermal distribution and hypocenter distribution at 380 °C were compared to evaluate the validity of the estimated temperature structure. Generally, the brittle-plastic transition is considered to indicate bottom of hydrothermal convection and the bottom of the fault zone; hence, the immediate surface distribution at 380 °C is considered to indicate the bottom of the hypocenter distribution that occurs in the shallow crust. Therefore, by comparing the estimated brittle-plastic transition depth and the bottom of the hypocenter distribution, we examined whether the estimated three-dimensional thermal structure reflects the actual thermal structure with high accuracy.

2. ESTIMATE OF SUBSURFACE THERMAL STRUCTURE IN TOHOKU DISTRICT

The “*Atlas of Hydrothermal Systems in Japan*” collected 7203 points of hot spring data and 3066 points of geothermal exploratory well data from all over Japan to assess the distribution and regional characteristics of the hydrothermal systems and geothermal potentials in Japan (Muraoka *et al.*, 2007). They were also originally paper-based data, but a digital-version on CD-ROM was published later (GSJ, 2009). Among the 6522 points of data consisting of 3456 points of hot spring data and 3066 points of geothermal exploratory well data include temperature and depth data. The 3066 well data are mainly "data described in the report of a geothermal survey conducted in the past" on 572 points, "thermal gradient database" on 1809 points (Tanaka *et al.*, 1999), and "temperature profiles of boreholes database" on 685 points (Sakagawa *et al.*, 2004)(Muraoka *et al.*, 2007). It is known that part of the data overlaps (Muraoka *et al.*, 2007). In this paper, 6414 data was used from which duplicates were removed. Moreover, since the latitude and longitude of some data were recorded by different geodetic systems, we reviewed the position information.

Suzuki *et al.* (2016) collected hot spring and well data in Aomori prefecture in the Tohoku region, and created the “Aomori Prefecture Geothermal Resource Database”. The “Aomori Prefecture Geothermal Resource Database” consists of chemical data for 786 points of hot springs, temperature data for 26 points of natural hot springs and subsurface temperature data for 35 points of geothermal exploratory well data (Suzuki *et al.*, 2016). In this paper, from the database, 434 data in which the temperature and drilling depth were described in the “*Record of Hot Spring Geology in Aomori Prefecture*” was also used. Finally, we used 6414 data, including 3456 hot spring data and 2524 well data.

3. ESTIMATION OF 380 °C ISOTHERM DISTRIBUTION BY ACTIVITY INDEX IN TOHOKU DISTRICT

It is important to understand the detailed underground temperature structure when evaluating underground geothermal resources that cannot be seen. However, because there are few geothermal wells with deep temperature profiles, it is difficult to determine the detailed temperature structure. Therefore, Suzuki *et al.* (2014) applied the simple thermal structure estimation method using an activity index (Hayashi *et al.*, 1981) to the active geothermal area of hydrothermal convection. The estimated thermal structure was accurate when compared with the actual thermal structure (Suzuki *et al.*, 2014).

The activity index is a normalized index curve for quantitatively evaluating the activity in the geothermal area. In the area with active hydrothermal convection, temperature changes are regulated by the boiling curve of pure water and thermal convection. This is based on the generally known fact that the temperature changes linearly in the non-active conduction heat region. The activity index is determined by the following equation:

$$\text{Activity Index} = \frac{a}{b} \times 100 = \left(1 - \frac{T_b - T_m}{T_b - T_g}\right) \times 100 \quad (1)$$

where T_m , T_b , T_g are maximum temperature at the observed depth, boiling point temperature curve of pure water at the observed depth and an average geothermal gradient ($30 \text{ }^\circ\text{C / km}$) at the observed depth, respectively. In addition, a and b show the $T_m - T_g$ and $T_b - T_g$ respectively. The curve with an activity index of 100 represents the boiling curve of pure water, which was obtained using the approximation by Haas (1971). If the activity index at a certain depth is determined, then the temperature at that depth can be easily estimated by Equation (1). The data used in this study include hot spring and well data associated with drilling. With these data, the activity index was calculated using the maximum temperature (T_m) measured at the well depth. In addition, Hayashi *et al.* (1982) stated that the activity index is valid even at a depth of 0 m as an extreme case. In this study, we used the temperature of natural hot springs as the value of the activity index.

In general, pure water is known to reach a critical point at a depth of approximately 3500 m. However, the curve of the activity index was simply extrapolated to a depth of 15 km because the critical point shifted toward the high-temperature side as salt concentration increased. Because the brittle-plastic transition indicates the bottom of hydrothermal convection, we attempted to estimate the brittle-plastic transition depth from the three-dimensional thermal structure estimated from the activity index. In particular, the transition of metamorphic rocks from brittle to plastic state in fault zones is known to occur under a relatively wide range of temperature and pressure conditions (Sibson, 1977). This range corresponds to approximately 250–400 $^\circ\text{C}$ in the quartz or potassium-feldspar-rich granitic continental crust.

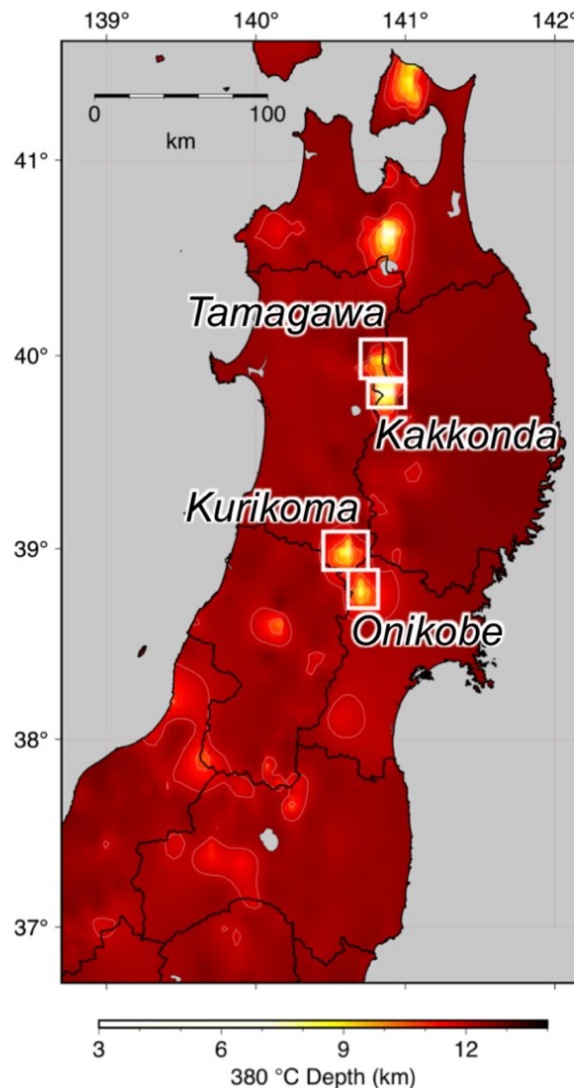


Figure 1: Map of the depth of the 380 °C isotherm in Tohoku district, Japan.

In the actual field, it is difficult to measure the brittle-plastic transition temperature because it is too high to measure in the well using the conventional method. However, in the WD-1a well drilled in the Kakkonda geothermal area, Iwate Prefecture, drilling was carried out to a depth of 3729 m and well-bottom temperature exceeding 500 °C; thus, we succeeded in capturing the brittle-plastic transition temperature (Ikeuchi *et al.*, 1998; Muraoka *et al.*, 1998). The temperature profile of the WD-1a well is shown as an inflection point at 380 °C and depth of 3100 m. Hydrothermal convection occurs in the shallow region as shown by the boiling point curve, hence, hydrothermal convection does not occur in the deeper region as indicated by the extremely high gradient temperature curve. That is, the inflection point at 380 °C indicates the brittle-plastic transition (BPT) in the granitic crust. On the other hand, there appears to be a high-density fault zone at 340 °C and depth of 2000 m. The measurement results by differential strain curve analysis (Strickland and Ren, 1980) and the mechanical strength of the rock by the WD-1a well showed good agreement, which indicates a brittle-ductile transition (BDT). As the BDT shows the maximum stress field, the relationship between seismic activity and the fault zone is rather important. From the viewpoint of geothermal heat, the brittle-plastic transition (BPT) is considered more important because it indicates the hypocenter distribution, fault zones, and bottom of hydrothermal convection. Therefore, the most reliable brittle-plastic transition temperature in the shallow crust is considered to be 380 °C.

Figure 1 shows the isotherm depth distribution at 380 °C in the Tohoku region, estimated from the activity index. GMT 5.4.3 (Wessel *et al.*, 2013) was used for drawing, and smoothing was performed at intervals of 100 m; the tension factor was set to 0.3. In the volcanic area and active geothermal area, the isotherm depth distribution at 380 °C was estimated as relatively shallow.

4. COMPARISON OF 380 °C ISOTHERMAL DISTRIBUTION AND HYPOCENTER DISTRIBUTION IN MAJOR GEOTHERMAL AREAS IN TOHOKU DISTRICT

In the region where the isothermal surface depth was determined to be shallow at 380 °C, good agreement was obtained between the distribution of quaternary volcanoes and active geothermal areas. In particular, the isothermal surface at 380 °C was estimated to be relatively shallow in the Tamagawa hot spring area, Kakkonda area, Kurikoma area, and Onikobe area, where several geothermal development surveys have been conducted in the past (Figure 2). In this study, the isothermal surface at 380 °C was estimated to be relatively shallow, and the validity of the isothermal distribution was estimated from the activity index in four areas: the Tamagawa hot spring area, Kakkonda area, Kurikoma area, and Onikobe area. For the purpose of evaluating the properties, we compared these with the hypocenter distribution using the Japan Meteorological Agency (JMA) unified source catalog (Okada *et al.*, 2004). Seismic data is considered appropriate for validation because it is completely independent of the temperature data used to estimate the isotherm at 380 °C. In addition, the relationship between hypocenter distribution and subsurface thermal structure has been reported by multiple studies, and the inflection point (temperature 380 °C, depth 3100 m) captured by the WD-1a well indicates the bottom of the BPT and hypocenter distribution. It was inferred that the hypocenter distribution was concentrated in the shallower area than the BPT isothermal surface at 380 °C.

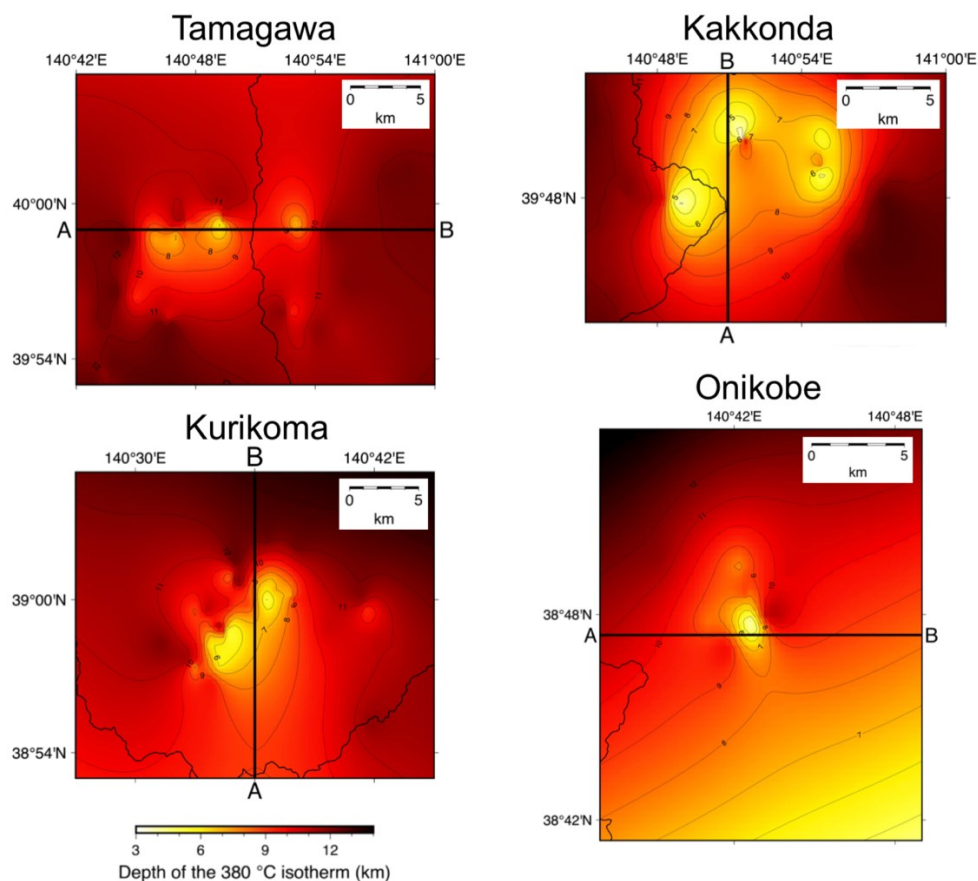


Figure 2: Map of the depth of the 380 °C isotherm in the Tamagawa hot spring area, Kakkonda area, Kurikoma area, and Onikobe area.

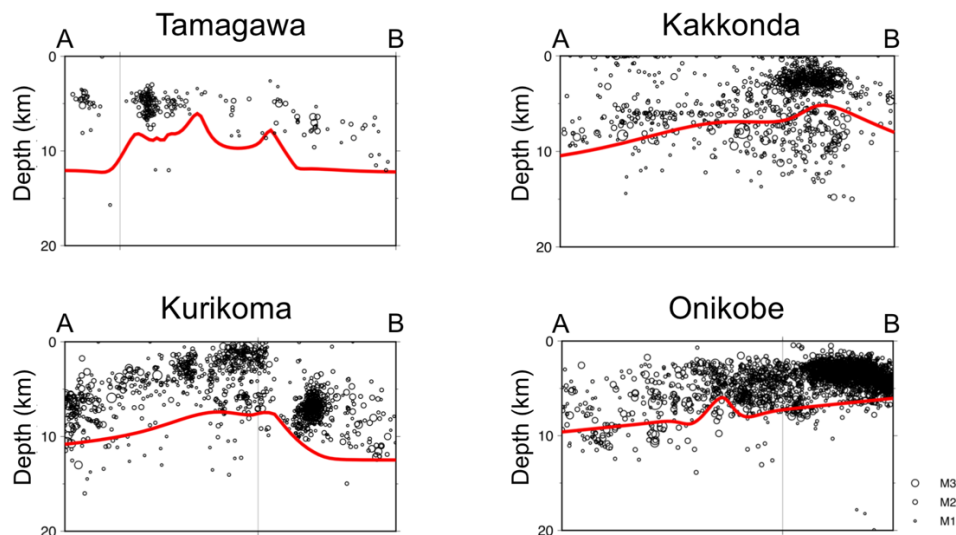


Figure 3: Comparison between the 380 °C isotherms and seismicity on cross sections in the Tamagawa hot spring area, Kakkonda area, Kurikoma area, and Onikobe area. Red lines show the 380 °C isotherm and open circles show epicenters of earthquakes enlarging the diameter with magnitude.

Figure 2 shows the distribution of the isothermal surface at 380 °C estimated in the Tamagawa hot spring area, Kakkonda area, Kurikoma area, and Onikobe area; and the cross-sectional views created along the lateral lines described in the plan of each area. The white circle indicates the location of the hypocenter enlarging the diameter with magnitude. The seismic data used was the M1 or higher-magnitude earthquakes, which occurred during the 1997–2018 period. The seismic data of the JMA unified source catalog has been improving annually in terms of the accuracy in determining the location of the source, especially the velocity structure used since 2003. Therefore, Figure 4 (b) is compared with the estimated isotherm at 380 °C using only earthquakes that occurred in the period from 2003 to 2018. The hypocenter determination was made after 2003, and the result of using only data with high hypocenter determination accuracy is more strongly correlated with the isothermal distribution at 380 °C. The earthquakes whose hypocenters were determined in the period from 2003 to 2018, and the one with an accuracy of less than 1 km in depth direction, are plotted in Figure 4 (c). In this result, the correlation with the estimated isotherm depth at 380 °C becomes stronger. The results of the above three patterns are summarized in Figure 4, which contains data on earthquakes that occurred in 1997–2018, 2003–2018, and 2003–2018, and data of hypocenter determination accuracy of less than 1 km in depth direction. The ratio of earthquakes that occurred in the deeper part from the estimated isothermal surface at 380 °C was compared in three ways. It was found that the proportion of earthquakes that occurred deeper than the isothermal surface at 380 °C, where the “best” was estimated, was small. This implies that the estimated three-dimensional thermal structure reflects the actual thermal structure with high accuracy, and that the isothermal surface at 380 °C indicates the hypocenter distribution, fault zone, and bottom of the hydrothermal convection. This result provides important information not only for conventional geothermal development but also for supercritical geothermal development.

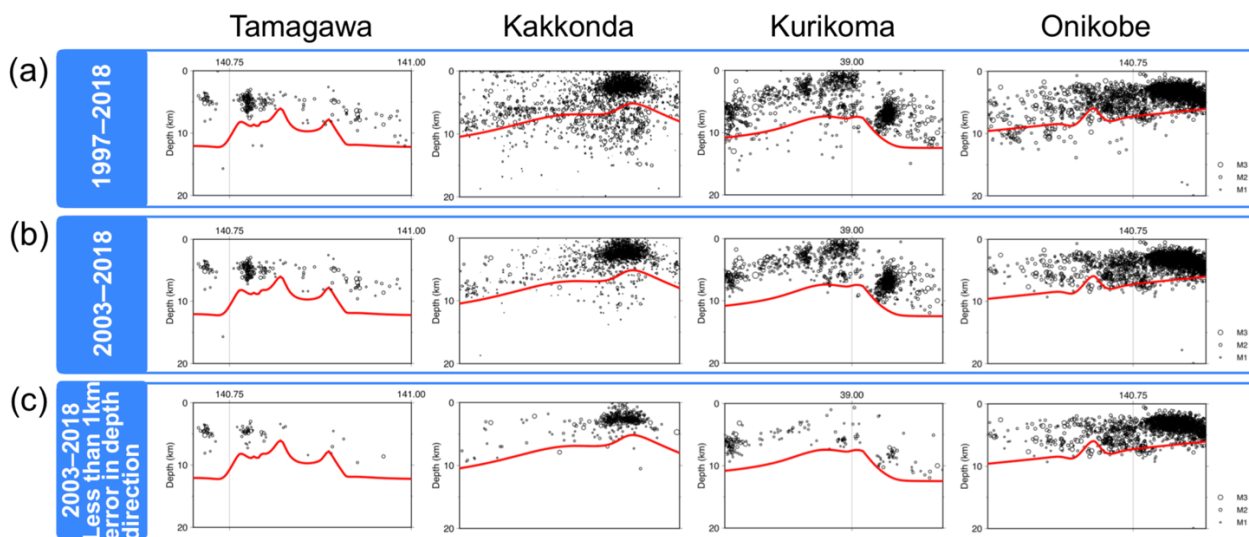


Figure 4: Comparison between the 380 °C isotherms and seismicity depth data: (a) event occurred in 1997–2018; (b) event occurred in 2003–2018; (c) event occurred in 2003–2018 and data of hypocenter determination accuracy of less than 1 km in depth direction.

5. CONCLUSIONS

A strong correlation was found between the isothermal distribution at 380 °C estimated using the activity index and the hypocenter distribution in the main geothermal area of the Tohoku region. This result suggests that the isothermal surface at 380 °C estimated from the activity index indicates the BPT, which is the boundary where hydrothermal convection and shallow earthquakes occur, in the main geothermal area of the Tohoku region. Moreover, since it is assumed that supercritical geothermal resources in Japan will be located just under the BPT, the isothermal distribution at 380 °C obtained in this study can be an effective indicator for estimating the set depth of supercritical geothermal resources.

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