BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 54 (1979) pp. 45-73

3. *Compilation of Eleven New Heat Flow Measurements on the Japanese Islands.*

By Satoru HONDA, Yukio MATSUBARA, Teruhiko WATANABE,
Seiya UYEDA and Kunihiko SHIMAZAKI,

Earthquake Research Institute,

Kenichi NOMURA,

Nikko Exploration and Development Co. Ltd., Tokyo, Japan

and

Naoyuki FUJII,

Department of Earth Sciences, Kobe University, Kobe, Japan

(Received April 25, 1979)

Abstract

New land heat flow data at eleven localities in Japan are presented. There are four localities in the Tohoku District, one in the Kanto District, three in the Shikoku District, one in the Chugoku District and two in the Kyushu District. The obtained heat flow values, varying from 1.28 HFU (1HFU$=10^{-6}$ cal/cm^2 sec) to 21.6 HFU, (i.e. from 53.5 to 905 mW/m^2), are in general agreement with the previously estimated heat flow distribution in the area.

Introduction

Since the first measurement in 1957, the terrestrial heat flow has been measured at about 500 localities in and around Japan (HORAI, 1964; UYEDA and HORAI, 1964; UYEDA, 1972). Among these, about 100 are on land. Although, from these data, we know the gross feature of heat flow distribution in and around the Japanese Islands, there are still many gaps in the data to define its fine structure. For example, the precise spatial relation of the distribution of heat flow with the front of active volcanoes should be better defined. We should also have a clearer idea about how wide an area a measured value of heat flow represents. Especially on the land area the latter problem has been unexplored in comparison with the oceanic area where some local variations have been explained as due to the geothermal hydro-circulation in the crust (e.g. WILLIAMS *et al.* 1974; ANDERSON *et al.*, 1977).

The present data have been taken during the last decade on occasional field trips by the five last named authors. Most of the thermal conductivity measurements were conducted by T. Watanabe. The first named two authors have undertaken the compilation of these data.

Results

In this report we present eleven heat flow data sets obtained at Shimokita, Kosaka, Koma, Yamagata Yoshino of Oshima, Shirataki, Hirota, Okuki, Tottori, Kyomachi and Ibusuki of which localities are shown in Fig. 1, together with the heat flow values obtained and summarized in Table 12 of this paper. The contour lines in Fig. 1 represent the regional heat flow distribution compiled earlier (UYEDA, 1972; UYEDA *et al.*, 1973). As one can see in Fig. 1, the new heat flow values generally confirm the previously obtained regional distribution. In the following some details of each measurement will be given.

To obtain the heat flow values, which are calculated by multiplying the geothermal gradients and thermal conductivity values, we measured the underground temperature in boreholes and drifts of mines and the thermal conductivity of rocks collected from the sites.

The thermal conductivity has been measured with a QTM apparatus commercially developed by Syowa Denko Co. Ltd. and by the Schröder method (SCHRÖDER, 1963). The QTM (Quick Thermal Conductivity Meter) is based on the box probe method (SUZUKI *et al.*, 1975) which takes only half a minute to measure the thermal conductivity values. After this quick method became available, we have measured the conductivity values of most of the samples in both wet (water saturated) and dry (naturally desiccated) states. In most cases, the conductivity values measured in the wet state were used for heat flow calculation in the present work as most holes used were filled with water.

In this paper, we have not considered the effects of topography, sedimentation, long period temperature variation and so forth on the geothermal gradients. Also, the temperature and pressure effects on the thermal conductivity have not been considered.

Description of sites

1) *Shimokita (SH)*

This site is located near the northern end of Honshu. The temperature was measured in borehole No. 44 EASM-2 (Fig. 2) drilled by the Metal Mining Agency as a part of its Regional Geological Survey Program. The measurements were made by placing a multi-conductor

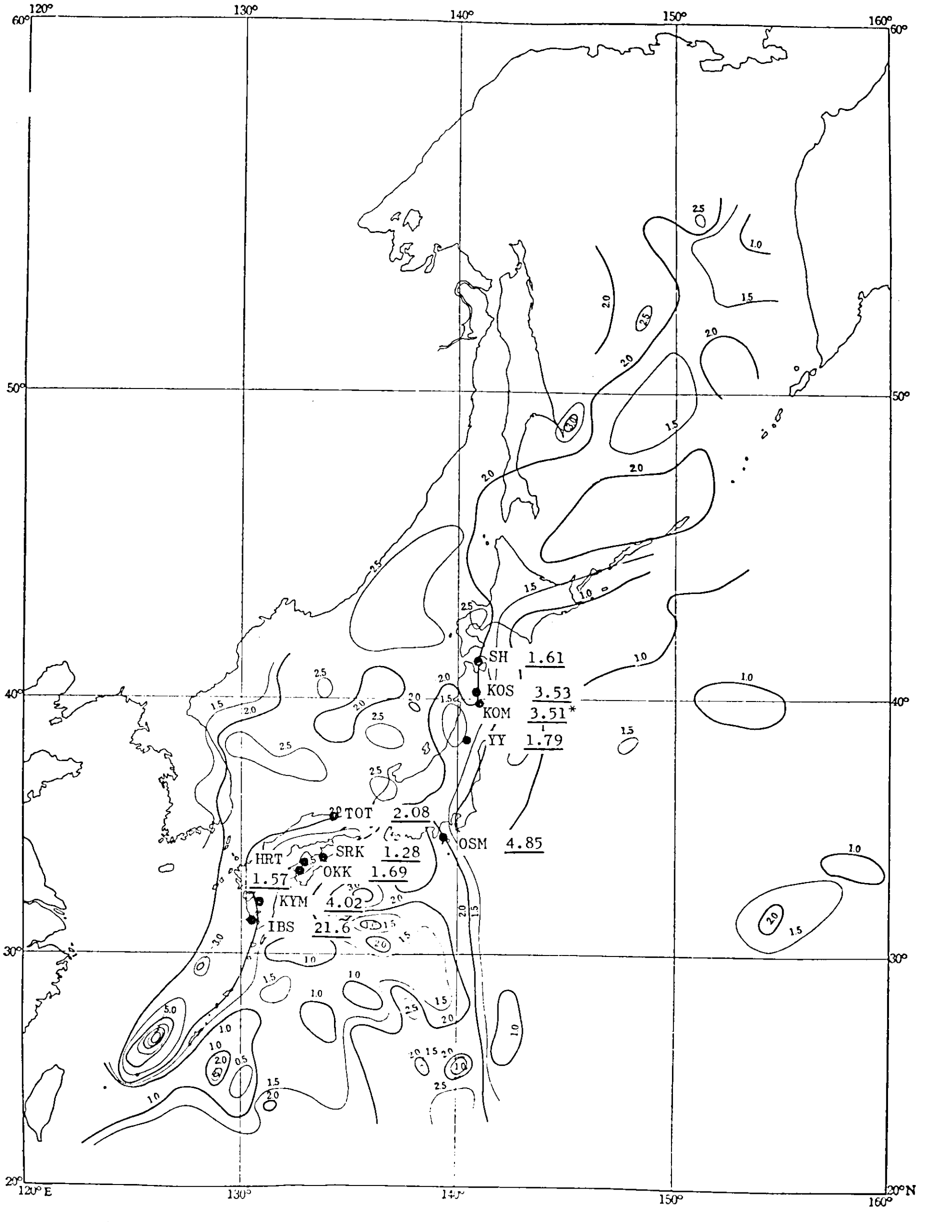


Fig. 1. Locations of heat flow stations. The base map is the contoured heat flow distribution after UYEDA, 1972 and UYEDA *et al.*, 1973. See text and Table 12 for abbreviations.

* means reference values.

cable with a number of thermistors semi-permanently in the borehole. This method was used for the purpose of making the temperature measurements repeatedly to observe the decay of the thermal distur-

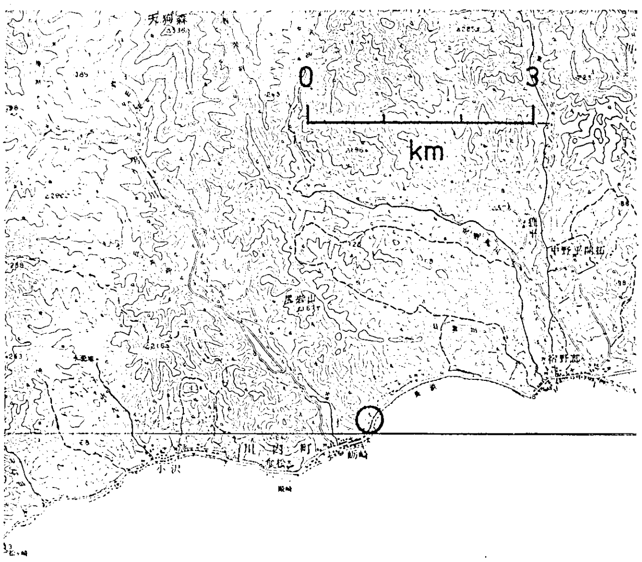


Fig. 2. The locality of borehole No. 44 EASM-2, Shimokita. The map indicates the area from 41°09′N to 41°13′N in latitude and from 140°51′E to 140°57′E in longitude.

bances due to drilling. UYEDA *et al.* (1974) proposed a wide use of this "Buried Thermistor Method". The results from the Shimokita borehole were cited in their paper (their Fig. 2a and Fig. 2b). Although the temperature in the hole has been measured at 9 times, since November 11, 1969 when the first observation was done, we use the latest data (November 19, 1970) which appears to represent the stable state. The temperature was measured from 90m to 390m as shown in Fig. 3, but we used only the deepest set of data, *i.e.* at 290m and 390m, because the upper temperature profile is slightly convexed downward, making the assumption of simple steady conduction doubtful. Using the two lowest data points, we determined the geothermal gradient as,

$$\frac{\Delta T}{\Delta Z}=7.22\ ^{\circ}\mathrm{C}/100\mathrm{m}\ .$$

The conductivity, K, was estimated from the mean of two rock samples, as 2.23 (0.15) mcal/cm sec °C (Table 1). The figure in brackets means $R/2$ (UYEDA and HORAI, 1964), *i.e.* the half amplitude of the variation of conductivity values, $(K_{\max}-K_{\min})/2$. The same notation will be used throughout this paper. With these values, the heat flow can be culculated as

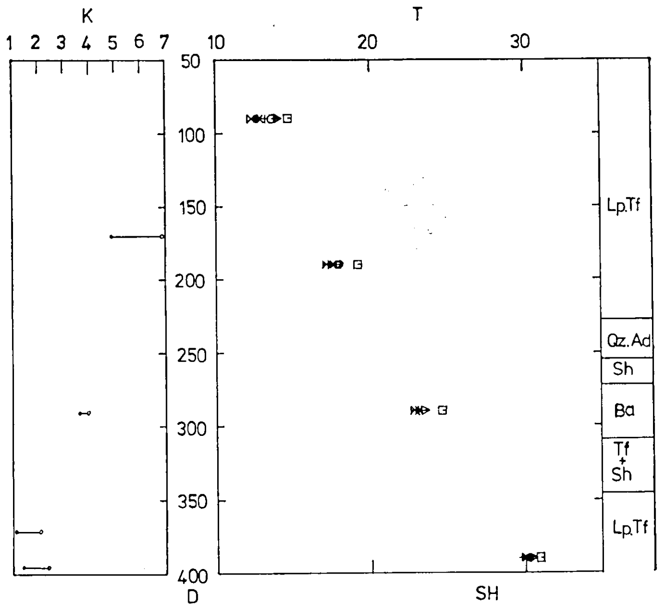


Fig. 3. The distribution of the temperature and the conductivity in relation to the depth, and geologic column in borehole, No. 44 EASM-2. Unit;

Conductivity (K) in mcal/cm sec °C
Depth in m (measured from the surface)
Temperature (T) in °C

Bars in K mean the variations of conductivity measured in wet and dry states.

Abbreviations;

Lp. Tf: Lapilli Tuff,
Sh: Shale,
Tf+Sh: Tuff and Shale.
Qz.Ad: Quartz Andesite,
Ba: Basalt,

Symbols indicated in T-D curve mean the date when the measurement was made.

⊟ : November 27, 1969,
▷ : December 9, 1969,
× : January 13, 1970,
⇾ : April 16, 1970,
N : November 19, 1970.
⊖ : December 8, 1969,
+ : December 17, 1969,
◇ : February 16, 1970,
⋊ : July 23, 1970,

$$Q = 1.61\,\mathrm{HFU}\ (67.5\,\mathrm{mW/m^2})\ .$$

2) *Kosaka (KOS)*

This site is located in the area of a typical Kuroko type copper mine (Kosaka Mine) situated in the Neogene volcanic zone, the Green Tuff zone (MINATO *et al.*, 1956). We measured the geothermal gradient at two localities, the surface boreholes 871 and MR909, near Kosaka Mine (Fig. 4), drilled by the Dowa Mining Co. Ltd. Since the measurements were made several times during the period between about 24

Table 1. Characteristics of rocks at Shimokita

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks	
169.5*	conglomerate	4.856-6.817	dry-wet**	QTM***
291	basalt	3.639-3.928	dry-wet	QTM
370.6	pumice tuff	1.108-2.075	dry-wet	QTM
395	pumice tuff	1.433-2.378	dry-wet	QTM
mean		2.23 (0.15)****	mean of 370.6 and 395 (wet)	

* Depth in meter. (m)

** Condition of measurement.

*** Method of measurement.

**** $R/2$ (i.e. $(K\max - K\min)/2$).

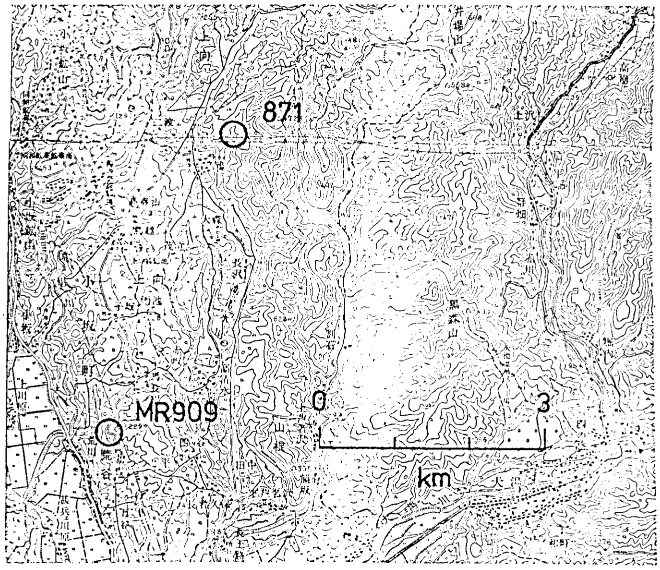
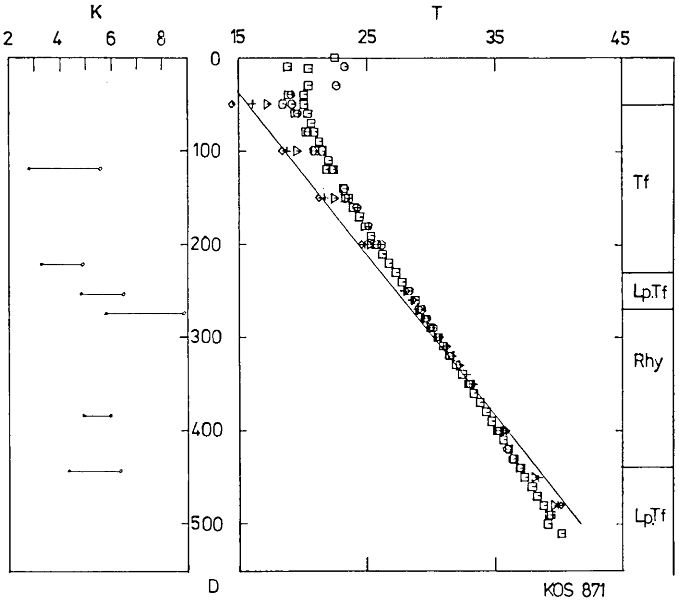


Fig. 4. Localities of boreholes 871 and MR909, Kosaka. The map indicates the area from 40°17′N to 40°21′N in latitude and from 140°45′E to 140°51′E in longitude.

hours and 43 hours after the end of drilling at each station, the disturbances on temperature caused by drilling were appreciable. We corrected such effects on the basis of Bullard's estimate (BULLARD, 1947), in which the temperature T is represented as,

$$T = A \ln(1 + t_1/t) + T_\infty \,. \qquad (1)$$

Here, A is a constant which relates to the strength of the heat source produced by the drilling, t is time which starts from the end of drilling, t_1 is time during which the disturbance continued, and T_∞ is the temperature when t approaches infinity. Applying the equation (1) to the 'raw' data at each depth, T is obtained and shown in Fig.



(a)

Fig. 5a. The distribution of the temperature and the conductivity in relation to the depth and the geologic column in borehole 871. Symbols indicated in T-D curve mean the time when the measurement was made.

⊟ : July 19, 1969, 14 hr.
⊖ : 〃 18 hr.
▷ : July 20, 1969, 15 hr.
+ : July 21, 1969, 7 hr. 30 min.
◇ : Corrected temperature (see text)

Abbreviations;
Tf: Tuff, Lp. Tf: Lapilli Tuff,
Rhy: Rhyolite.

5a and Fig. 5b, together with the 'raw' data.

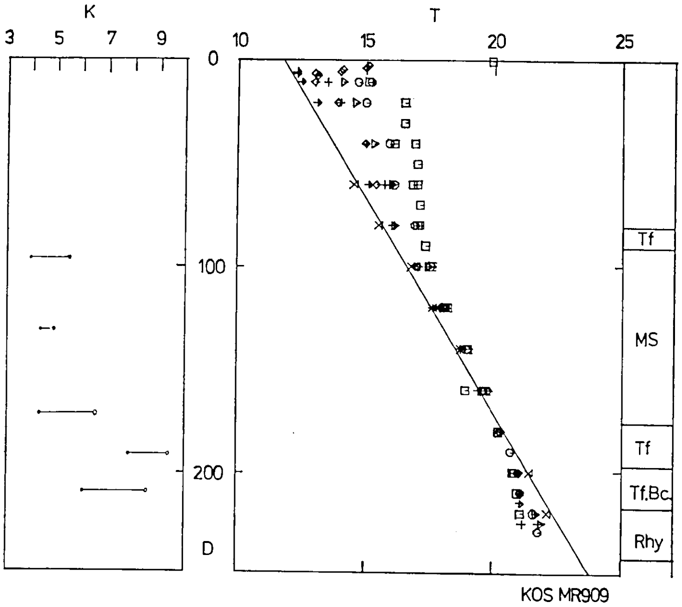
The geothermal gradients are determined from T_∞, making use of the least squares method as,

$$\frac{\Delta T}{\Delta Z}=5.88\pm0.14\ \text{°C/100m at borehole 871},$$

$$\frac{\Delta T}{\Delta Z}=4.79\pm0.12\ \text{°C/100m at borehole MR909}.$$

The second figure in the right hand side shows the standard deviation.

The mean conductivity values are 6.34 (2.00) mcal/cm sec °C for seven samples from hole 871, and 6.94 (2.25) mcal/cm sec °C for five



(b)

Fig. 5b. The distribution of the temperature and the conductivity in relation to the depth in borehole MR909 and the geologic column.

Symbols have the same meaning as Fig. 5a.

⊟ : September 1, 1968, 7 hr. 53 min.
⊖ : 〃 10 hr. 43 min.
▷ : 〃 13 hr. 21 min.
+ : 〃 17 hr. 29 min.
× : 〃 22 hr. 40 min.
◇ : September 2, 1968, 7 hr. 21 min.
-▷ : Corrected temperature (see text)

Abbreviations;
Tf: Tuff,
MS: Mudd Stone,
Rhy: Rhyolite,
Tf. Bc.: Tuff Breccia.

samples from hole MR909 (Table 2). The values of heat flow are, thus,

$$Q=3.73 \text{ HFU } (156 \text{ mW/m}^2) \text{ at borehole 871 ,}$$
$$Q=3.32 \text{ HFU } (139 \text{ mW/m}^2) \text{ at borehole MR909 ,}$$
$$Q=3.53 \text{ HFU } (148 \text{ mW/m}^2) \text{ average of the two .}$$

Bullard's estimate is based on the following approximation, *i.e.*,

$$E_i(-Z)=-\int_Z^\infty e^{-u}/u\,du=\log_e Z+0.577 \text{ .}$$

This approximation is valid only if z is sufficiently small (<0.01). In

Table 2. Characteristics of rocks at Kosaka.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks	
871				
118*	tuff	2.789-5.536	dry-wet**	QTM***
222	tuff	3.267-4.856	dry-wet	QTM
253	tuff	4.828-6.467	dry-wet	QTM
274	rhyolite	5.769-8.856	dry-wet	QTM
383	rhyolite	4.942-5.994	dry-wet	QTM
442	tuff	4.322-6.353	dry-wet	QTM
475	tuff	3.689	dry	QTM
MR909				
110		3.964-5.467	dry-wet	QTM
145	mudstone	4.347-4.861	dry-wet	QTM
186	tuff	4.292-6.456	dry-wet	QTM
205	tuff breccia	7.806-9.361	dry-wet	QTM
223	rhyolite	6.053-8.553	dry-wet	QTM
mean(871)		6.94 (2.00)****	mean of all except 475 (wet)	
mean (MR909)		6.94 (2.25)	mean of all (wet)	

*, **, ***, **** See Table 1.

the problem of boreholes $Z=a^2/4kt$ where a is the radius of the hole, k the thermal diffusivity of the strata and t is the time. In our case, the above approximation is justified for $t>33$hr (Hole 871) and $t>3$hr (Hole MR909). Therefore, Hole 871 may not be fully warranted. But according to Jaeger's estimate (1961) the departure from the steady-state temperature-depth curve is significant only near the surface and the bottom. This situation is clearly represented in Fig. 5a and Fig. 5b suggesting the error may be small.

3) *Koma* (*KOM*)

This site is also located in the Green Tuff region and near the front of the volcanoes. In Koma (Fig. 6), the temperature profile was obtained from borehole KO-3 drilled by the Dowa Mining Co. Ltd. The resultant distribution of the temperature is illustrated in Fig. 7 showing a very dispersive nature, especially below 600m. Supposing that the temperature from 300m to 600m which seems to be approximately linear may be representing the conductive thermal scheme of this region, and data below 600m is disturbed by some flow of hot water, we calculated the least squares geothermal gradient.

$$\frac{\Delta T}{\Delta Z}=7.45\pm0.19\ ^{\circ}\mathrm{C}/100\mathrm{m}\ .$$

Here, the standard deviation (0.19) may be an artifact caused by the

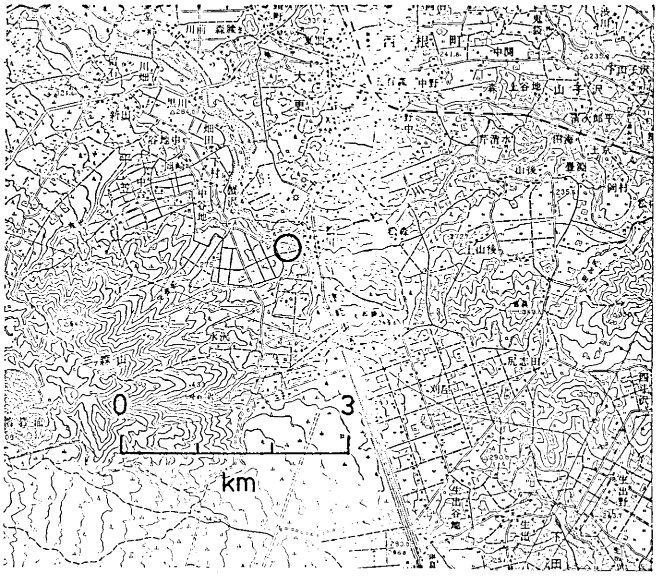


Fig. 6. The locality of the borehole at Koma. The map indicates the area from 39°51′N to 39°55′N in latitude and from 141°03′E to 141°09′E in longitude.

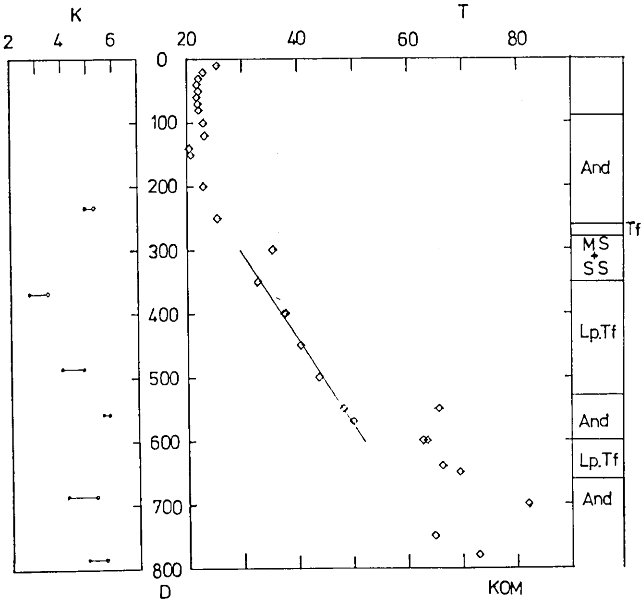


Fig. 7. The distribution of the temperature and the conductivity in relation to the depth and the geologic column in the borehole.

Abbreviations;

And: Andesite, Tf: Tuff,

MS+SS: Mudstone and Sandstone,

Lp. Tuff: Lapilli Tuff.

Note the abnormal distribution of temperature around 700m.

Table 3. Characteristics of rocks at Koma.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks	
235*	andesite	4.917-5.236	dry-wet**	QTM***
368.5	tuff	2.767-3.472	dry-wet	QTM
486	lapilli tuff	4.017-4.831	dry-wet	QTM
556.6	andesite	5.628-5.814	dry-wet	QTM
686	tuff	4.239-5.436	dry-wet	QTM
784	volcanic breccia	5.006-5.647	dry-wet	QTM
mean		4.71 (1.17)****	mean of 368.5, 486 and 556.6 (wet)	

*, **, ***, **** See Table 1.

selection of data.

Averaging the thermal conductivity values of three rock samples, we decided the representative conductivity as 4.71 (1.17)mcal/cm sec °C and heat flow as,

$$Q=3.51 \text{ HFU } (147 \text{ mW/m}^2) .$$

Again, because of the apparent disturbed nature of the underground temperature, we regard this result as only a reference value. This site needs further investigation.

4) *Yamagata Yoshino* (*YY*)

This site is also located in the Green Tuff region. The underground temperature was measured in borehole No. 44 EAYY-3 (Fig. 8), drilled by the Metal Mining Agency as a part of its Regional Geological Survey Program. As at Shimokita, the "Buried Thermister Method" was employed at this site.

Since February 1, 1970, when the first measurement was made, we have measured the temperature in the borehole five times (Fig. 9). The time variation of temperature was found to be very small, and the geothermal gradient was calculated from the latest data, *i.e.* the data taken on November 21, 1970. The least squares geothermal gradient is,

$$\frac{\Delta T}{\Delta Z}=3.95\pm0.16 \ \text{°C/100 m}.$$

The average conductivity value of ten samples of lapilli tuff is 4.54 (0.69) mcal/cm sec°C (Table 4), giving the heat flow values as,

$$Q=1.79 \text{ HFU } (75.0 \text{ mWm/m}^2) .$$

5) *Oshima* (*OSM*)

Oshima is an active volcanic island located at about 120 km south

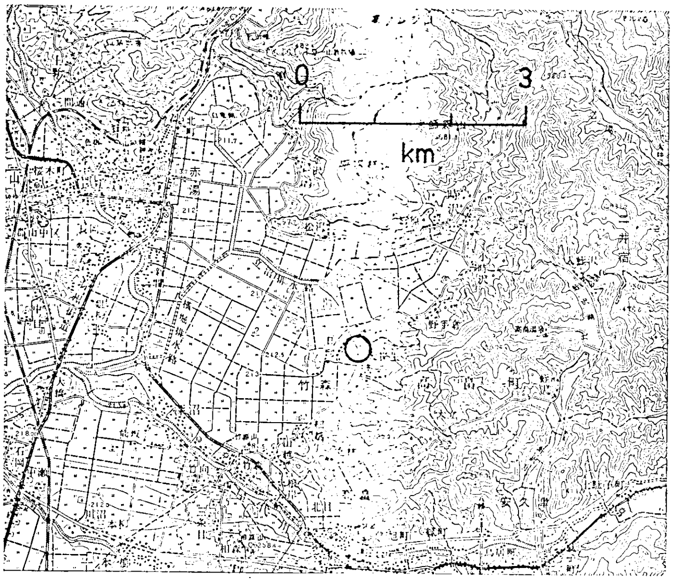


Fig. 8. The locality of borehole No. 44 EAYY-3, Yamagata Yoshino. The map indicate the area from 38°00′N to 38°04′N in latitude and from 140°09′E to 140°15′E in longitude.

of Tokyo. The temperature profile was assessed for borehole Mitsumine No. 1 at a site near the northwestern end of the island (Fig. 10). The obtained temperature profile seems to consist of two parts, *i.e.* the parts above and below 500 m depth (Fig. 11). We consider that the deeper more linear part may be closer to the true conductive temperature gradient rather than the shallower part. The lower gradient found in the shallower depth range may be caused by the movement of the underground water. The mountain body of an active volcano may be quite permeable, often giving rise to a small temperature gradient. On Oshima Island such a case was observed previously in a borehole drilled at a higher altitude on the caldera rim (UYEDA, 1961). Thus the geothermal gradient in this site was estimated as,

$$\frac{\Delta T}{\Delta Z}=22.1\ ^{\circ}\mathrm{C}/100\,\mathrm{m}\ .$$

Although the geologic column is not available for this hole, the conductivity of the rocks which may be representative of this site is 2.19 mcal/sec cm °C (Table 5). From these figures of the conductivity and geothermal gradient, the tentative heat flow value is obtained as,

$$Q=4.85\ \mathrm{HFU}\ (203\,\mathrm{mW/m^2})\ .$$

This value is tentative for another reason also. That is the lower-

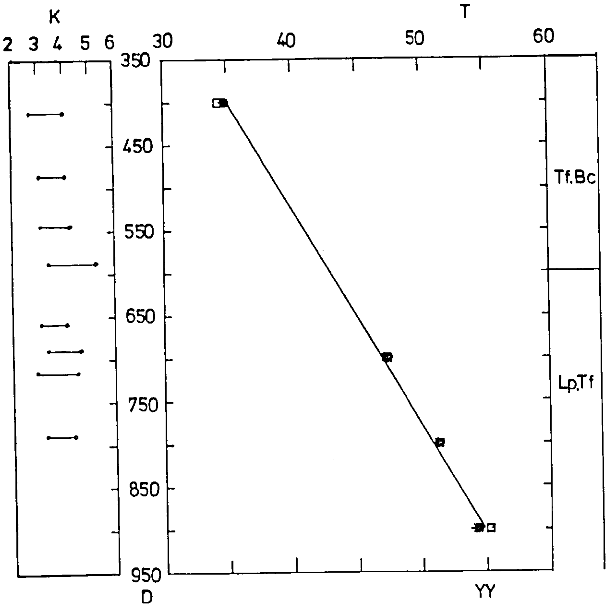


Fig. 9. The distribution of the temperature and the conductivity in relation to the depth and the geologic column in borehole, No 44 EAYY-3. Symbols indicated in T-D curve mean the data when measurement was made.

⊟ : February 1, 1970, ⊖ : February 22, 1970,
▷ : April 17, 1970, + : July 24, 1970,
× : November 21, 1970.

Abbreviations;
Tf. Bc: Tuff Breccia, Lp. Tf: Lapilli Tuff.

Table 4. Characteristics of rocks at Yamagata Yoshino.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks	
235*	lapilli tuff	3.781-5.422	dry-wet**	QTM***
412.3	lapilli tuff	2.794-4.131	dry-wet	QTM
484.7	lapilli tuff	3.086-4.033	dry-wet	QTM
545	lapilli tuff	3.172-4.297	dry-wet	QTM
545.2	lapilli tuff	3.475-4.283	dry-wet	QTM
589.5	lapilli tuff	3.439-5.294	dry-wet	QTM
660.3	lapilli tuff	3.114-4.194	dry-wet	QTM
690	lapilli tuff	3.453-4.697	dry-wet	QTM
718.7	lapilli tuff	3.064-4.561	dry-wet	QTM
789.8	lapilli tuff	3.372-4.472	dry-wet	QTM
mean		4.54 (0.69)****	mean of all	(wet)

*, **, ***, **** See Table 1.

most three temperature data in Fig. 11 appear to deviate from the linear trend, suggesting some further complication in the temperature

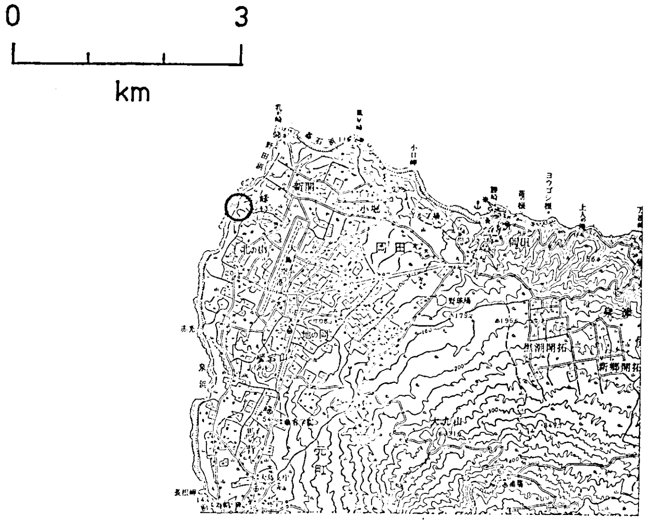


Fig. 10. The locality of borehole Mitsumine No. 1, Oshima. The map indicates the area from 34°45′N to 34°49′N in latitude and from 139°19′E to 139°25′E in longitude.

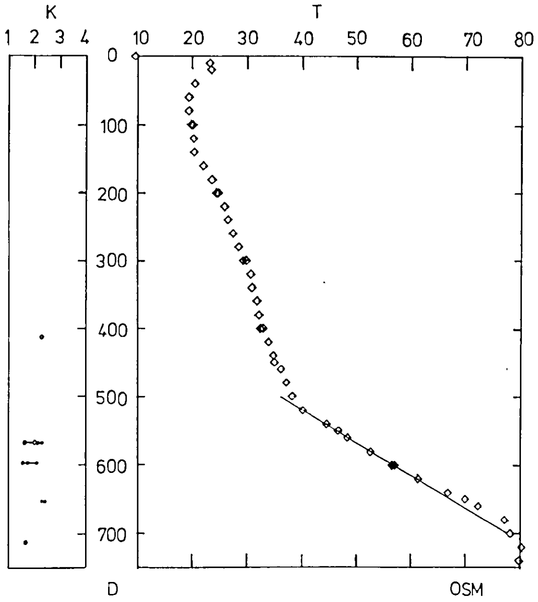


Fig. 11. The distribution of the temperature and the conductivity in relation to the depth in borehole, Mitsumine No. 1. Note the two parts of the temperature profile.

depth relation.

6) *Shirataki* (*SRK*)

Shirataki is a copper mine of the so-called Kieslager-type in

Table 5. Characteristics of rocks at Oshima.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks
411.3*		2.27	dry** Schröder***
		2.10	
566.6		1.67-2.12	dry-wet Schröder
		2.05-2.31	
596.1		1.58-2.10	dry-wet Schröder
		1.75-2.09	
713.8		1.68	Schröder
654.2		2.45	wet Schröder
		2.32	
mean		2.19	

*, **, ***, **** See Table 1.

central Shikoku and is located in the Sanbagawa metamorphic belt. This mine is operated by the Nippon Mining Co. Ltd. At this site, we made use of borehole Taniko No. 1 and drifts of the mine for the purpose of determining the geothermal flux (Fig. 12). When the temperatures at about 3 km apart are plotted against the *altitude* (Fig. 13), it indicates a remarkably more linear feature than when they are plotted against the local depth. This appears to mean that the

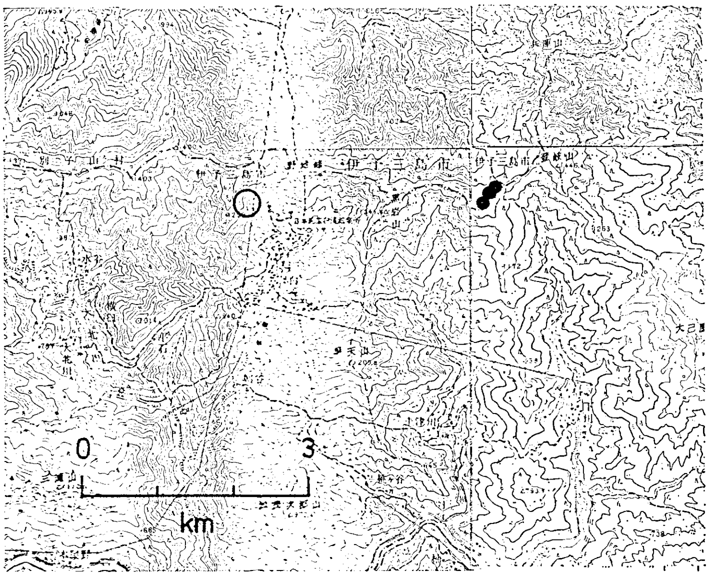


Fig. 12. Localities of the borehole and drifts of mines at Shirataki Mine. The map indicates the area from 33°47′N to 33°51′N in latitude and from 133°26′E to 133°32′E in longitude.

The open circle indicates the site of the borehole and the filled circles indicate sites of drifts of the mine.

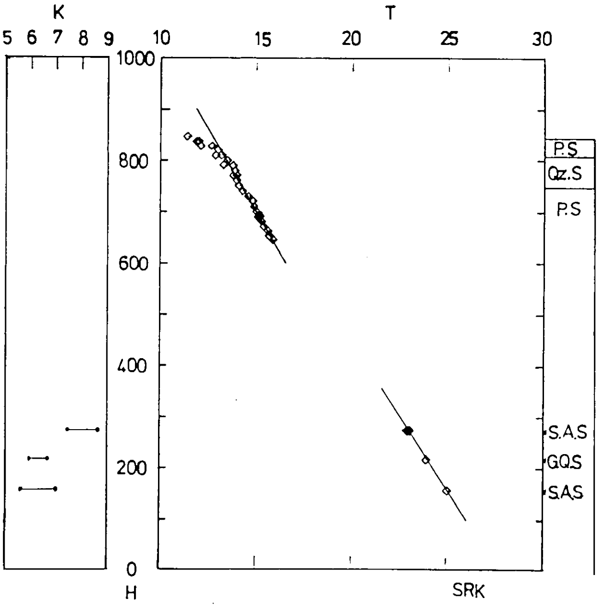


Fig. 13. The distribution of the temperature and the conductivity in relation to the "*altitude*" and the geologic column at Shirataki.
H means height above sea level.
The temperature distribution in the upper part was measured in the borehole and in the lower part in drifts.
Abbreviation:
P.S: Pelitic Schist, Qz.S: Quartz Schist,
S.A.S: Spotted Amphibole Schist,
G.Q.S: Garnet Quartz Schist.

temperature profile in this area may be the "L type" of Uyeda and Horai (1964): namely the geotherm is more parallel to horizontal than to the surface relief. The thermal gradients are,

$$\frac{\Delta T}{\Delta Z}=1.56\pm0.05\ ^{\circ}\mathrm{C}/100\mathrm{m}\ \text{(determined from the temperature in the borehole)},$$

$$\frac{\Delta T}{\Delta Z}=1.73\pm0.06\ ^{\circ}\mathrm{C}/100\mathrm{m}\ \text{(determined from the temperature in the drifts)}.$$

We used the latter value for the heat flow determination, because the conductivity values in the upper part are scattered (Table 6). The mean conductivity of the lower part is 7.39 (0.99) mcal/cm sec °C.

$$Q=1.28\ \mathrm{HFU}\ (53.6\ \mathrm{mW/m^2}).$$

Table 6. Characteristics of rocks at Shirataki.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks	
Taniko				
39*	pelitic schist	6.278-9.006	dry-wet**	QTM***
66	pelitic schist	5.514-5.969	dry-wet	QTM
88	quartz schist	15.14-17.90	dry-wet	QTM
120	pelitic schist	10.38-10.54	dry-wet	QTM
In drifts				
274†	spotted amphibole schist	7.464-8.589	dry-wet	QTM
217†	garnet quartz schist	5.978-6.614	dry-wet	QTM
156†	spotted amphibole schist	5.583-6.972	dry-wet	QTM
mean		7.39 (0.99)****	mean of 274,217,156 (wet)	

*, **, ***, **** See Table 1.

† Measured from sea level (m)

7) *Hirota* (*HRT*)

Hirota is also a Kieslager-type copper mine in Shikoku and in the Sanbagawa metamorphic belt. Making use of borehole Sarudani No. 4 owned by the Nippon Mining Co. Ltd., in Hirota Mine (Fig. 14), measurement of underground temperature was made. The result is shown in Fig. 15. The geothermal gradient calculated from these data by means of the least squares method is,

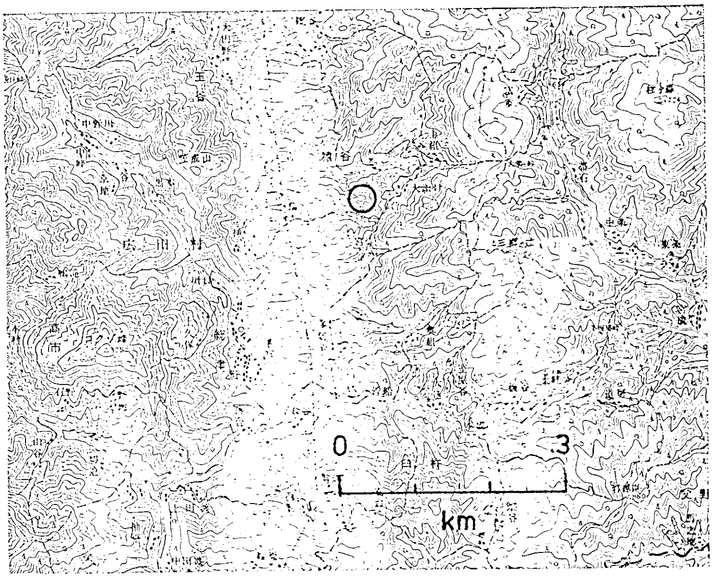


Fig. 14. The locality of borehole Sarudani No. 4, Hirota. The map indicates the area from 33°36′N to 33°40′N in latitude and from 132°46′E to 132°52′E in longitude.

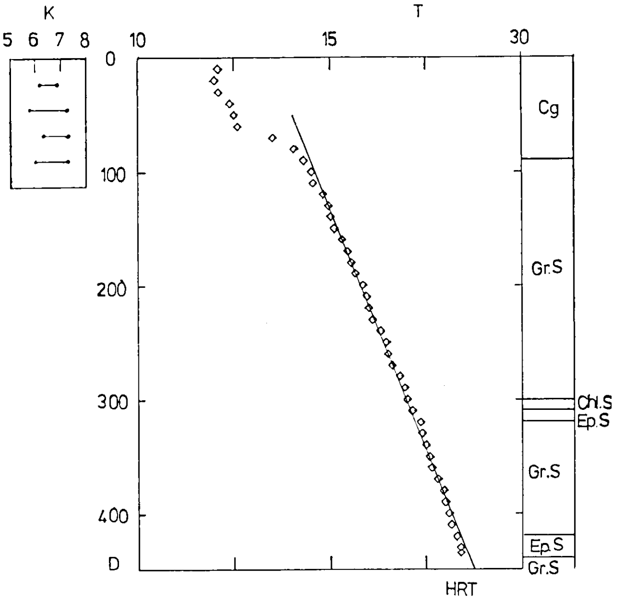


Fig. 15. The distribution of the temperature in relation to the depth, the geologic column and the conductivity at Hirota.
Abbreviations:
Cg: Conglomerate, Gr.S: Green Schist,
Chl.S: Chlorite Schist, Ep.S: Epidote Schist.

Table 7. Characteristics of rocks at Hirota.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks	
No. 5				
550*-1	green schist	6.239-6.850	dry-wet**	QTM***
550-2	green schist	5.825-7.219	dry-wet	QTM
A-6				
159	green schist	6.386-7.292	dry-wet	QTM
260	green schist	6.056-7.247	dry-wet	QTM
mean		7.15 (0.22)****	mean of all (wet)	

*, **, ***, **** See Table 1.

$$\frac{\Delta T}{\Delta Z}=2.37\pm0.03 \ ^{\circ}\mathrm{C}/100\mathrm{m} .$$

Because we could not get a core sample at this site, estimation of the thermal conductivity was made using four core samples recovered at a nearby site. The averaged thermal conductivity of these samples is 7.15 (0.22) mcal/cm sec °C (Table 7), giving the heat flow value as,

$$Q=1.69 \text{ HFU } (70.8 \text{ mW/m}^2) .$$

8) *Okuki* (*OKK*)

This is also a site in a Kieslager-type copper mine in the Sanba-

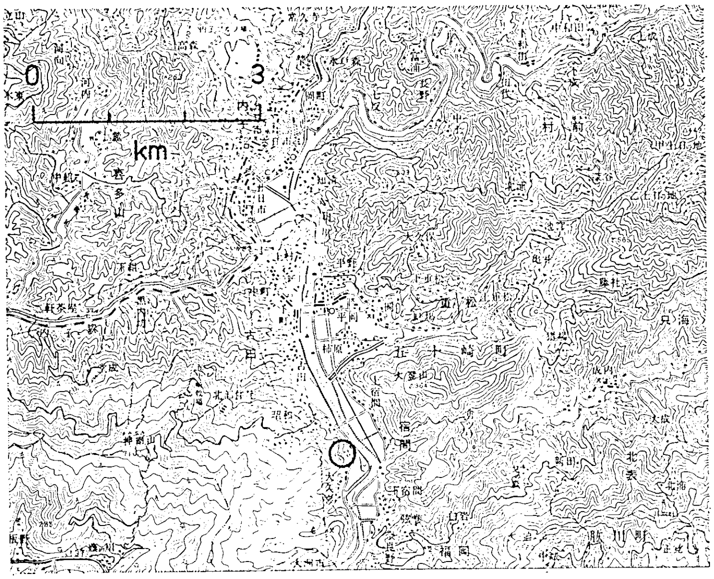


Fig. 16. The locality of borehole No. 62021, Okuki. The map indicates the area from 33°30′N to 33°34′N in latitude and from 132°37′E to 132°43′E in longitude.

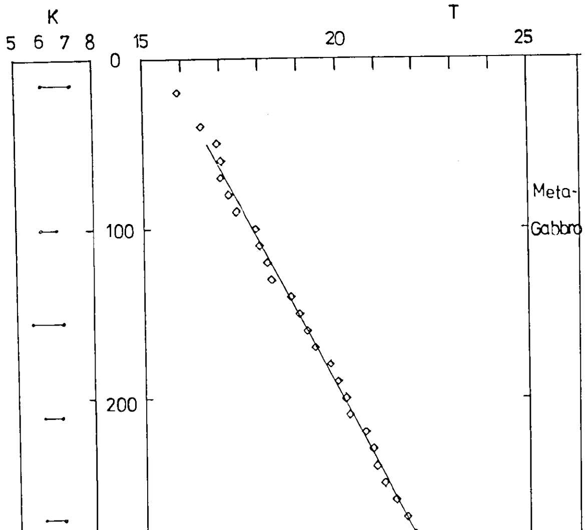


Fig. 17. The distribution of the temperature and the conductivity in relation to the depth, and the geologic column in borehole No. 62021.

Table 8. Characteristics of rocks at Okuki.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks	
15*	meta-gabbro	6.025-7.172	dry-wet**	QTM***
100	meta-gabbro	6.567-5.944	dry-wet	QTM
155	meta-gabbro	5.603-6.808	dry-wet	QTM
210	meta-gabbro	6.042-6.711	dry-wet	QTM
250	meta-gabbro	5.947	dry	QTM
275	meta-gabbro	6.064-6.786	dry-wet	QTM
300	meta-gabbro	6.239-6.147	dry-wet	QTM
500	meta-gabbro	7.411-7.433	dry-wet	QTM
mean		6.71 (0.36)	mean of all (wet)	

*, **, ***, **** See Table 1.

gawa metamorphic belt in Shikoku. In Okuki Mine operated by the Syowa Mining Co. Ltd., the temperature was measured in borehole No. 62021 (Fig. 16). The temperature depth relation obtained in this borehole is shown in Fig. 17. Using the least squares method, the geothermal gradient is estimated as,

$$\frac{\Delta T}{\Delta Z}=2.34\pm0.04 \ \text{°C/100m} .$$

The value of the thermal conductivity used to obtain the heat flux was assessed from the mean of eight rock samples as 6.71 (0.36) mcal/sec cm °C (Table 8). Then, the heat flow is obtained as,

$$Q=1.57 \ \text{HFU} \ (65.8 \, \text{mW/m}^2) .$$

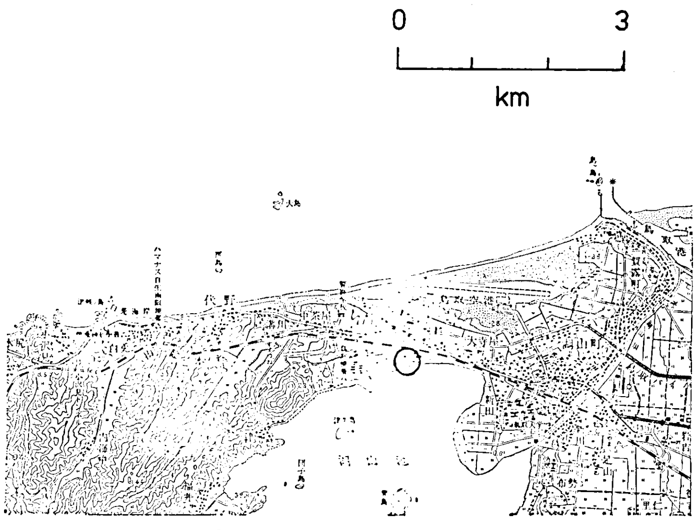


Fig. 18. The locality of the borehole at Tottori. The map indicates the area from 35°30′N to 35°34′N in latitude and from 134°06′E to 134°12′E in longitude.

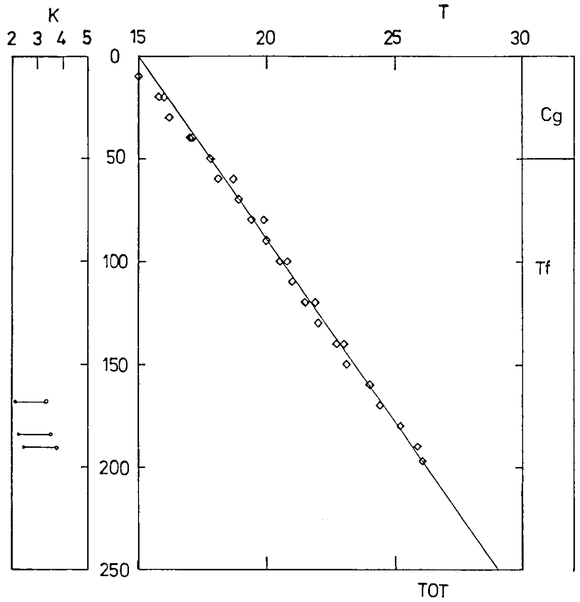


Fig. 19. The distribution of the temperature and the conductivity in relation to the depth, and the geologic column in the borehole.
Abbreviations;
Cg: Conglomerate, Tf: Tuff,

Table 9. Characteristics of rocks at Tottori.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks	
184*	tuff breccia	2.275-4.008	dry-wet**	QTM***
168	tuff breccia	2.164-3.367	dry-wet	QTM
191	tuff breccia	2.494-3.764	dry-wet	QTM
mean		3.71 (0.32)****	mean of all (wet)	

*, **, ***, **** See Table 1.

9) *Tottori (TOT)*

This locality is situated near Tottori City on the Japan Sea coast of southwest Japan (Fig. 18). High heat flow values were found previously in both the Japan Sea (Yasui *et al.*, 1968) and the coastal area including the present site (Uyeda and Horai, 1964). Utilizing a borehole, the underground temperature was observed as shown in Fig. 19. The thermal gradient was assessed as,

$$\frac{\Delta T}{\Delta Z}=5.61\pm0.10\ ^{\circ}\mathrm{C}/100\mathrm{m}\ .$$

Averaging the thermal conductivity values of three rock amples, we determined the thermal conductivity as, 3.71 (0.32) mcal/cm sec °C (Table 9).

As a result, the heat flow is estimated as,

$$Q=2.08 \text{ HFU } (87.2 \text{ mW/m}^2) .$$

10) *Kyomachi* (*KYM*)

Kyomachi is located in Kakuto Basin, southern Kyushu, where many hot springs are distributed (Fig. 20). The heat flow measurement was made in a borehole owned by the Kyomachi Kanko Hotel. The results are indicated in Fig. 21, showing some abnormal temperature distribution. The calculation of the thermal gradient was made by using the data between 350 m and 440 m. The reason why we did so is that the temperature curve at that range appears to be more linear. The geothermal gradient, then, was calculated, as

$$\frac{\Delta T}{\Delta Z}=7.57\pm0.16 \ {}^{\circ}\text{C}/100 .$$

The representative value of the thermal conductivity at this site is 5.31 mcal/°C cm sec (the mean of two rock samples) (Table 10). The heat flow is obtained as,

$$Q=4.02 \text{ HFU } (168 \text{ mW/m}^2) .$$

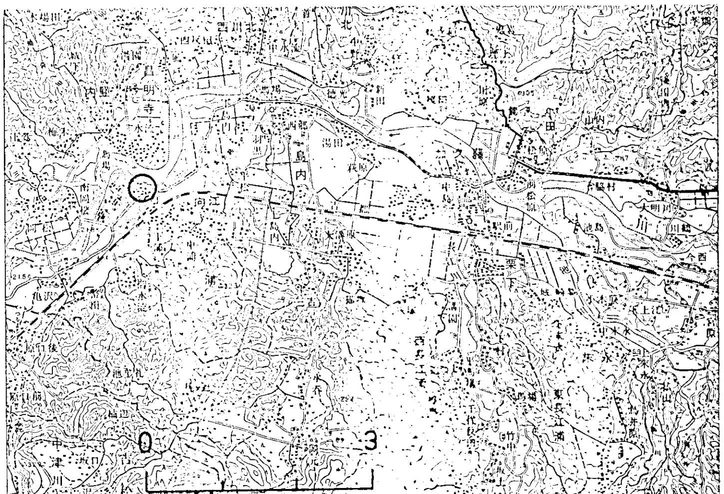


Fig. 20. The locality of the borehole at Kyomachi. The map indicates the area from 32°00′N to 32°04′N in latitude and from 130°45′E to 130°51′E in longitude.

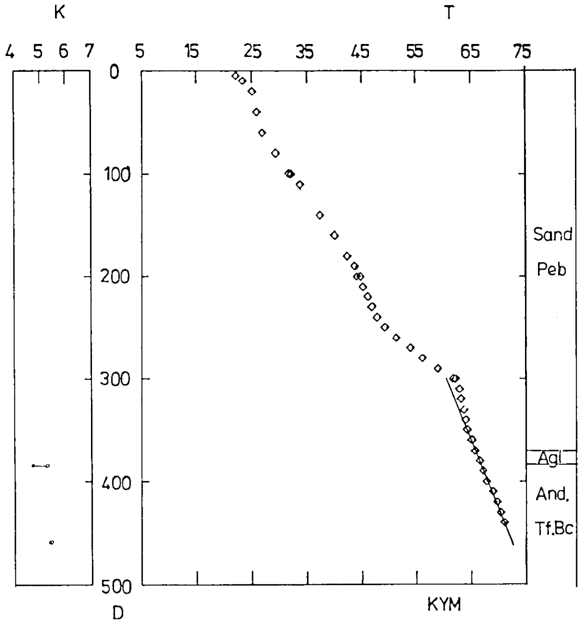


Fig. 21. The distribution of the temperature and the conductivity in relation to the depth in the borehole and the geologic column. Note the peculiar distribution of the temperature.
Abbreviations;
Sand Peb: Sand and pebble. Agl: Agglomerate,
And. Tf. Bc: Andesite and Tuff breccia.

Table 10. Characteristics of rocks at Kyomachi.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks
383.5*	propylite	4.725-5.231	dry-wet** QTM***
458	propylite	5.336-5.397	dry-wet QTM
mean		5.31 (0.08)****	mean of all (wet)

*, **, ***, **** See Table 1.

11) *Ibusuki* (*IBS*)

Ibusuki is also in the southern Kyushu hot spring area and located between Kagoshima Bay, a volcanic depression, and Kaimondake volcano. Ibusuki is also known as a geothermal area. The temperature was observed in borehole GI-3 (Fig. 22) drilled by the Electric Power Development Co. Ltd. The results, shown in Fig. 23, indicate that the temperature profile is reasonably linear. The geothermal gradients were assessed in two depth regions, *i.e.* from 100m to 160m and from 200m to 300m. The reason why we did so is that in the former part the hole was dry, and in the latter it was filled with water. This situation may be the cause of the slight change in the temperature-depth curve. The gradients are,

$$\frac{\Delta T}{\Delta Z}=49.1\pm 1.1\ ^{\circ}\mathrm{C}/100\mathrm{m}\ \text{(in the air)}\ ,$$

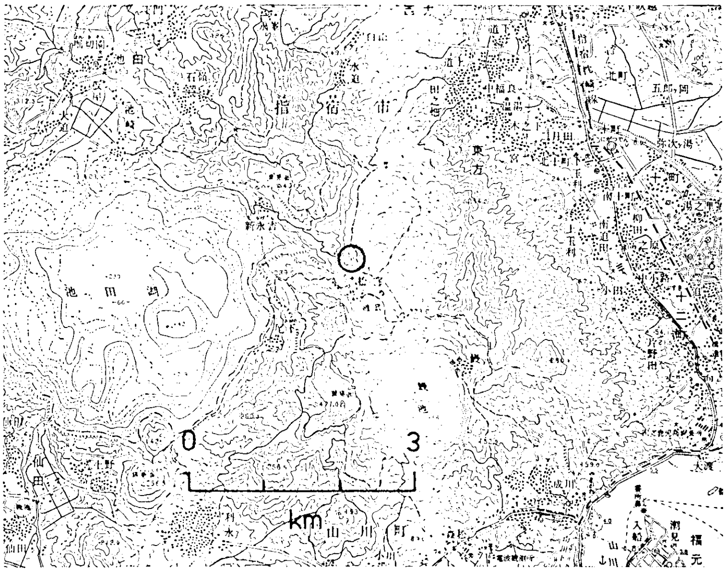


Fig. 22. The locality of borehole GI-3, Ibusuki. The map indicates the area from 31°12′N to 31°16′N in latitude and from 130°33′E to 130′39′E in longitude.

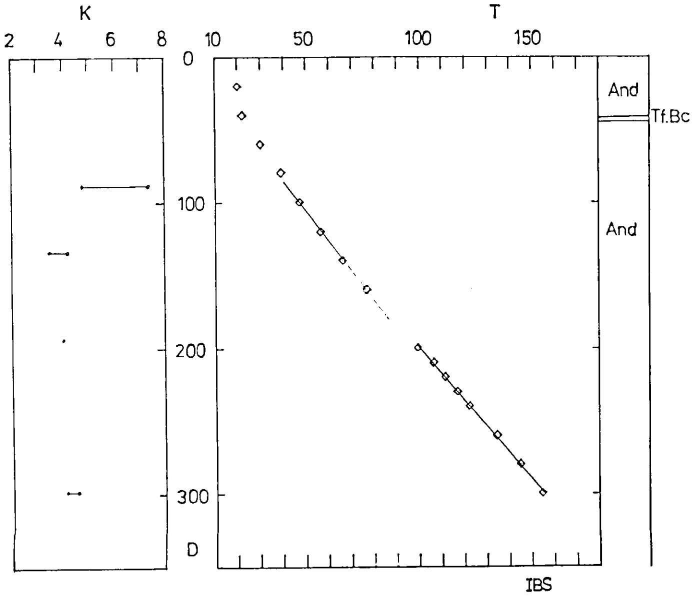


Fig. 23. The distribution of the temperature and the conductivity in relation to the depth and the geologic cloumn in borehole GI-3. Note the kink near 200m depth which was probably produced by the environmental effects. (see text)

$$\frac{\Delta T}{\Delta Z}=55.7\pm 0.9 \ ^{\circ}\mathrm{C}/100\mathrm{m} \ \text{(in water)} .$$

The difference in the gradients may be due to the convective motion of fluids in the hole, *i.e.* the air is less viscous than the water. If this was really the case, temperature measurements in a dry hole may often be affected by convection, requiring further investigation.

"In the air part of the hole" we calculated the conductivity from the mean of two samples (No. 133 and 193) in both wet and dry states, and "in the water part of the hole" we took the conductivity of one wet sample (No. 298) (Table 11).

Table 11. Characteristics of rocks at Ibusuki.

Specimen	Rock type	Thermal conductivity (mcal/cm sec °C)	Remarks
88*	propylite	4.814-7.394	dry-wet** QTM***
133	propylite	3.486-4.181	dry-wet QTM
193	propylite	4.022-4.000	dry-wet QTM
298	propylite	4.131-4.564	dry-wet QTM
mean (upper part)		3.95	mean of 133,193
		(0.27)****	(dry)
		4.09	(wet)
		(0.09)****	
mean (lower part)		4.56	only 298 (wet)

*, **, ***, **** See Table 1.

Heat flow values are,

$Q=19.4$ HFU (813 mW/m^2) ("in the air" part and dry conductivity),

$Q=20.1$ HFU (842 mW/m^2) ("in the air" part and wet conductivity),

$Q=25.4$ HFU (1060 mW/m^2) ("in the water" part and wet conductivity),

$Q=21.6$ HFU (901 mW/m^2) (mean)

Discussion

The results obtained in the present work are compiled in Table 12, and all the simplified temperature versus depth relations are shown in Fig. 24.

The eleven new heat flow determinations appear to be in good harmony with the previously proposed distribution of heat flow of the Japanese region, although some sites near volcanoes and hot-springs showed high values that may be too local to be included in the regional contouring. It is known, however, that some extremely high heat flow values in the sea area are also due to local hydrothermal

Table 12. Heat flow data.

Station	Abbre-viation	Latitude	Longitude	Site*	Maximum depth(m)	Measured** depth(m)	Logging***	Gradient (°C/100m)	Conduc-tivity****	Heat flow (HFU)	(mW/m²)
Shimokita	SH	41°10′N	140°54.5′E		1600	290, 390	BTM	7.22	2.23(0.15)	1.61	67.5
Kosaka	KOS									3.53	148
871		40°20′N	140°47′E	MM	535.3	50-480	1	5.88±0.14	6.34(2.00)	3.73	156
MR909		40°17′N	140°46′E	MM	229	60-220	1	4.79±0.12	6.94(2.25)	3.32	139
Koma	KOM	39°53.5′N	141°05.5′E		780	350-570	1	7.45±0.19	4.71(1.17)	3.51†	147
Yamagata	Y. YY	38°01.5′N	140°12′E		1300	400-900	BTM	3.95±0.16	4.54(0.69)	1.79	75.0
Oshima	OSM	34°47′N	139°22′E	near volcano	740	500-700	1	22.1	2.19	4.85	203
Shirataki	SRK	33°50′N	133°30′E	MM	800	156-274††	1, 2	1.73±0.06	7.39(0.99)	1.28	53.6
Hirota	HRT	33°39′N	132°49′E	MM	440	100-435	1	2.31±0.03	7.15(0.22)	1.69	70.8
Okuki	OKK	33°31′N	132°40′E	MM	300	100-270	1	2.34±0.04	6.71(0.36)	1.57	65.8
Tottori	TOT	35°31′N	134°09.5′E		200	50-197	1	5.61±0.10	3.71(0.32)	2.08	87.2
Kyomachi	KYM	32°03′N	130°46′E	hot spring	440	350-440	1	7.57±0.16	5.31(0.08)	4.02	168
Ibusuki	IBS	31°14′N	130°36′E	GA	300		1			21.6	905
						100-160		49.1±1.1	3.75(0.27)	19.4	813
									4.09(0.09)	20.1	842
						200-300		55.7±0.9	4.56	25.4	1060

* MM, Metal Mine; GA: Geothermal Area.

** Range that was used to calculate the gradient.

*** 1, borehole; 2, drifts of mines; BTM, Buried Thermister Method (UYEDA *et al.*, 1974).

**** Unit; mcal/cm sec °C, figures in bracket mean $R/2$.

† Reference values.

†† Measured from sea level.

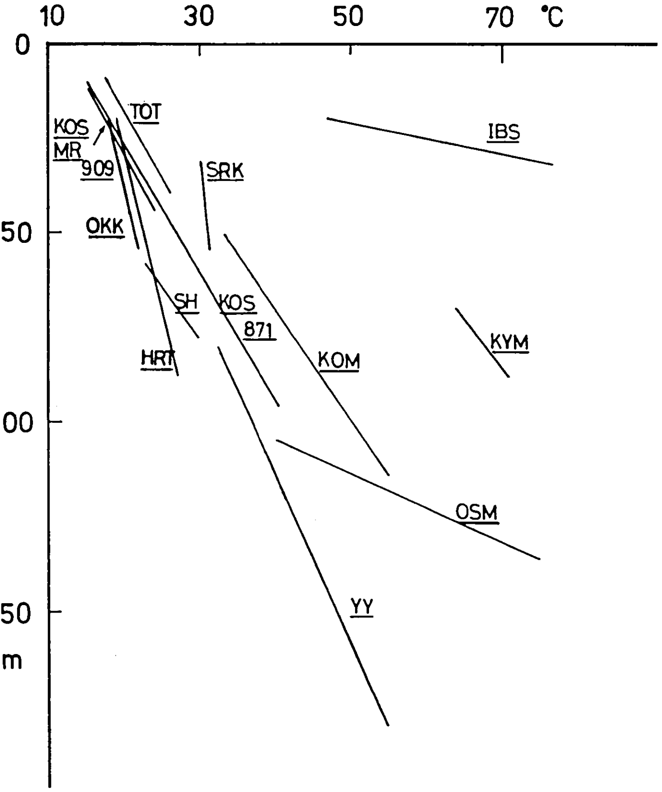


Fig. 24. The schematic temperature versus depth relations at sites studied in this paper. The lower part at Ibusuki and the upper part at Shirataki are not shown.

effects (ANDERSON and UYEDA, 1979). It now seems that we need to know more detailed heat flow distribution in both land and sea areas to be able to comprehend the thermal state and processes in tectonically active areas such as Japan.

Acknowledgement

The authors would like to thank Dr. N. Isshiki, Dr. N. Isezaki, Dr. Y. Honkura, Dr. J. Miyakoshi, Dr. H. Mizutani, Mr. N. Hasebe, Mrs. M. Kono and many colleagues who kindly assisted the authors in the field work. Also we thank Mr. S. Nakashima who helped the authors in the identification of rocks. The staff of the Metal Mining Agency, the Dowa Mining Company, the Nippon Mining Company, the Syowa Mining Comyany, the Electric Power Development Company and the Kyomachi Kanko Hotel are greatly thanked for their kind offices to make the measurements possible.

References

ANDERSON, R. N., M. LANGSETH and J. G. SCLATER, 1977, Mechanism of heat transfer through the floor of the Indian Ocean, *J. Geophys. Res.*, **82**, 3391-3409.

ANDERSON, R. N. and S. UYEDA, 1979, Heat flow in the ocean—especially on the hydrothermal circulation in the crust—, *Kagaku*. **49**, 99-107. (in Japanese)

BULLARD, E. C., 1947, The time necessary for a borehole to attain temperature equilibrium, *Monthly Notices Roy. Astron. Soc., Geophys. Suppl.*, **5**, 127-130.

HORAI, K., 1964, Terrestrial heat flow in Japan (A summary of terrestrial heat flow measurements in Japan up to December, 1962), *Bull. Earthquake Res. Inst.*, **42**, 94-132.

JAEGAR, J. C., 1961, The effect of the drilling fluid on temperatures measured in boreholes, *J. Geophys. Res.*, **66**, 563-569.

MINATO, M., K. YAGI and M. HUNAHASHI, 1956, Geotectonic synthesis of the green tuff regions in Japan, *Bull. Earthquake Res. Inst.*, **34**, 237-264.

SCHRÖDER, J., 1963, Apparatus for determining the thermal conductivity of solids in the temperature range from 20 to 200°C, *Rev. Sci. Instr.*, **34**, 61-5621.

SUZUKI, S., S. SUMIKAWA, S. MATSUMOTO, J. ITO and Y. ARAKAWA, 1975, Study on the application of a new rapid instrument for determination of thermal conductivity, paper read at 1975 Pittsburgh Conf. on Analytical Chemistry and Appl. Spectroscopy.

UYEDA, S., 1961, An interpretation of the transient geomagnetic variations accompanying the volcanic activities at volcano Mihara, Oshima Island, Japan, *Bull. Earthquake Res.* Inst., **39**, 579-591.

UYEDA, S., 1972, Heat flow, in *The Crust and Upper Mantle of the Japanese Area, part* 1, *Geophysics*, Earthquake Res. Inst., Chapter 5, 96-105.

UYEDA, S. and K. HORAI, 1963, Studies of the thermal state of the Earth. The eighth paper: Terrestrial heat flow measurements in Kanto and Chubu Districts, Japan, *Bull. Earthquake Res. Inst.*, **41**, 83-107.

UYEDA, S. and K. HORAI, 1964, Terrestrial heat flow in Japan, *J. Geophys. Res.*, **69**, 2121-2141.

UYEDA, S., T. WATANABE, N. MIZUSHIMA, M. YASUI and S. HORIE, 1973. Terrestrial heat flow in Lake Biwa, Central Japan, preliminary report, *Proc. Japan Acad.*, **49**, 341-346.

UYEDA, S., K. NOMURA and T. WATANABE, 1974, A proposal for regional heat flow studies, Buried thermister probe method—. *Chishitsu news*, **233**, 26-29. (in Japanese)

WILLIAMS, D. L., R. P. VON HERZEN, J. G. SCLATER and R. N. ANDERSON, 1974, The Galapagos spreading center: Lithospheric cooling and hydrothermal circulation, *Geophys. J. Roy. Astron. Soc.*, **38**, 587-608.

YASUI, M., T. KISHI, T. WATANABE and S. UYEDA, 1968, Heat flow in the Japan Sea, in *The Crust and Upper Mantle of the Pacific Area*, edited by L. Knopoff *et al.*, *Amer., Geophys. Union Monogr.*, **12**, 3-16.

3. 日本列島における陸上地殻熱流量の追加測定結果 (11地点)

地震研究所
本多　了
松原幸夫
渡部暉彦
上田誠也
島崎邦彦

日鉱探開株式会社　野村拳一
神戸大学理学部　藤井直之

日本での未発表の陸上地殻熱流量の値をまとめて報告する．測定地点は東北地方に4地点，関東地方に1地点，四国地方に3地点，中国地方に1地点，九州地方に2地点の合計11地点である．地殻熱流量の値は1.28 HFU ($1\mathrm{HFU}=10^{-6}\,\mathrm{cal/cm^2\,sec}$) から21.6 HFUまで ($53.6\,\mathrm{mW/m^2}$ から $905\,\mathrm{mW/m^2}$ まで) 変化しているが，これまでに得られた地殻熱流量分布の傾向とほぼ一致している．