Research Notes of the National Research Center for Disaster Prevention, No. 21, March 1976

550.361:550.343:551.24(521.2)

Terrestrial Heat Flow At The Iwatsuki Deep Well Observatory And Crustal Temperature Profiles Beneath The Kanto District, Japan

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Abstract

Terrestrial heat flow at Iwatsuki in the Kanto plain is determind. The average value of the observed heat flow at different depths in the deep borehole is 0.56×10^{-6} cal/cm^2 sec. Based on the existing heat flow data for the Kanto district, the vertical distributions of crustal temperature are estimated. The estimated temperature at the Moho discontinuity beneath the mountainous part of the Kanto district (about 35-km depth) is about 900 °C, and that beneath the plain part (about 30-km depth) is about 300 °C. Most microearthquakes are concentrated around the 60-km depth beneath the central region in the Kanto plain. The estimated temperature at this depth is about 400 °C. On the other hand, microearthquakes are concentrated around the 15-km depth beneath the mountainous part, where the estimated temperature is also about 400 °C. This fact might suggest that the microearthquake is closely related to the temperature, about 400 °C, of the earth's interior.

1. INTRODUCTION

The value of the terrestrial heat flow gives important informations concerning the thermal structures of the crust and uppermost mantle. Systematic measurements of the heat flow in and around the Japanese Islands have been made since 1957 by Uyda et al. (1958). In the Kanto district, nine measurements were made and reported by Uyeda and Horai (1964). Characteristic features in the distribution of the heat flow values in this district are that (1) the eastern part (the plain part) of the district has low heat flow ($<1.0 \times 10^{-6}$ cal/cm^{2}sec) and (2) the western part (the mountainous side) has high heat flow ($\sim 2.0 \times 10^{-6}$ cal/cm^{2}sec).

In the present paper, terrestrial heat flow datum at Iwatsuki in the Kanto district is measured. Based on these heat flow data in the Kanto district, the vertical temperature distributions in the crust beneath the eastern and western parts of this district are investigated.

2. SITUATION OF THE MEASURED POINT

A borehole (3500 m deep) at Iwatsuki City was used for the measurements of temperature gradient. This was bored for observation of crustal activities (earthquakes and ground tilt) during the period from 1970 to 1971 (Takahashi and Hamada, 1975). This borehole is situated in the central part of the Kanto plain (35°55′N, 139°44′E), where the thickness of the Quaternary and Tertiary sediments amounts to about 2900 m as shown by the columnar diagram on the right-hand side of Fig. 1.

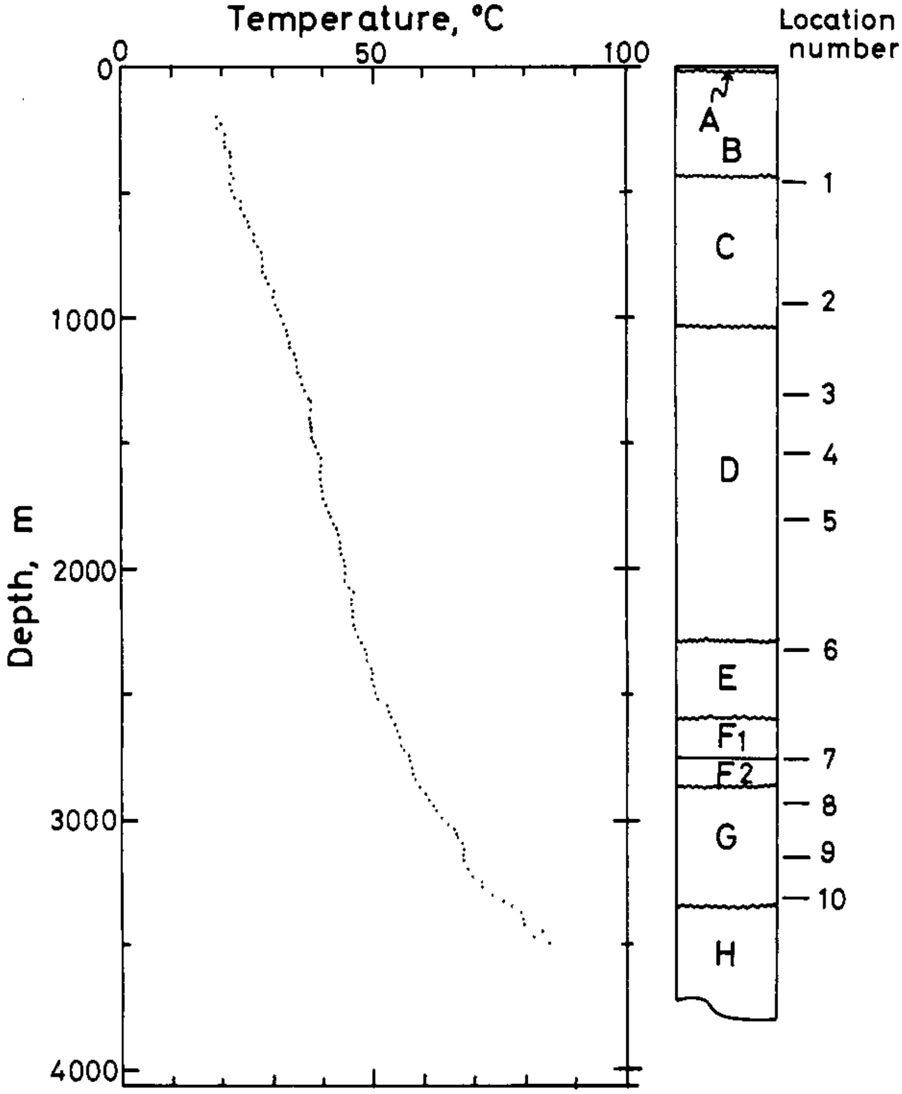

Fig. 1. Temperature-depth profile in the borehole at the Iwatsuki observatory. The temperatures averaged for 10 meters of depth are plotted.
A: Yurakucho F. (clay); B: Narita G. (conglomerate, sandstone); C: Kazusa G. (congl., sandst.); D: Tokigawa G. (congl., sandst.); E: Fukuda F. (tuffaceous mudstone); F1: Arakawa F. (mudstone); F2: Kozono F. (congl.); G: (quartz porphyry); H: (metamorphic rocks). A and B: Quaternary; C~F: Tertiary; G and H: Pre-Tertiary. (After Takahashi and Hamada, 1975).

3. GEOTHERMAL GRADIENT, THERMAL CONDUCTIVITY AND TRRESTRIAL HEAT FLOW

For estimation of the terrestrial heat flow Q it is required to determine the two quantities, the geothermal gradient dT/dZ (T: temperature, and Z: depth) and the thermal conductivity K of rocks in which dT/dZ has been measured. Q is determined by the relation $Q = K\, dT/dZ$.

3-1. Geothermal gradient

Temperatures at different levels in the borehole were measured by means of a thermistor thermometer by the Teikoku Oil Co. The measurement was carried out after three months from the completion of all constructions related to the borehole, in order to get a stationary state in temperature.

The temperature-depth profile in the borehole is shown in Fig. 1. The columnar diagram in this figure illustrates the variations of the rock types and the formation. The averaged thermal gradients for 200 m were used for the present study. The values of the vertical thermal gradients at different depths are listed in Table 1. The value at the 3324-m depth is extremely high; this may be due to the short distance from the measuring point to the bottom of the borehole, and this value is omitted from calculation.

3-2. Thermal conductivity

Rock specimens were collected at different levels of depth in the borehole for the measurement of thermal conductivity. The thermal conductivity was measured by the needle probe methods for the specimens of sedimental rocks and by the Schröder method for those of quartz porphyry. Each of the specimens was measured in the water-saturated state. The results are listed in Table 1. The specimen of location number 8 was measured by both the methods, and the nearly same values were obtained. The measurements were made by Sumiko Consultants Co.

The thermal conductivity of the specimens of the numbers 8, 9 and 10 have the values lower than the usual one in quartz porphyry. These results will be due to many cracks in the strata from which the specimens were taken.

3-3. Terrestrial heat flow

The heat flow Q is given by $Q = K\, dT/dZ$. The calculated values at different depths are

Table 1. Heat flow at different depths in the borehole at Iwatsuki.

Location number	Depth (m)	Geothermal gradient (deg/100 m)	Thermal conductivity† (10^{-3} cal/m sec deg)	Heat flow (10^{-6} cal/cm^2 sec)
1	452	1.2	3.1*	0.37
2	952	1.7	4.0*	0.68
3	1312	1.5	3.4*	0.51
4	1552	0.92	3.9*	0.36
5	1806	1.7	3.0*	0.51
6	2337	1.9	2.1*	0.40
7	2765	2.0	2.7*	0.54
8	2943	3.2	2.8*+	0.89
9	3163	2.7	2.9+	0.78
10	3324	(5.8)	3.0+	(1.74)
average				0.56

† measured in water saturated state, *needle probe method,
+ Schröder method.

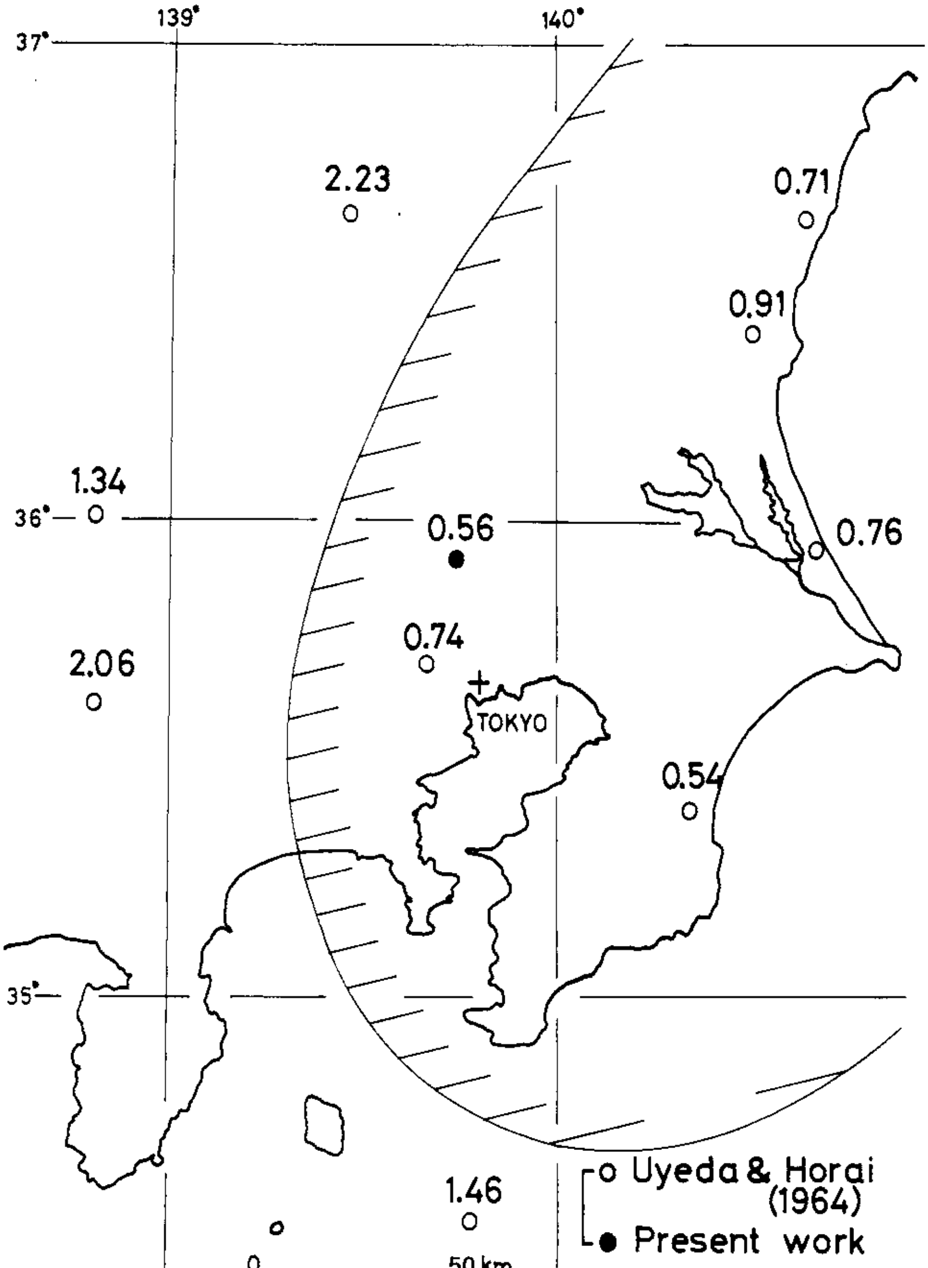

Fig. 2. Distribution of terrestrial heat flow in the Kanto district. Heat flow values are in the unit of 10^{-6} cal/cm^{2}sec. The hatched area shows the low heat flow region ($< 1.0 \times 10^{-6}$ cal/cm^{2}sec).

Table 2. Uranium, thorium and potassium contents in granitic rocks and the rates of total heat production of the rocks in radioactive equilibrium.

Locality	Number of samples	U (ppm) (mean value)	Th (ppm) (mean value)	K (wt.%) (mean value)	Rate of total heat production ($x10^{-13}$ cal/cm^{3}sec)
Kyushu*1	30	2.7	8.1	2.5	3.7
Shikoku*2	21	3.9	10.7	3.1	5.1
Chugoku*3	60	2.7	8.9	3.0	4.0
Hyogo*4	47	2.3	9.0	2.6	3.6
Fukui*5	33	2.6	10.7	3.4	4.3
average					4.1

*1 Katsura et al. (1969), *2 Yagi et al. (1968), *3 Nishimura et al. (1968), *4 Nishimura and Katsura (1969), *5 Katsura and Nishimura (1969).

listed in Table 1. The values of the thermal conductivity used in this caluculation are measured under normal temperature and pressure. Since the pressure and temperature in the borehole cover their small ranges as 1 – 300 bars and 10 – 80 °C, respectively, the effects of the pressure and temperature variations on the value of K are negligible. Therefore, no corrections regarding the pressure and temperature are made in the present study.

The average value of the heat flow in this borehole is obtained as $0.56x10^{-6}$ cal/cm^{2}sec. This value is plotted in Fig. 2 with the results by Uyeda and Horai (1964). The borehole is situated in the area of the anomalously low heat flow defined by Uyeda and Horai. The low heat flow value obtained from this borehole is quite consistent with those by Uyeda and Horai.

4. TEMPERATURE-DEPTH PROFILES BENEATH THE KANTO DISTRICT

4-1. Vertical distribution of heat source in the crust

The exponential distribution of heat production (radioactive elements) is adopted as

$$A(Z) = A_o \exp(-Z/D) \qquad (1)$$

where $A(Z)$ is the rate of heat production per unit volume at depth Z, A_o the rate of heat production at the surface of the earth, and D the decrement of the exponential function. The relation (1) is supported by the data in the shields or the large old platform areas of Sierra Nevada and eastern United States (Lachenbruch, 1968).

In the state of radioactive equilibrium, the rate of total heat production H of the rocks are derived as

$$H = (6.6\,U^* + 1.7\,Th^* + 2.3\,K^*) \times 10^{-14}\ \mathrm{cal/cm^3 sec},$$

where U^* and Th^* are the contents of uranium and thorium in ppm, respectively, and K^* the content of potassium in weight percentage (Roy et al., 1968).

The concentrations of radioactivity in surface granitic rocks in Japan are listed in Table 2. The values of H are also listed in the same table. Lachenbruch (1968) reported

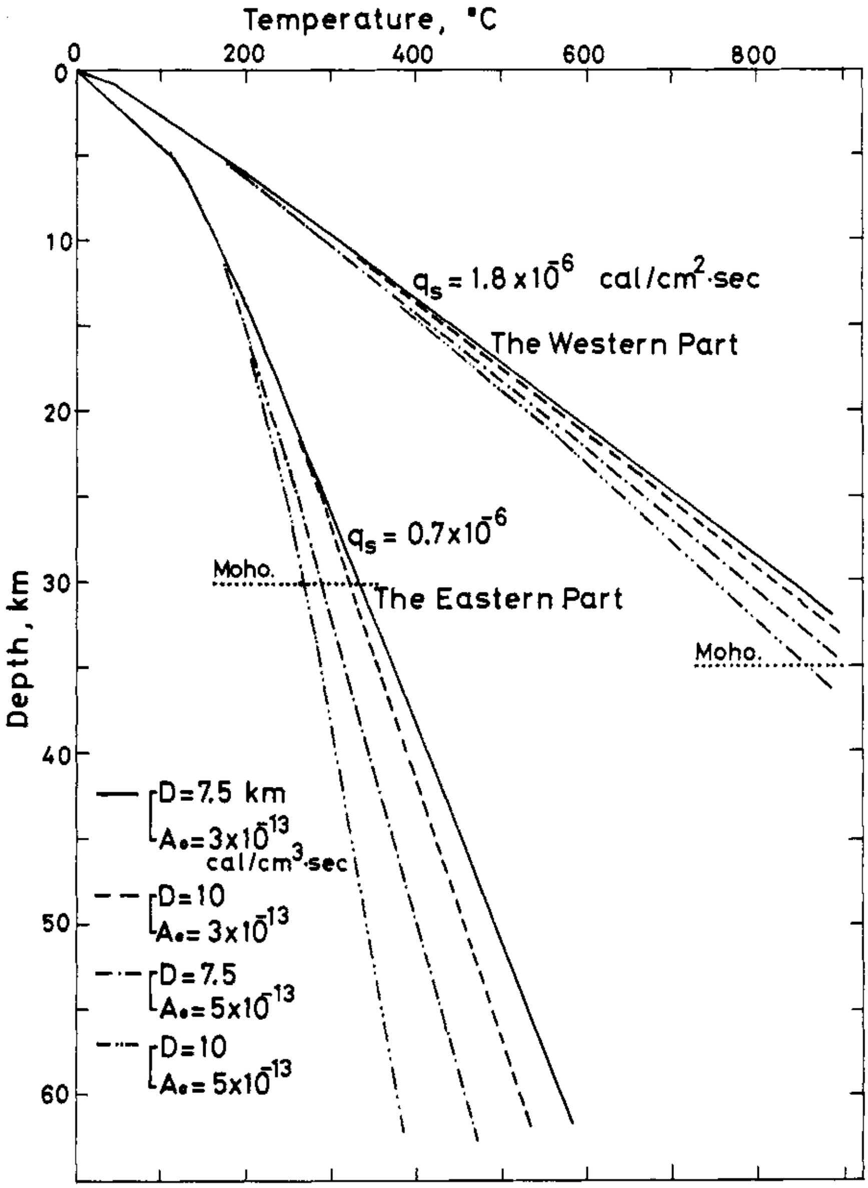

Fig. 3. Temperature-depth profiles in the crust beneath the eastern part and the western part of the Kanto district.

that the values of surface heat production A_o at various locations on the same pluton are varying systematically in relation to the eroded depth. However, in the cases of geologically and geophysically complicated areas as island arcs, the evaluation of the eroded depth is very difficult and ambiguous. Furthermore, we have no data of A_o beneath the Kanto plain. Tentatively, the averaged value of H is adopted as the value of A_o in the Kanto district, that is, $A_o = (3\sim5)\times10^{-13}$ cal/cm^{3}sec. This value is used as the heat production at the top of the granitic layer. The sediments above the granitic layer are assumed to produce no heat.

The value of D in (1) was estimated as 7.5~10 km in the cases of Sierra Nevada and eastern United States (Lachenbruch, 1970). As the values in such geologically complicated areas as Japan have not been clearly known, this value is adopted for the Kanto district, tentatively.

The depths z_o of the top of the granitic layer beneath the eastern and western parts of the Kanto district are estimated as 5 km and 1 km, respectively.

Consequently, the vertical distribution of the rate of heat production $A(Z)$ beneath the Kanto district is expressed as follows:

For $0 \leqq Z < z_o$,

$$A(Z) = 0 \qquad (2)$$

For $z_o \leqq Z <$ ~the depth of the Moho discontinuity,

$$A(Z) = A_o \exp(-(Z-z_o)/D) \; , \qquad (3)$$

where $A_o = (3\sim5)\times10^{-13}$ cal/cm^{3}sec, $D = 7.5\sim10$ km, and $z_o = 1$ km for the western part of Kanto district and $z_o = 5$ km for the eastern part.

4-2. Temperature-depth profiles

When the one dimentional heat flow from the interior to the surface attains a steady state, the vertical temperature distribution $T(Z)$ in the crust is derived from (2) and (3) as follows.

For $0 \leqq Z < z_o$,

$$T(Z) = q_s Z/K_1 \; , \qquad (4)$$

where q_s is the surface heat flow, and K_1 the averaged thermal conductivity of the rocks for $0 \leqq Z < z_o$.

For $z_o \leqq Z <$ ~ the depth of the Moho discontinuity,

$$T(Z) = T(z_o) + q_m (Z-z_o)/K_2 + A_o D^2 (1 - \exp(-(Z-z_o)/D))/K_2 \; , \qquad (5)$$

where q_m is the heat flow below the Moho discontinuity uniformely contribution to the surface heat flow, and is expressed by $q_m = q_s - A_o D$, and K_2 is the averaged thermal conductivity of the granitic layer and the basaltic layer.

The rough values of q_s at the western and eastern parts of the Kanto district are obtained from the values plotted in Fig. 2 as 1.8×10^{-6} and 0.7×10^{-6} cal/cm^{2}sec, respectively. Further, the numerical values of K_1 and K_2 are assumed as 3.5×10^{-3} and 6×10^{-3} cal/cm^{2}sec deg, respectively.

As mentioned in the previous section (4-1), Lachenbruch reported that the value of A_o was not constant in shields or large old platform areas due to erosion and he assumed that

q_m would be constant under these regions. On the other hand, the thermal processes beneath the Japanese Islands are very complicated, and q_m would not be constant. Therefore, we do not use the assumption of constant q_m that Lachenbruch (1968) did. Constant A_o is assumed instead of constant q_m.

Fig. 3 shows a comparison of the vertical temperature distributions in the crust beneath the western part of Kanto district with those beneath the eastern part. The temperatures below the Moho discontinuity have much ambiguity due to the uncertainty of the distribution of heat production in the mantle. This figure shows large differences in temperature between the two regions. For example, the temperature at the Moho discontinuity beneath the western part is about 900 °C, and that beneath the eastern part is about 300 °C.

Kobayashi (1975) pointed out that the temperature at the depth where microearthquakes occurred most frequently was 300~500 °C, beneath the Hokuriku district, the central part of Chubu district, the Mikawa district and the eastern part of Kanto district.

In the Kanto district, most microearthquakes are concentrated around the 60-km depth beneath the central region of the plain part, and around the 15-km depth beneath the western part (Tsumura, 1973). According to the present author's calculation, the temperatures at the depths where the microearthquakes occur most frequently beneath the plain part and the western part of Kanto district have the similar values, i.e. 300~500 °C. This fact might suggest that the microearthquake is closely related to the temperatures of 300~500 °C.

Acknowledgements

The author is very grateful to H. Takahashi and Dr. K. Hamada of the National Research Center for Disaster Prevention for their critical reading of the manuscript, and to Y. Kobayashi (Kanazawa University) for helpful suggestions and discussions. The author is also grateful to M. Takahashi and H. Suzuki of the above-mentioned Center for valuable discussions.

REFERENCES

Katsura, K. and S. Nishimura (1969): Uranium, thorium and potassium content of Kumotaniyama and Mihama granitic bodies. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **62**, 50–53.

Katsura, K., S. Nishimura, S. Yagi, Z. Hatsuda, and T. Asayama (1969): Uranium, thorium and potassium content of rocks in Japan (3); rocks from Kyushu district. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **62**, 90–101.

Kobayashi, Y. (1975): The depth of the microearthquakes, the thermal structure of the crust and the physical properties of the rocks. Abstract for 1975 Meeting of Seismological Society of Japan, No. 1, 139.

Lachenbruch, A. H. (1968): Preliminary geothermal model of the Sierra Nevada. *Jour. Geophys. Res.*, **73** 6977–6989.

Nishimura, S. and K. Katsura (1969): Uranium, thorium and potassium content of Rokko granitic bodies, Hyogo Prefecture. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **62**, 44–49.

Nishimura, S., S. Yagi, K. Katsura, Z. Hatsuda, and T. Asayama (1968): Uranium, thorium and potassium content of rocks in Japan (1); rocks from Chugoku district. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **59** 206–213.

Roy, R. F., D. D. Blackwell and F. Birch (1968): Heat generation of plutonic rocks and continental heat flow provinces. *Earth Planet. Sci. Lett.*, **5**, 1–12.

Takahashi, H. and K. Hamada (1975): Deep borehole observation of the earth's crust activities around Tokyo – Introduction of the Iwatsuki observatory. *Pure Appl. Geophys.*, **113**, 313–320.

Tsumura, K. (1973): Microearthquake activity in the Kanto district, *Publications for the 50th Anniversary of the Great Kanto Earthquake, 1923*. Earthquake Res. Inst., Univ. Tokyo, 67–87.

Uyeda, S. and K. Horai (1964): Terrestrial heat flow in Japan. *Jour. Geophys. Res.*, **69**, 2121–2141.

Uyeda, S., T. Yukutake, and I. Tanaoka (1958): Studies of the thermal state of the earth, the first paper, preliminary report of terrestrial heat flow in Japan. *Bull. Earthq. Res. Inst.*, **36**, 251–273.

Yagi, S., S. Nishimura, K. Katsura, Z. Hatsuda, and T. Asayama (1968): Uranium, thorium and potassium content of rocks in Japan (2); rocks from Shikoku district. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, **60**, 182–190.

(Manuscript received 28 January 1976)

岩槻地殻活動観測井における地殻熱流量及び 関東地方の地殻温度分布

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岩槻における地殻熱流量を算出した．平均値は，0.56×10^{-6}cal／cm²secであった．この値とUyeda and Horaiが得た地殻熱流量の値とから，関東地方の地殻温度分布を推定した．山地と平野部では大きな差のあることが明らかになった．例えば，モホ面の温度は，山地では900°C前後であるのに対して，平野部では300°C程度である．

東京直下では，津村によると微小地震は約60 kmの深さで最も多く起こっている．ここの温度は約400°Cである．一方，関東西部の山地では，15 km前後の深さで最も多く微小地震が起こっている．ここの温度も又400°C程度である．400°C近傍の温度と微小地震の発生は，小林が指摘したように，大変密接な関係があるように思われる．