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Temperature distribution and focal depth in the crust of the northeastern Japan

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The thickness of seismogenic crust layer correlates with surface heat flow in most interplate seismic areas of the world (e.g., Sibson, 1982). Although the inverse relationship between heat flow and the base of seismogenic zone is obvious, the quantitative relationships are less certain and there should be variability of the focal depths among different tectonic settings. Comparisons of the heat flow (Yamano *et al.*, 1997), thermal gradient (Tanaka *et al.*, 1999) and earthquake (Japan Meteorological Agency, JMA) databases for the northeastern Japan provide detailed geologic and geophysical information about the earthquake process of island arc. Temperatures in the crust were calculated using a steady-state, one-dimensional, heat conductive transport model with heat generation as a function of heat flow and thermal gradient. The evaluated temperatures for D_{90}, the depth above which 90% of earthquakes occur, range between 200°C and 500°C except for high heat flow and thermal gradient data. The consistency of temperature for D_{90} over a large depth interval supports that the temperature is the dominant factor governing the focal depth in the crust.

1. Introduction

Temperature has long been regarded as an important variable in determining the seismogenic portion of the lithosphere. Sibson (1982) and others highlighted the general correlation of shallow seismicity with high heat flow and deep seismicity with low heat flow. However, the quantitative relationships are less certain. Heat flow measurements are often widely spaced, requiring an extrapolation of the data to estimate the thermal structure in the crust in some regions. The uncertainties associated with these extrapolations preclude improving on the general correlation between heat flow and depth of seismicity. A new compilation of thermal gradient data around Japan (Yano *et al.*, 1999; Tanaka *et al.*, 1999) yields indirect information about the shallow thermal structure. These new thermal gradient data increase our understanding of the relationship between the thermal regime and the depth limit of seismicity in the crust.

In this paper, we compile, assemble and interpret thermal data beneath the northeastern Japan where both thermal data and seismicity data are relatively well known, in an effort to understand the variations in the thermal regime within the crust. We also estimate the thermal structure of the crust from heat flow and thermal gradient data and compare it with the shallow seismicity.

2. Distributions of Data

Ueno *et al.* (2002) relocated hypocenters of Japan Meteorological Agency (JMA) Earthquake Catalog. We used this re-determined data for the hypocentral distribution. We selected well-determined shallow crustal earthquakes with depth shallower than 20 km and magnitude greater than 1 recorded more than 10 stations between October 1997 and January 2002 and eliminated low-frequency events (Fig. 1(a)). Using this JMA data, the earthquake focal depths are evaluated the depth above which 90% of earthquakes occur, D_{90} (e.g., Doser and Kanamori, 1986). We compared this dataset with well-determined focal depths by Tohoku University (Hasegawa and Yamamoto, 1994; Hasegawa *et al.*, 2000). We could not find the difference in D_{90} between Tohoku University and JMA, even though the observation period is different from that of JMA.

Terrestrial surface heat flow studies and their relationships to other geophysical parameters provide useful insights into the thermal state of the crust. Although the general features of the heat flow distribution in and around Japan had been revealed by the early 1970s (e.g., Uyeda, 1980), the distribution of heat flow measurements from the recent data compilation (Yamano *et al.*, 1997) is often insufficient to define regional thermal structures (Fig. 1(b)). On the other hand, a new compilation of thermal gradient data around Japan (Yano *et al.*, 1999; Tanaka *et al.*, 1999) yields indirect information about the shallow thermal structure (Fig. 1(c)). This dataset is based on borehole temperature measurements. Thermal gradient was calculated from the difference between the temperature at the bottom of each borehole or the maximum temperature in the borehole and the average surface temperature. Although they have used the borehole data of 300 m or more in depth, below the transient effects of surface temperature variations and below the groundwater infiltration zone, their thermal gradient data have less accuracy than heat flow data. However, the number and distribution of thermal gradient data is more and wider than heat flow data, and it may be possible to estimate more detailed shallow thermal structure using thermal gradient data.

Figures 2(a) and (b) represent North-South and East-West

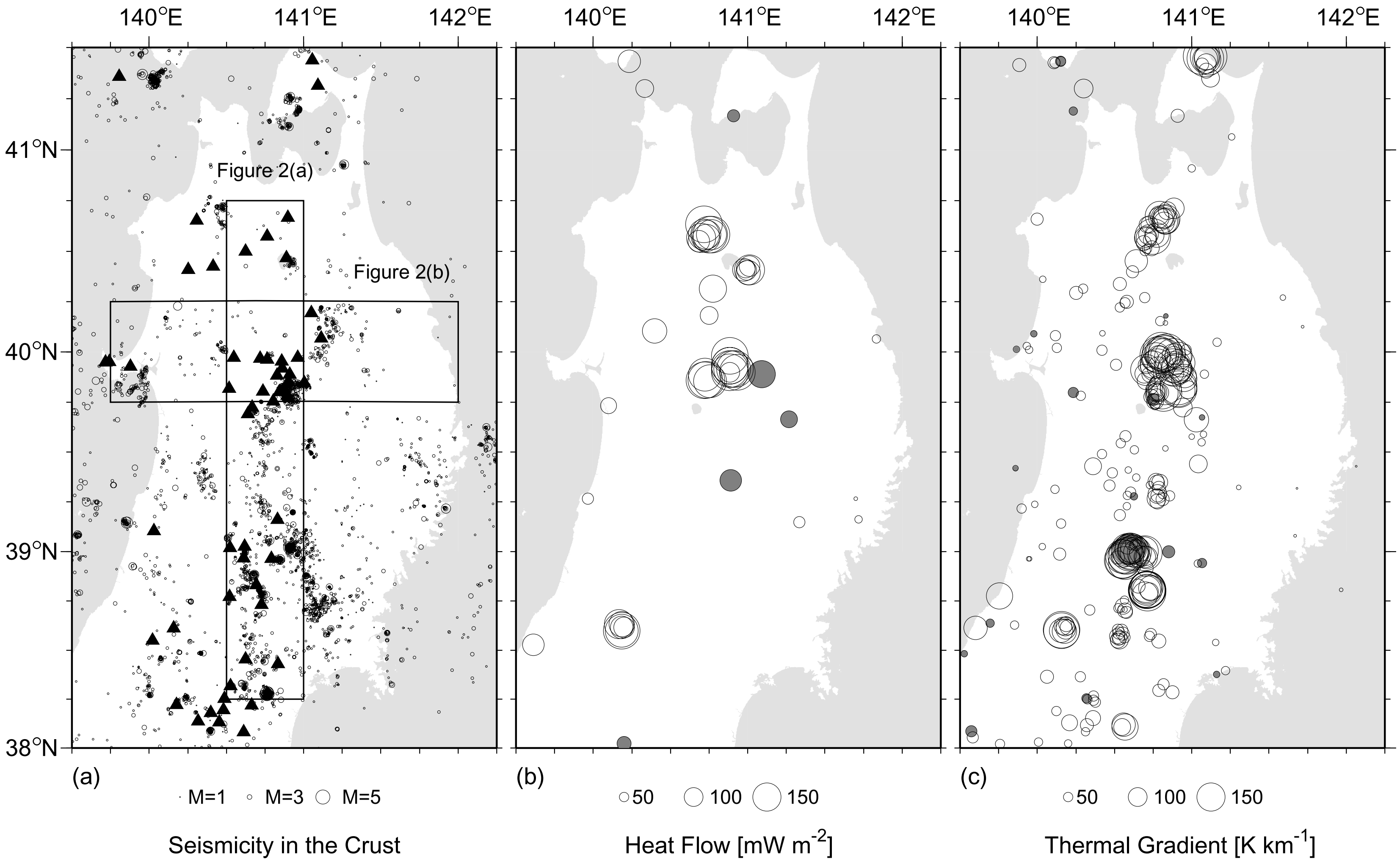

Fig. 1. The distribution of (a) epicenters of shallow earthquakes (1 km ≦ depth ≦ 20 km) (Ueno *et al.*, 2002), (b) heat flow (Yamano *et al.*, 1997) and (c) thermal gradients (Yano *et al.*, 1999; Tanaka *et al.*, 1999) for the northeastern Japan. Mercator projection is used. (a) The hypocentral distributions for the period from October 1997 to January 2002 by the seismic network of Japan Meteorological Agency (JMA). The rectangles show locations of Fig. 2. The diameter of each circle is proportional to the magnitude. Solid triangles show active volcanoes (Committee for Catalog of Quaternary Volcanoes in Japan, 1999). (b) (c) Circle sizes are proportional to the magnitudes of heat flow and thermal gradient data. Solid gray circles are used in Fig. 3.

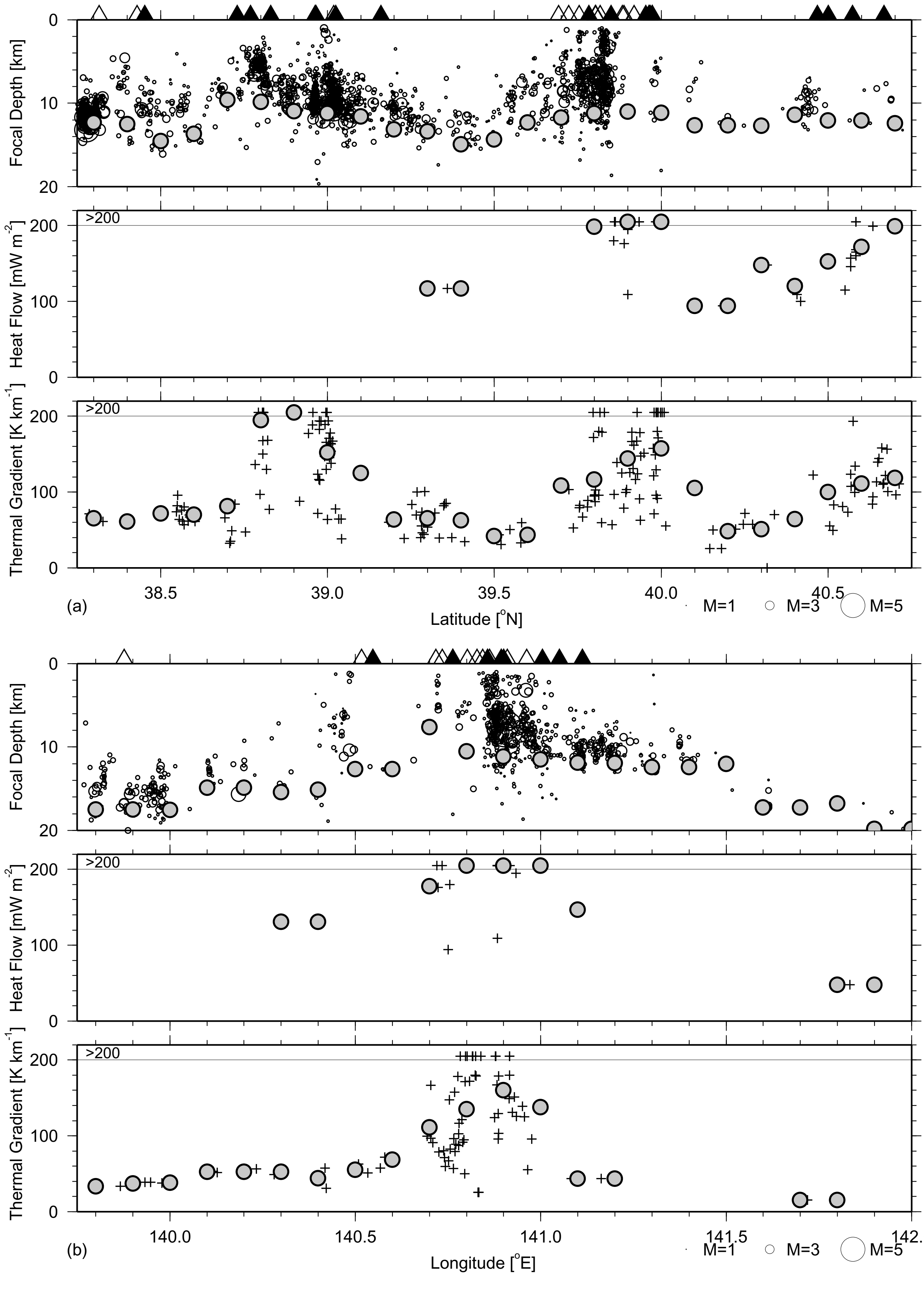

Fig. 2. (a) Cross-section of epicenter (Ueno *et al.*, 2002), heat flow (Yamano *et al.*, 1997), and thermal gradient (Yano *et al.*, 1999; Tanaka *et al.*, 1999) distribution within a distance of 0.25° across the northeastern Japan along longitude 139.75°N. Solid and open triangles on the top denote active volcanoes with volcanic products of greater and less than 10 km^3, respectively (Committee for Catalog of Quaternary Volcanoes in Japan, 1999). Gray circles show D_{90} (upper) and moving averages of heat flow (middle) and thermal gradient (lower) every 0.1°. (b) Cross-section along latitude 40°E. Same conventions as in Fig. 2(a).

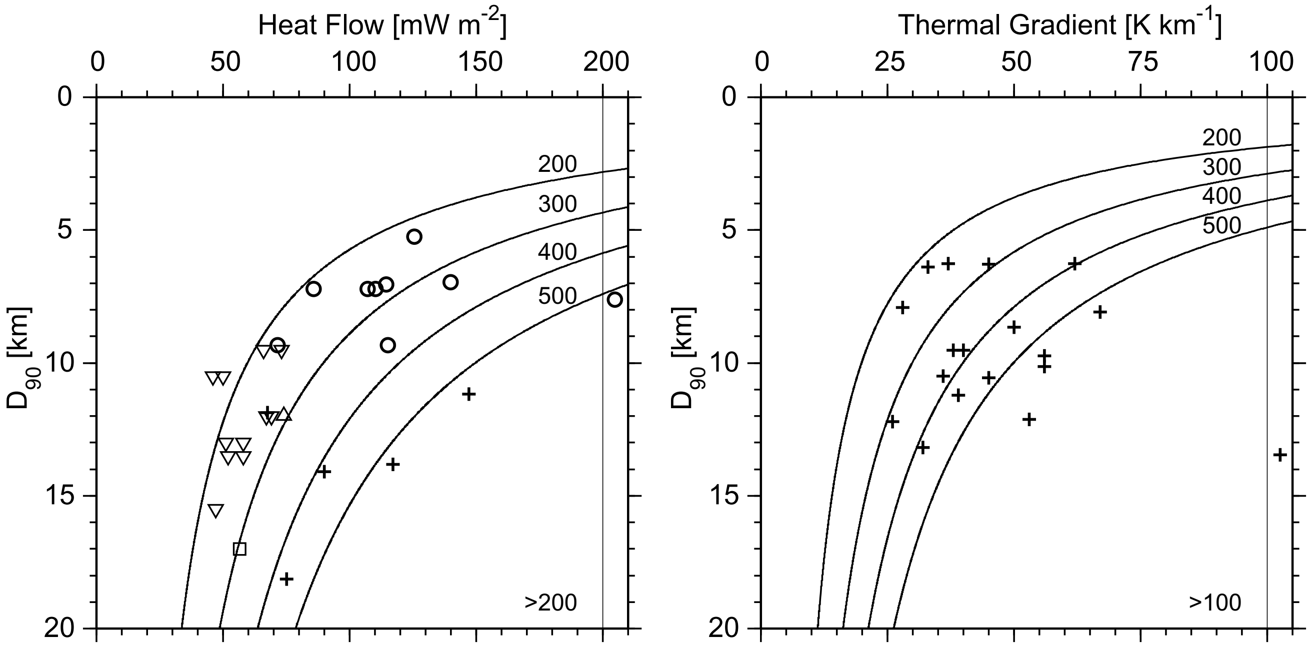

Fig. 3. Plot of D_{90} against heat flow and thermal gradient data in the northeastern Japan, indicated by crosses. Estimated isotherms of 200°C to 500°C are shown by solid lines. Previous data since 1990 for heat flow data against maximum focal depth of crustal earthquakes or D_{95}, the depth above which 95% of earthquakes occur, are also plotted. Seismic and heat flow data are: triangle for KTB (Zoback *et al.*, 1993), inverted triangles for Landers faults (Williams, 1996), square for Nojima fault (Kitajima *et al.*, 2001), circles for the western Nagano Prefecture area (Tanaka and Ito, 2002).

vertical cross-sections in the northeastern Japan, respectively. Figure 2 shows focal depths (upper), heat flow (middle), and thermal gradients (lower) within boxes shown in Fig. 1(a). Gray circles are moving averages of heat flow and thermal gradient data every 0.1° with 0.2° intervals. D_{90} are calculated using focal depths every 0.1° with 0.2° intervals shown by gray circles. D_{90} and averages of heat flow and thermal gradient data are well correlated, although there are some data gaps, especially in heat flow data.

Figure 2(a) shows the cross-section almost along the volcanic front. The depth limit of earthquakes is about 15 km or less, and it changes remarkably with location. It is locally shallow as 10 km beneath active volcanoes, indicated by triangles in Fig. 2. Although the resolution of thermal structure by heat flow data is often hindered by a lack of data, heat flow and thermal gradient data well correlate with D_{90}. At almost the same area of Fig. 2(a), Hasegawa *et al.* (2000) estimated the temperature distribution within the crust from P wave velocity perturbations. Their results are coincident with ours. On the other hand, Fig. 2(b) shows the cross-section almost across the volcanic front. Heat flow and thermal gradients around trench side, the east side, are low, whereas those around the volcanic front are significantly high with large scatter. It is clear that to use thermal gradient data will increase our understanding of the relationship between thermal regime and D_{90}.

3. Temperatures in the Crust

In one-dimensional steady-state case under assumptions that the direction of the temperature variation is vertical, Fourier's law takes the form,

$$k\, d^2T/dz^2 = -A(z)$$

where T is the temperature, k is the thermal conductivity, and A is the heat production. Radioactive heat generation cannot be neglected, in calculating the temperatures of a continental-type crust. It has been suggested that radioactive heat generation decreases exponentially with depth in the continental crust (Lachenbruch, 1970). In this case, the temperature is given by

$$T = T_0 + ((q_0 - Az_1)/k)\, z + \left(Az_1^2/k\right)(1 - \exp(-z/z_1)) \quad (1\text{-}1)$$

$$T = T_0 + (\Delta T/\Delta z - Az_1/k)\, z + \left(Az_1^2/k\right)(1 - \exp(-z/z_1)) \quad (1\text{-}2)$$

where q_0 is the heat flux and $\Delta T/\Delta z$ is the thermal gradient. Thermal conductivities, k, of continental rocks ranges from 1–5 $\mathrm{Wm^{-1}K^{-1}}$ (Stein, 1995) and heat production, A, of average continental upper crust is 1.0 $\mu\mathrm{Wm^{-3}}$ (Fowler, 1990). The characteristic thickness of the layer enriched in radioactive elements has been estimated to be about 10 km. The average temperature of ground surface all over Japan is about 13.51°C (National Astronomical Observatory, 1998). We estimate the temperature using the following values, $T_0 = 13.51$°C, $k = 3\ \mathrm{Wm^{-1}K^{-1}}$, $A = 1.0\ \mu\mathrm{Wm^{-3}}$, $z_1 = 10$ km. Thermal gradient data does not include information about thermal conductivity and lithology, unfortunately. However, it may be reasonable to use the same values as heat flow data and thermal gradient data, in case of deep reliable borehole data.

4. Discussions and Conclusion

Figure 3 shows the correlation of D_{90} with heat flow and thermal gradient values. The inverse relationship between heat flow or thermal gradient and D_{90} is obvious. We choose heat flow data that has information about thermal conductivity and thermal gradient data whose standing time of longer than 6 hours and depth of deeper than 1000 m. We calculate D_{90} using seismic events within a distance of 0.05°. We estimate the temperatures using heat flow data (Eq. (1-1)), and thermal gradient data (Eq. (1-2)). The estimated temperatures are shown as isotherms in Fig. 3. Variations in the evaluated temperatures for D_{90} range between 300°C and 500°C in case of heat flow data. We also plot the previous studies in various regions in Fig. 3(a). Compilation of our results and previous studies show that the evaluated temperatures for D_{90} range between 200°C and 500°C with some exceptions, although isotherms change depending on assumed equations and parameters. It is shown that the temperatures are higher in the northeastern Japan. It may result in the geological context. We used heat flow data in the areas where Late Oligocene volcanic and sedimentary rocks cover pre-Tertiary basement rocks and are overlain by Quaternary volcanic rocks (Editorial Committee for the Geology of the Japanese Islands, 2002).

In case of thermal gradient data (Fig. 3(b)), most of the evaluated temperatures for D_{90} range between 200°C and 550°C except for some exceptions. Figure 3(b) shows considerable scatter, although D_{90} diminish with decreasing thermal gradient data. Our data shows higher temperature, and this may be explained in lithology of this area. Very high thermal gradient values may not reflect the thermal structure in the crust and may reflect the thermally significant fluid flow and volcanic and geothermal activities. Another reason for this discrepancy comes from the estimation of D_{90}. We used the seismic events within a distance of 0.05° and this distance cannot reflect a locally shallow focal depth. In some areas, sparse seismicity of the target area offers little information.

Thermal data with seismicity catalogues of re-determined and well-located events can be used to investigate the thermal influence on the depth extent of seismicity in the crust. We compile a data set of D_{90} versus corresponding heat flow and thermal gradient data. Although it is difficult to estimate the absolute values of the D_{90} temperature, the consistency of temperature for D_{90} over a large depth interval supports that the temperature is the dominant factor governing the focal depth in the crust. It also suggests that the pattern of the heat flow and thermal gradient data is useful as an index of the thermal structure in the crust and D_{90}. A comparison of our results with other tectonic regions could provide evidence for variations in temperatures for D_{90}.

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