THERMAL GRADIENT *MAP* AND THERMAL MODEL OF THE JAPANESE ISLANDS

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SUMMARY - The thermal structure of the Japanese Islands is estimated based on geothermal gradients from temperature logging data of 1943 drillholes and a temperature-depth diagram obtained from a deep drillhole at the Kakkonda geothermal field. The temperature-depth diagrams in non-volcanic areas represent conductive heat transfer and low geothermal gradient values less than 50 K km^{-1}, indicating lack of local and shallow heat sources. On the other hand, a deep drilling at the Kakkonda field reveals a hydrothermal convection of active volcanic areas, which cools local and shallow heat sources. Several small partial melting zones must lie at the depth of several kilometers, generating a complex geothermal structure. A conductive zone appears at an outer-margin of the melting zone. The heat is transferred upward at a high rate through the conductive zone and the overlying hydrothermal convection zone.

1. INTRODUCTION

Extensive observations of the Japanese Islands in the past reveal that the heat flow variation is related to the distance from the trench axis and forms linear high anomalies over volcanic chains and low zones over forearc basins (Uyeda and Horai, 1964; Yamano, 1995). Chains of active volcanoes mark high heat flows reaching 140 mWm^{-2} (Nagao and Uyeda, 1995). On the contrary, heat flow values of the forearc regions are 30 - 50 mWm^{-2}. The backarc basins represent intermediate values of about 100 mWm^{-2} (Yasui *et al.*, 1968). Such variation is interpreted as created by characteristic crustal thermal structures of islandarcs associated with the subducting oceanic plate and mantle wedge (eg., Honda, 1985; Furukawa and Uyeda, 1989).

Recently, many thermal data have been collected from exploration of hot springs and geothermal areas (Yano et *al.*, 1999). These activities have given us valuable geothermal data leading to intensive data coverage in the Japanese Islands. They compiled the data to make a map of the geothermal gradient of the Japanese Islands. Over non-volcanic regions, simple assumptions can produce a first-order estimate of the geothermal structure that may lead to an improved understanding of the geothermal system of island arcs (Okubo et *al.*, 1998).

On the other hand, as often observed, geothermal structures over active volcanoes are complex. Consequently, the thermal convection reflects disturbances in observed temperature-depth curves. Deep drilling at the Kakkonda geothermal field reveals a thermal structure over an 'activegeothermal field The new observational evidence gives us an outline of large hydrothermal convection system above a heat source, such as a magma.

In this paper, based on the compiled thermal data and the thermal structure revealed by the deep drilling, we discuss the geothermal structure of the Japanese Islands.

2. COMPILATION AND MAPPING OF TEMPERATURE DATA

The past temperature logging data of 1943 drillholes, whose depths are greater than 300 m, were compiled in Japan (Yano *et al.*, 1999). The number of drillholes is 1943. The maximum frequency appears in the depth range between 1000-1500 m. The second frequency is in the depth between 500-1000 m.

The geothermal gradient was determined by the temperature difference between the bottom and the surface of drillhole. The surface temperatures were estimated based on the average of ambient atmospheric temperatures, which vary in the range between 10 ℃ and 20 ℃.

Figure 1 is the geothermal gradient map of the Japanese Islands based on the gradients calculated as above. Although the data density in volcanic areas are high, there are several areas with sparse data in the forearc non-volcanic areas. These areas are, for example, the central part of Hokkaido, eastern Tohoku, southern Shikoku, and eastern Kyushu.

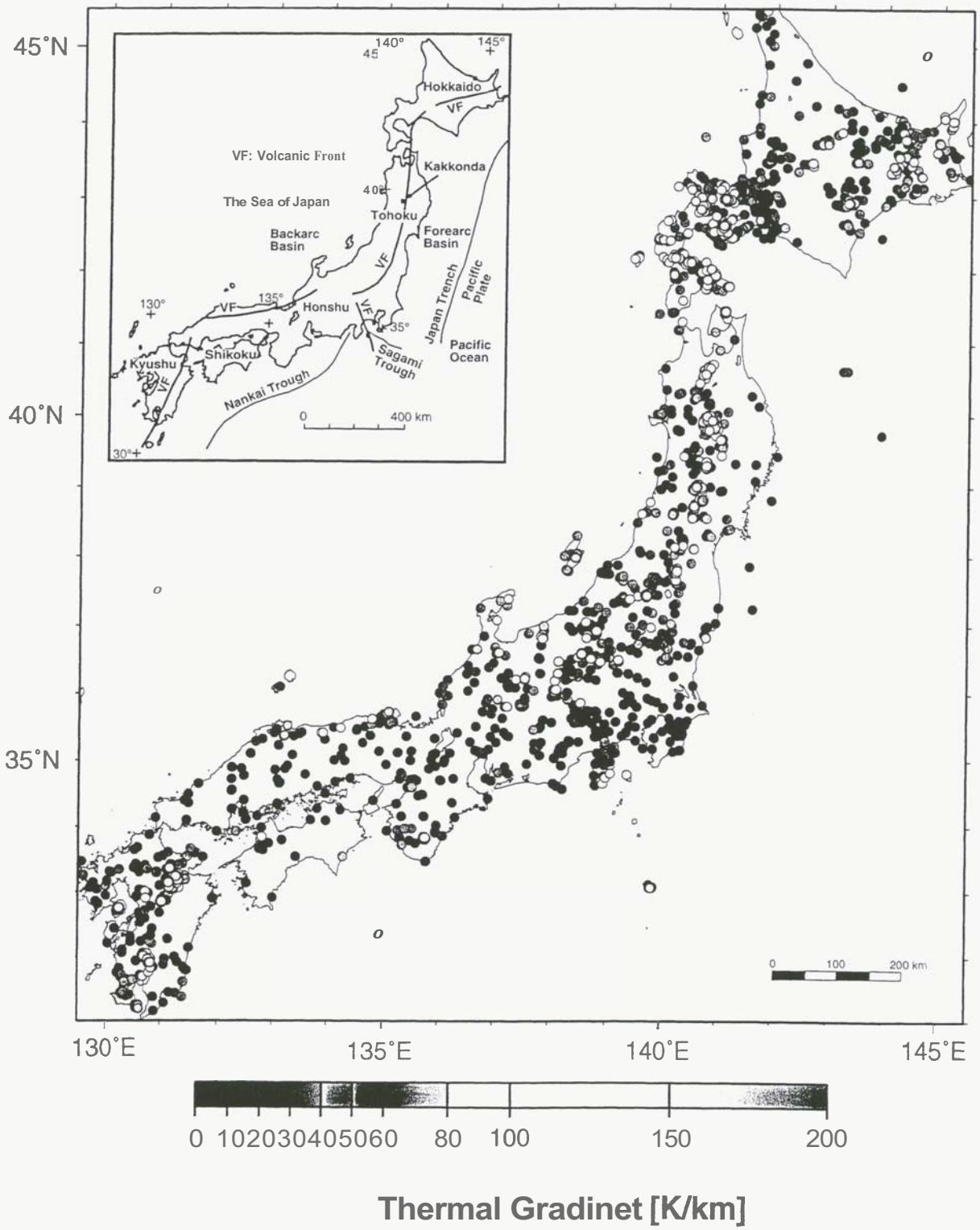

Figure 1- Geothermal gradient map of the Japanese Islands (Yano et *al.*, 1999).

The temperature-ckpth diagram of a non-volcanic area, which exhibits a conductive heat flow regime, forms an almost straight line (Fig. 2 (a)). However, a hydrothermal convection, which often appears in active geothermal fields and produces up- and down-flows, yields disturbances to the straight line (Fig. 2 (b), (c)). It is believed that magma bodies induce large-scale motions of groundwater in the surrounding rocks. In this case, the approach based on the steady state model must yield wrong interpretations. We discuss the thermal structures separately based on evidences of deep drill-holes of the Kakkonda geothermal field.

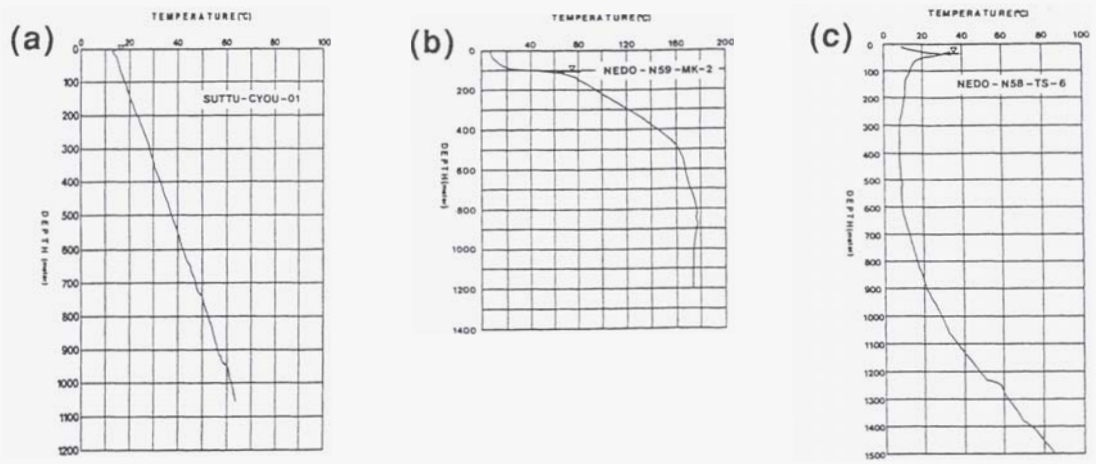

Figure 2- Typical temperature-depth curve.
(a) Conductive pattern, a typical pattern in non-volcanic areas. (b) Up-welling pattern observed in an active geothermal field. (c) Down-going pattern observed in an active geothermal field.

3. THERMAL STRUCTURE OF VOLCANIC AREA

A deep drill-hole at Kakkonda geothermal area (see Fig. 1) reveals one of typical thermal structures in active geothermal fields (Muraoka *et al.*, 1998). The temperature-ckpth diagram in the range between the ground level and about 3100 m in depth marks a typical hydrothermal convection above a heat source. The curve is close to the boiling curve of water. The curve reaches about 380 ℃ at the depth of 3100 m (Fig. 3), which is around the critical point of water. The temperature-depth curve below the convection zone turns to be a straight line. The thermal gradient of the line is about 280 K km^{-1}. The ambient rock of this zone is a Quaternary plutonic body named the Kakkonda granite (Muraoka *et al.*, 1998).

The deep thermal structure, which is interpreted to be a conductive zone, suggests high heat flows. Thermal conductivity of granite rocks at 500 ℃ ranges around 2 W $K^{-1}m^{-1}$ (Cermak and Rybach, 1982), therefore, heat flows at the depth of 3100 m is estimated to be 500 - 600 mW m^{-2}.

4. DISCUSSION

Most of the temperature-depth diagrams in forearc and backarc basins mark straight lines, suggesting the conductive heat transfer and the absence of local heat source in the crust. Therefore, the gradient could keep nearly constant to the depth. In forearc basins, the geothermal gradient is mostly less than 30 K km^{-1}. The gradients in backarc basins of inland areas are over 40 K km^{-1}. If we take the thermal conductivity to be 2.5 $Wm^{-1}K^{-1}$, apparent heat flows are over 100 mW m^{-2} in the backard basins. Since observations in the *Sea* of Japan indicate that the average heat flow is around 100 mW m^{-2} (Nagao and Uyeda, 1989), the high gradients of inland areas are inferred to spread extensively toward the Sea of Japan.

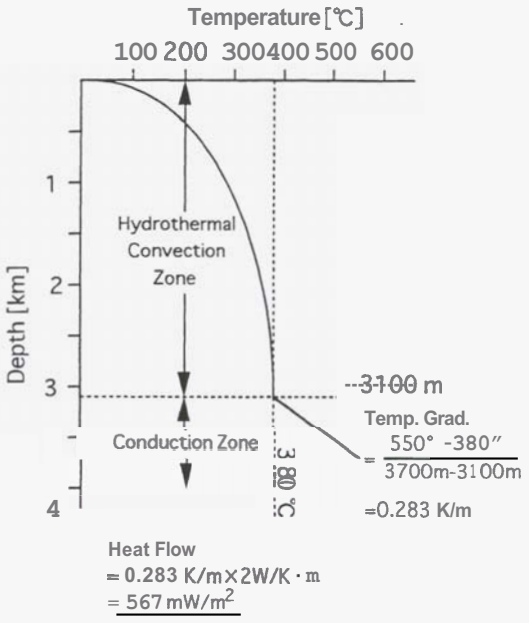

Figure 3- Schematic diagram of temperature-depth curve of the Kakkonda geothermal field.
This diagram is schematically drawn based on the data obtained by the New Energy and Industrial Technology Development Organization and published by Muraoka *et al.* (1998).

The thermal structure of the convective zone must be controlled by a hydrothermal convection which creates a large-scale cooling system. The geothermal

gradients of the deep conductive zone of the Kakkonda granite are much greater than 200 K km^{-1}. Extrapolation of the high thermal gradient indicates existence of partial melting zone at the depth of several kilometers below the surface, and consequently, the Kakkonda granite at depth is interpreted to be a heat source of the high heat flow. Several deep drillings at the Kakkonda geothermal field suggest that the horizontal scale of heat source is less than 10 km (Muraoka *et al.*, 1998). The hydrothermal convection, which the temperature-depth curve reflects, must transfer the heat upward from the source.

Figure 4 represents an interpreted thermal cross-section across the Japanese Islands. In backarc basins, the 350 ℃ isotherm lies at the depth of 10 km and 580 ℃ is around 15 km. In the forearc basins, the 350 ℃ isotherm deepens to 20 km and the 580 ℃ isotherm is much deeper than 20 km.

In active volcanic areas, several small partial melting zones must lie at the depth of several kilometers, generating a complex geothermal structure. Conductive zone must appear just above the melting zone and hydrothermal convection behaves to cool the heat sources. The thermal structure above the partial melting zone must be controlled by the above mechanism (Fig. 4).

The Curie point depth is the transition boundary of magnetic rocks at which crustal temperature reaches the Curie point of the dominant magnetic minerals, probably titanomagnetite with a Curie temperature of 580 ℃ or less (Nagata, 1961). The map of Curie point depth obtained by the spectral analysis of magnetic anomalies expresses the distribution of temperature (e.g. Bhattacharyya and Leu, 1975).

several studies suggest a close relationship between seismic activity and the thermal structure (e.g. Smith *et al.*, 1974). Seismic activity in the crust is largely confined to the upper crust. Laboratory experiments of rock deformation suggest that the lower boundary of the seismic zone corresponds to the brittle-ductile transition zone (Brace and Byerlee, 1970). Recent studies reveal that the brittle-ductile transition zone is chiefly controlled by the thermal structure in the island arc (e.g. Ito, 1990).

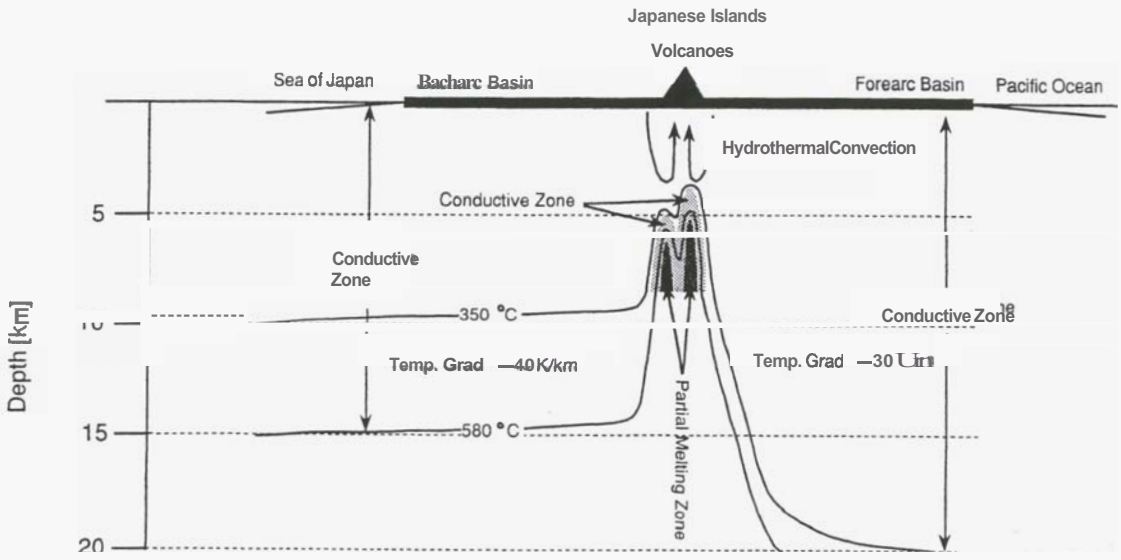

Figure 4- Schematic thermal cross-section across the Japanese Islands.

Comparison of the subsurface temperatures obtained from deep drillholes with seismicity around the drillholes suggest that the temperature at the depth of seismic lower boundary ranges 300 - 350 ℃ (Kobayashi *et al.*, 1997). Therefore, the map of 350 ℃ isotherm could correspond to the depth of seismic lower boundary. Shallow 350 ℃ isotherm depths, 5 km or less, are expected to be in volcanic areas and deep areas lie mainly in non-volcanic areas (Fig. 4).

5. CONCLUSIONS

A high density data coverage delineates a general conductive thermal structure of non-volcanic areas, wheregeothermal gradients are mostly less than 50 K km^{-1}.

A first-order estimate suggests that the 350 ℃ isotherm lies at the depth of 10 km and the 580 ℃ isotherm is around 15 km in the backarc basins. In the forearc basins, the 350 ℃ isotherm deepens to 20 km and the 580 ℃ isotherm is much deeper than 20 km.

Deep drilling reveals a model of hydrothermal convection of active volcanic areas. Several small partial melting zones must lie at the depth of several kilometers, generating a complex geothermal structure. A conductive zone appears just above the melting zone and the hydrothermal convection takes a role of cooling system for the heat sources. Shallow 350 ℃ isotherm depths, 5 km or less, are expected to be in the volcanic areas.

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