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Terrestrial Heat Flow in Hokkaido, Japan

—— Preliminary Report ——

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Abstruct

The nineteen new measurements of the terrestrial heat flow in Hokkaido, Japan are reported in this paper. The distribution of the terrestrial heat flow in its southwestern part has been clarified, though the other parts remain uncompleted. In the southwestern Hokkaido, the high heat flow values amounting to higher than 2 HFU (1 HFU$=10^{-6}$ cal/cm^2·sec) are observed and in the central Hokkaido, the normal or low heat flow values less than 1.5 HFU are observed. The high heat flow region observed in the southwestern part is coincident with the volcanic region and extends to the Sea of Japan. In the southwestern Hokkaido, the following predominant characteristics are found out: Extremely high heat flow values more than 4 HFU are observed at several sites in a region of the southwestern Hokkaido. On the other hand extremely low heat flow values amounting to 0.6∼0.8 HFU in average are observed in the Ishikari-Tomakomai lowland which is adjacent to the eastern side of the above-mentioned extremely high heat flow region. The former may be interpreted by the crustal temperature amounting to about 1000°C at a depth of 15∼20 km and the latter by the value of about 200°C at the same depth assuming a one-dimensional and a stationary state. In the present discussion, the relations between high heat flow and island arc structure are referred to briefly.

§ 1. Introduction

In and around the Japanese Island Arc, seismic and volcanic activities are very intense and further the anomalous distribution of the underground electrical conductivity inferred from geomagnetic variations is remarkable. From the geophysical and geological veiwpoints, accordingly, the Japanese Island Arc is a very interesting and important region. Recently various interpretations of island arc-trench systems have been presented and the distribution of heat flow is one of the important observations which should have conntact connection with the dyanamical and thermal structure under island arcs. The northeastern Japan is composed of the three active arcs — the Kurile Arc, the Northeastern Japanese Arc and the Izu-Mariana Arc and is more active tectonically in comparison with the southwestern Japan. The Kurile Arc and the Northeastern Japanese Arc intersect each other in Hokkaido; the region near the junction is very interesting geophysically and geologically. From such a viewpoint, the writer has made efforts to measure the terrestrial heat flow values at various points in Hokkaido.

Systematic measurements of the terrestrial heat flow in and around the Japanese Islands have been made since 1957 by Uyeda et al.[1] In Hokkaido the six measurements were made in 1963 by Horai.[2] Thereafter synthetic reports were published by Horai[3] and by Uyeda and Horai.[4] After this time, a number of measurements of the terrestrial heat flow through the ocean floor — the West Pacific Ocean, the Sea of Japan and the Sea of Okhotsk — have been carried out intensively by many Japanese and American geophysicists. As the result, the heat flow pattern around the Japanese Islands has become clearer, for example, which is shown in the paper by Uyeda and Vacquier.[5] Based on the distribution of the terrestrial heat flows, thermal models under island arcs were presented from the standpoint of the plate tectonics by Hasebe et al.[6] and by Oxburgh and Turcotte.[7]

The measurements of the terrestrial heat flow on land, which have various difficulties in comparison with those on the sea, were not further supplemented in the Japanese Islands during three years after 1964. As the structures of the crust and upper mantle beneath the continents and the oceans are essentially different from each other, the heat sources and the mechanisms of heat transfer beneath the continents and the oceans must be different accordingly. Considering such a situation, one may say that the detailed measurements of the terrestrial heat flow on land should be indispensable to the geothermal problems. In particular, in order to investigate the correlation between volcanic activity and terrestrial heat flow, a number of measurements of the terrestrial heat flow on land are necessary at any cost. Based on such a consideration, the writer has made efforts to increase the heat flow measurements in the southwestern Hokkaido.

§ 2. The measurements

Estimation of the terrestrial heat flow Q requires determinations of two different quantities, i.e. the geothermal gradient dT/dZ and the thermal conductivity K of rocks in which dT/dZ is measured. Q is determined by the relation $Q=K \cdot dT/dZ$. In the following, the methods of determinations of the geothermal gradient and those of the thermal conductivity are described briefly. The details of the measurements at each station were already given in the other papers by the writer and his colleagues.[8),9)]

1. Geothermal gradient

The geothermal gradients were determined by the three different methods. One is applicable to the cases of the determination utilizing vertical boreholes, and its example is shown in Fig. 1. Another is applicable to the cases of the determination utilizing horizontal short drill holes in mines or tunnels, and its example is shown in Figs. 2, 3 and 4. The other is applicable to the cases of the determination utilizing bottom temperatures of many vertical boreholes in a certain region, and its example is shown in Fig. 5.

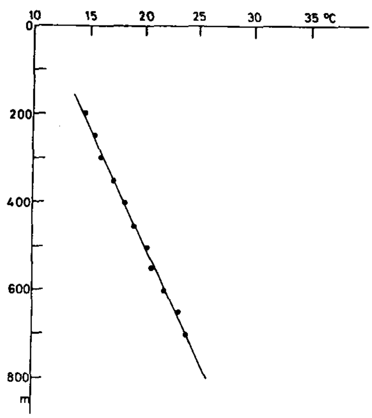


Fig. 1. Temperature-depth relation at Yufutsu II.

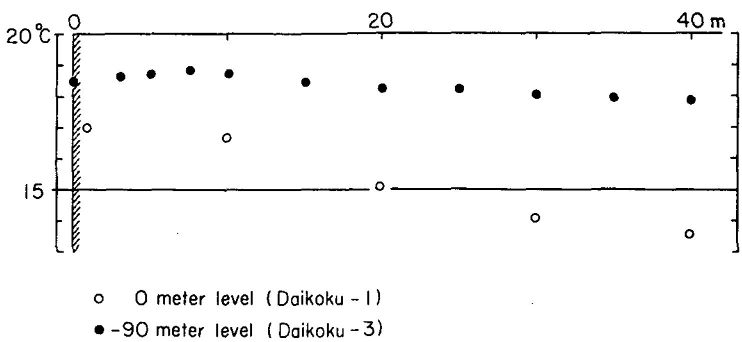


Fig. 2. Temperature distribution in the short horizontal drill holes at Bifue.

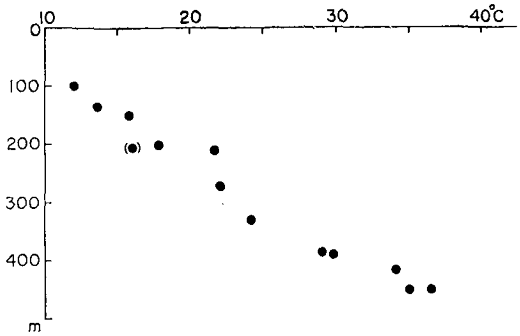


Fig. 3. Temperature-depth relation at Bifue.

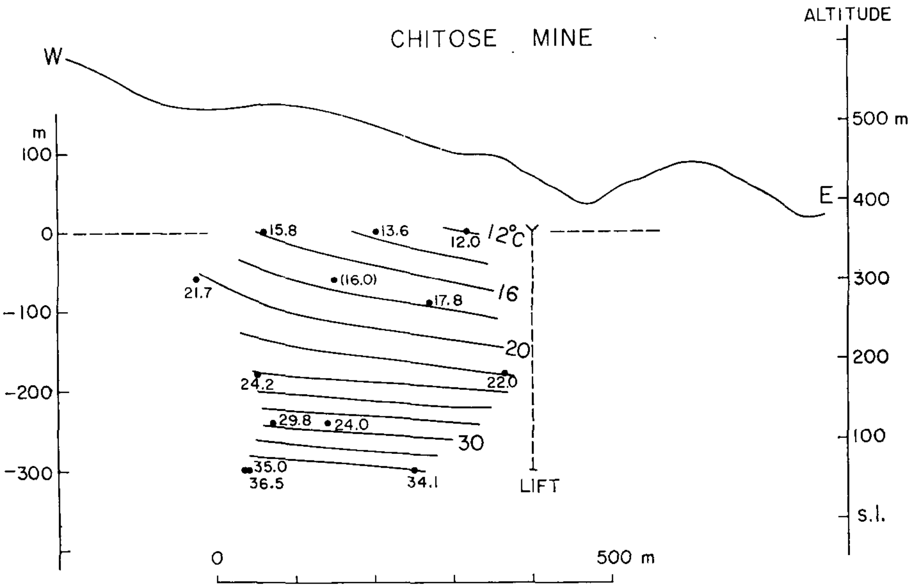
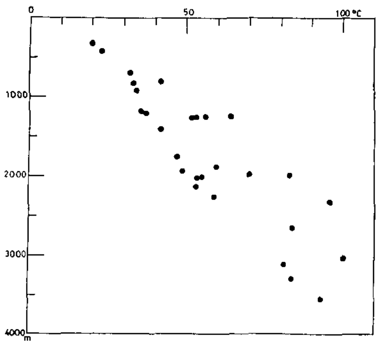


Fig. 4. Distribution of underground isotherms projected on a vertical section at Bifue.

Frequency diagram of the geothermal gradients on land in Hokkaido and the mainland (Japanese islands except Hokkaido) is shown in Fig. 6. In the above diagram, there are two peaks (2~3°C/100 m and 6~7°/100 m) in the data from Hokkaido, while one peak (2~3°C/100 m) for the mainland. In the former, the higher peak (6~7°C/100 m) is related to the extremely high heat flow region in the southwestern Hokkaido. In the latter, one knows that the mean value of the geothermal gradient is 2.51°C/100 m.



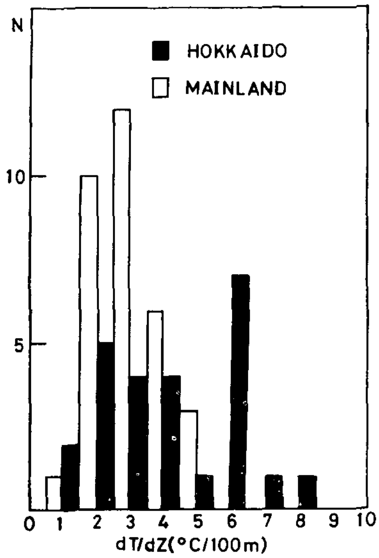


Fig. 5. Fig. 6.

Fig. 5. Bottom temperature-depth relation at various wells in Ishikari-Tomakomai lowland.

Fig. 6. Frequency diagram of geothermal gradient on land in Hokkaido.

2. Thermal conductivity

The thermal conducitivities of rock specimens from the boreholes were measured by the divided-bar method, which is described in detail in the papers by Benfield[10] and by Beck.[11] The error involved in an individual determination of thermal conductivities is about 5% in average in this measurement. Several examples of thermal conductivity measurements by the divided-bar method are shown in Fig. 7. As the estimation of the error of the thermal conductivity, Uyeda and Horai[12] assessed half the range of the thermal conductivities of rocks which compose the stratum. Under a certain circumstance, these values become so large and therefore most of the errors of the terrestrial heat flow values originate in the determination of the thermal conductivity of the stratum. After Horai,[3] probable error in heat flow determinations arising from the ambiguities of these two quantities (geothermal gradients and thermal conductivities) are, in most cases, a few tenths of 1 HFU in order of magnitude, amounting to 20 to 30% of the observed heat flow value. In this paper, the errors of the thermal conductivities are given in two manners:

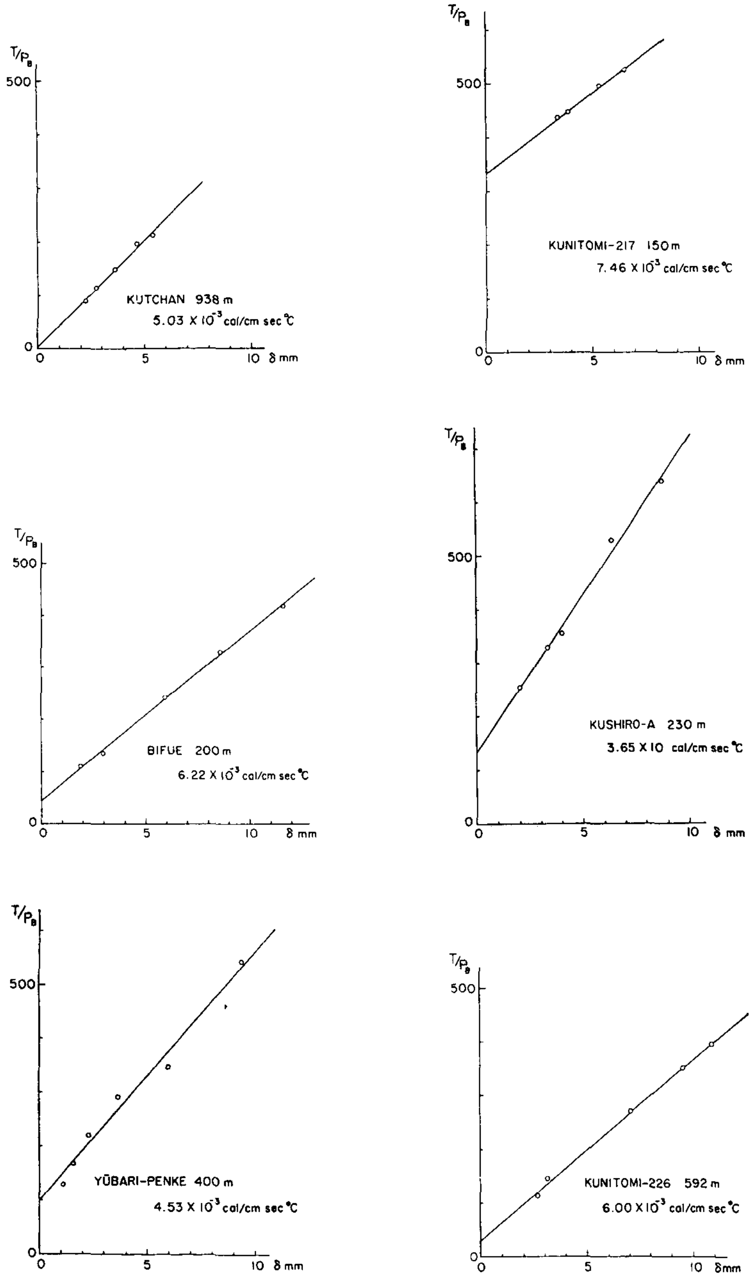


Fig. 7. Examples of thermal conductivity measurements by the divided-bar method.

One is probable error of a representative rock which composes the stratum, and the other in parenthesis in Table 1 shows half the range of the thermal conductivities of rocks which compose the stratum. The error in heat flow determinations may amount to 20~30% in this paper.

§ 3. Classification of the thermal conductivities of rocks

At some boreholes, for example, in oil and gas field, only the geothermal gradients were measured availing no rock specimens for the determination of the thermal conductivity. In these cases, the terrestrial heat flow values have not been determined though many data of underground temperatures have been obtained. If any empirical relations between terrestrial heat flow Q and geothermal gradient dT/dZ are known under some conditions, one may rougly estimate the terrestrial heat flow values. For this purpose, the results of the terrestrial heat flow measurements on land in Japan reported by Horai[3] are compiled. The relation between terrestrial heat flow Q and geothermal gradient dT/dZ is shown in Fig. 8 where the data may be divided into two groups A and B. They are expressed by the following relations:

Region A: $Q_A = (6.24 \pm 0.28) \times 10^{-3} \cdot dT/dZ + (0.08 \pm 0.14)$
Region B: $Q_B = (4.10 \pm 0.42) \times 10^{-3} \cdot dT/dZ + (-0.12 \pm 0.24)$

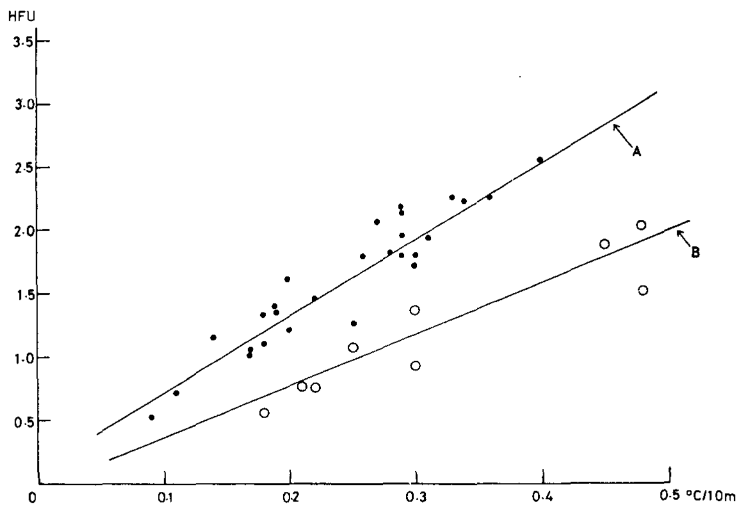


Fig. 8. Relation between terrestrial heat flow and geothermal gradient in Japan.

where Q is measured in HFU and dT/dZ in 10^6 °C/cm. As the errors of the determined values of terrestrial heat flow are relatively large, it may be possible to neglect the constant terms. In these relations, the coefficients of the geothermal gradient dT/dZ may be compared with the thermal conductivities themselves. The coefficients are considered as the apparent thermal conductivities or statistic thermal conductivities. From the detailed consideration of the geology at the boring sites, the two groups may be characterized as follows: Rocks of Region A are relatively hard (mainly volcanic rocks) while those of Region B are relatively soft (mainly sedimentary rocks). And it may be said in this connection that Region B contains oil and gas fields.

Using the above relations, we can roughly estimate the terresttrial heat flow values from only the geothermal gradients when rock samples are not available conceding that such a relation should be the next best method. In Fig. 9, the frequency diagrams of the individual thermal conductivities of rocks which compose the strata in Hokkaido and the mainland are shown divided into A and B region repectively. In both Hokkaido and the mainland, the maximum frequencies of the thermal conductivity are in the ranges

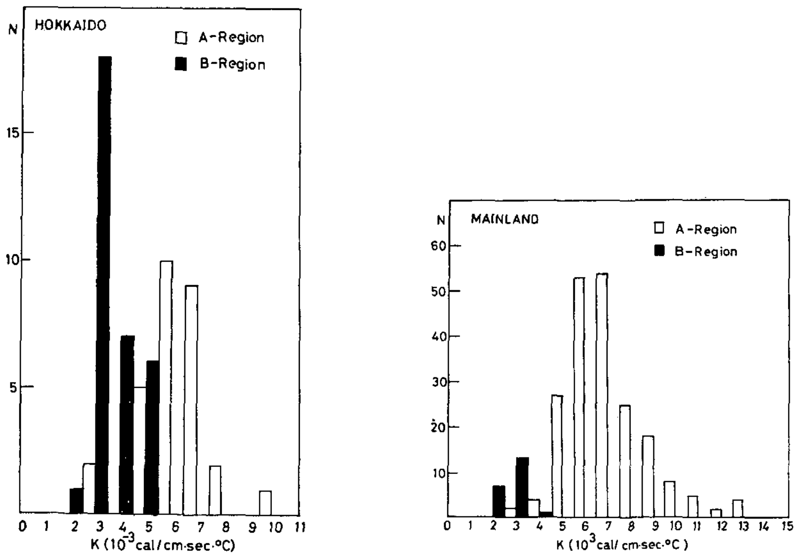


Fig. 9. Frequency diagrams of individual thermal conductivity of rocks from boreholes for heat flow measurements in Hokkaido and the mainland.

of $5\sim7\times10^{-3}$ cal/cm·sec·°C and $3\sim4\times10^{-3}$ cal/cm·sec·°C in the Region A and B respectively.

§ 4. Terrestrial heat flow in Hokkaido

Terrestrial heat flow values in and around Hokkaido calculated from the relation $Q=K\cdot dT/dZ$ are listed in Table 1. This distribution is shown in Fig. 10, where some remarkable features are noticeable.

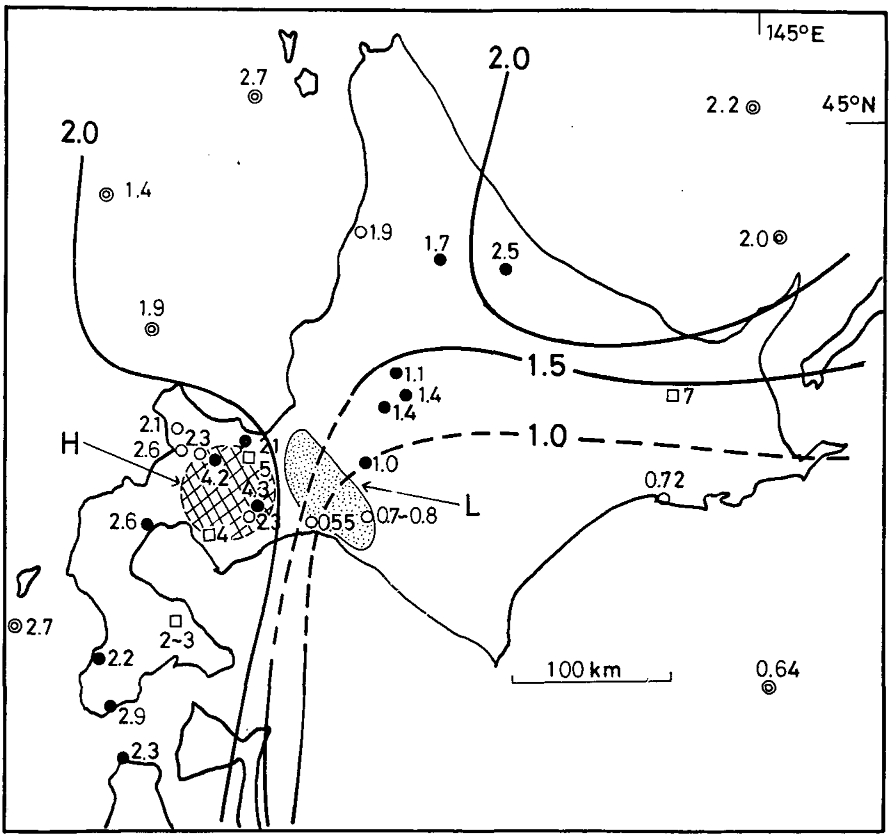


Fig. 10. Distribution of terrestrial heat flow in and around Hokkaido.

The distribution of Tertiary and Quaternary volcanic rocks is exactly coincident with the high heat flow (>2 HFU). If we consider the volcanic region in the southwestern Hokkaido of the Northeastern Japanese Arc, the

Table 1. Terrestrial heat

Station	Abbrev.	Latitude (N)	Longi- tude (E)	Site*	Maximum depth (m)	Temper- ature logging**
Yūfutsu	YFI	42°39′	141°44′	OF	3570	I
Ashibetsu	ASB	43°24′	142°11′	CM	630	I
Kushiro-A	KS	42°58′	144°25′	CM	235	I
Kushiro-B		42°57′	144°26′	CM	235	I
Kunitomi-No. 217	KNTI	42°59′	140°41′	MM	139	I
Kunitomi-No. 219	KNTII	42°59′	140°41′	MM	163	I
Kunitomi-No. 226		43°00′	140°38′	MM	600	I
	YB					
Yūbari-Katsura		42°57′	142°05′	CM	824	I
Yūbari-Penke	SG	42°59′	142°03′	CM	950	I
Sakazukigawa	OT	43°07′	140°32′	SP	347	I
Ōtaki	HT	42°42′	141°11′	SP	600	I
Hattari		43°02′	140°34′	SP	1180	I
Kutchan	KC	42°59,	140°49′	SP	950	I
Bifue	BF	42°43′	141°12′	MM	450	II
Teine	TN	43°06′	141°11′	MM	308	I, II
Jōkoku	JK	41°40′	140°03′	MM	214	II
Yūfutsu	YFII	42°43′	141°56′	OF	700	I
Oshamanbe	OM	42°30′	140°22′	OF	480	I
Yoshioka	YS	41°26′	140°14′	TN	294	II
Tappi	TP	41°18′	140°20′	TN	250	II
Shōwa-shinzan	SS	42°32′	142°52′	SP	349	I
Ōnuma	ON	41°59′	141°59′	SP	700	I
Haboro	HB	44°21′	141°52′	CM	350	I
Shimokawa	SMK	44°14′	142°41′	MM	533	II
Kōnomai	KNM	44°08′	143°21′	MM	524	I, II
Akabira	AB	43°32′	142°02′	CM	700	II
Ashibetsu	ASB	43°33′	142°12′	CM	500	I
Toyoha (after K. HORAI)	TH	42°54′	141°05′	MM	400	II

* CM: Coal mine, MM: Metal mine, OF: Oil field, SP: Borehole for structure

** I: in borehole, II: in drift *** A: good measurement, B: passable

**** Figures in parentheses show $(K_{max}-K_{min})/2$. K_{max} and K_{min} denote the

transition from the low or normal heat flow in the Pacific side of Japan to the high heat flow in the volcanic region and in the marginal sea occurs rather sharply, which shows that the heat source causing the high heat flow may lie at a fairly shallow depth. The terrestrial heat flow in this volcanic region flow in Hokkaido.

Geothermal gradient (°C/100 m)	Measured depth (m)	Thermal conductivity ($\times 10^{-3}$ cal/cm·sec·°C)	Terrestrial heat flow (HFU)	Averaged terrestrial heat flow (HFU)	Class***
1.70±0.14	1500~3570	3.24	0.55	0.55	B
		3.22	0.55		
3.81±0.08	330~ 410	3.74	1.42	1.19	A
1.89±0.03	410~ 630	5.10	0.96		
2.32±0.24	125~ 235	3.62	0.84	0.72	B
1.66±0.07	200~ 235	3.62	0.60		
6.77±0.29	10~ 139	7.46	5.05	4.48	A
6.81±0.21	25~ 163	5.74	3.91		
6.54±0.63	100~ 300	2.92	1.91	2.33	B
4.59±0.35	300~ 600	6.00	2.75		
2.22±0.05	250~ 550	3.86	0.86	0.98	A
2.42±0.06	100~ 550	4.53	1.10		
4.61±0.19	216~ 347	4.64	2.14		B
8.20±0.19	300~ 600	2.77	2.27		B
6.64±0.06	650~1180	3.88	2.58		B
6.02±0.16	150~ 450	6.37	3.83	4.21	A
9.12±1.05	800~ 950	5.03	4.59		
6.36±0.72	98~ 270	6.22	3.96	4.33	A
8.22±0.57	270~ 450	5.71	4.69		
4.29±0.30	0~ 308	4.93(0.71)****	2.11		A
4.00±0.30	0~ 214	5.5. (0.87)	2.20		A
2.05±0.06	200~ 700		0.7~0.8		B
7.23±0.05	125~ 480	3.56(0.61)	2.57		A
6.63±0.07	101~ 294	4.31(0.86)	2.86		A
5.9±	15~ 250	3.85(0.98)	2.27		A
10.0±0.2	160~ 340		~4		C
4.5±	100~ 700		2~3		C
4.54±0.05	—	4.12(0.61)	1.87		B
3.04±	—	5.63	1.71		A
3.96±	—	6.41(1.90)	2.54		A
2.49±0.04	—	4.31(0.72)	1.07		A
3.08±0.03	—	4.38(0.72)	1.35		A
11.3±	—	~5.00	>5.00		C

prospecting, TN: Tunnel
measurement, C: reference measurement
maximum and minimum values of thermal conductivities respectively.

amounts to 2.36 HFU~2.90 HFU in average. The maximum value exceeds 4 HFU. Generally speaking, the terrestrial heat flows increase from the Pacific side to the island arc and marginal sea side. But as seen in Fig. 10, regional anomalies are extremely remarkable. Both the extremely high heat flow region (H-region in Fig. 10) and the extremely low heat flow region (L-region in Fig. 10) exist in Hokkaido. In the H-region, five heat flow values more than 4 HFU are observed including two values (station SS and TH) in geothermal areas. On the other hand in the L-region, the average value of the terrestrial heat flows ranges from 0.6 HFU to 0.8 HFU.

In this paper terrain corrections have not been made. But the writer thinks that such a correction will not give serious influence to the results mentioned here because the anomalies in the heat flow values are remarkable. Frequency diagram of the observed heat flow values in Hokkaido and the mainland is shown in Fig. 11. For the mainland, the peak of the frequency distribution of the terrestrial heat flow is in the range of 1.0~1.5 HFU but for Hokkaido any remarkable feature is not found out. But corresponding to the many measurements in the volcanic regions, high heat flow values are observed more frequently in Hokkaido in comparison with the mainland.

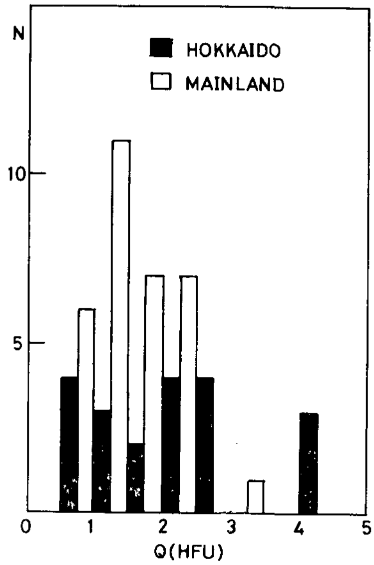


Fig. 11. Frequency diagram of terrestrial heat flow in Hokkaido and the mainland.

§ 5. Discussion

Assuming a one-dimensional and a stationary state, the temperature distribution in the crust is calculated as follows: From the equation of heat conduction

$$\nabla(K\nabla T)+H=0\,,$$

one gets $T=T_0+Q_s/K\cdot Z\text{-}H/2K\cdot Z^2$, where T denotes temperature, Z depth, T_0 surface temperature, K thermal conductivity, Q_s terrestrial heat flow and H heat production by radioactive heat sources.

Here the crust is divided into two layers, granitic and basaltic, and the ratios of their thicknesses are assumed as 1/2 and 2. The depths of the crust in Hokkaido are quoted from Kanamori's paper.[13] And the adopted values of K and H are as follows:

	K(cal/cm·sec·°C)	H(cal/cm^3·sec)
granitic layer	0.007	5500×10^{-16}
basaltic layer	0.005	1100×10^{-16}

In Fig. 12 an example of the results is shown. The vertical section is drawn nearly parallelly to the trend of the Kurile Island Arc in Fig. 13.

Corresponding to the distribution of the terrestrial heat flow, the temperature distribution in the crust shows remarkable contrast regionally. Because of uncertainties of the adopted assumptions and constants, absolute values of calculated temperatures are not so reliable. But the relative differences in temperature in the crust at various areas may be fairly reliable. Since the distributions of radioactive heat sources in the crust and upper mantle are not known in detail, we can not obtain the exact temperature distribution, even if the other assumptions are all right. Recently from the relation between terrestrial heat flow and heat production of surface rocks, some geochemical models of the distribution of the radioactive heat sources in the crust were presented by Roy et al.,[14] and by Lachenbruch.[15),16)] According to these models, it is expected that radioactive heat soruces concentrate into the upper crust than has ever been considered. Therefore the temperature distribution obtained here may give an upper limit of crustal temperatures.

From the volcanological viewpoint, the distribution of the terrestrial heat flow in Hokkaido has the following meanings: The high heat flow region (>2 HFU) approximately coincides with so called "Green Tuff Region". It is considered that Green tuff activity, which was extremely intense marine volcanic activity, started in early Miocene, about 3×10^7 years ago and is still preceeding. According to the calculation of heat conduction in the crust and upper mantle, if the temperature at the depth of 40 km has

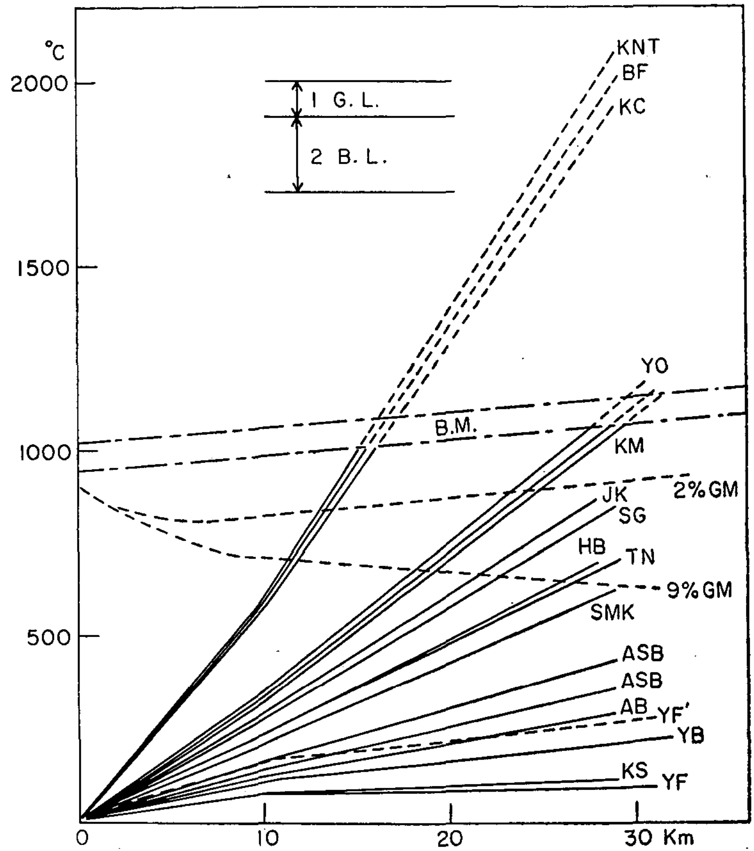


Fig. 12. Temperature distribution in the crust.

reached the melting point of the basaltic material, for example 1200°C and this state has continued to the present, in about 2×10^7 years the crustal temperature may have nearly attained the steady state and the high heat flow more than 2 HFU may be observed at the earth's surface as shown in Fig. 14. In this calculation, the thermal conductivity and the thermal diffusivity in the crust and upper mantle are assumed to be 7.0×10^{-3} cal/cm·sec·°C and 1.44×10^{-2} cm²/sec respectively. Therefore it may be reasonable to connect such a high heat flow observed at present with Green-tuff activity in the past.

According to the above calculations, the temperature at a depth of $30\sim50$ km in the crust or uppermost mantle reaches the melting point of basaltic

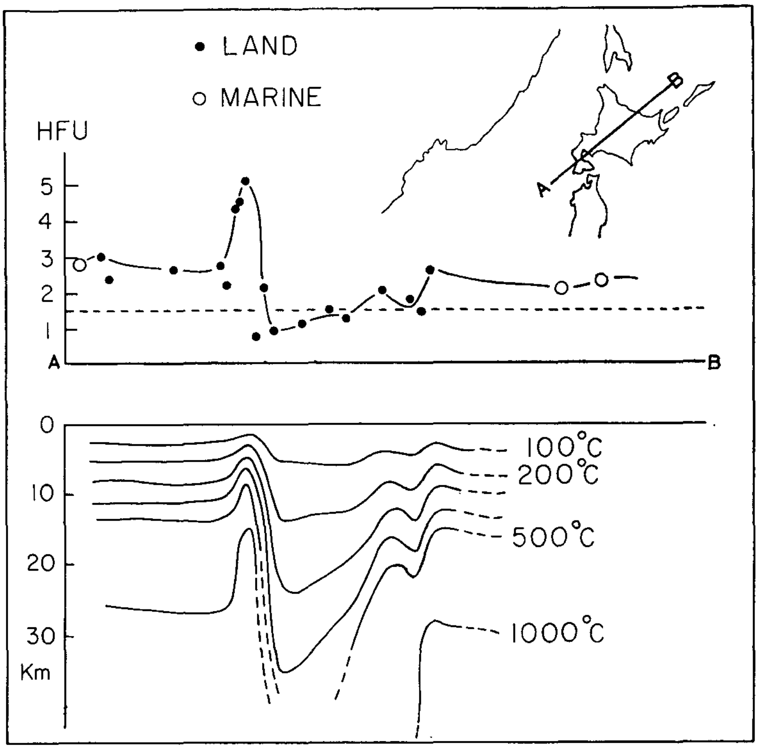


Fig. 13. Temperature distribution of the vertical section nearly parallel to the strike of Kurile Island Arc.

material in the high heat flow region (>2 HFU). Further in the extremely high heat flow region (>4 HFU, H-region in Fig. 10), the depth of the melting point of basaltic material may be shallower, 15~20 km. Utsu[17] points out that the upper surface of the Low-Q, Low-V zone in the continental side may be close to the Moho discontinuity. The depth of the melting point of basaltic material in the lower crust and the uppermost mantle beneath the high heat flow regions may be conincident with the depth of the upper surface of the Low-Q, Low-V zone.

From the viewpoint of the discharge of the thermal energy, volcanoes and hot springs may be considered as high heat flow activities modified by some factors such as tectonic stresses. The direction of the zonal arrangements of these phenomena in Hokkaido nearly corresponds with the

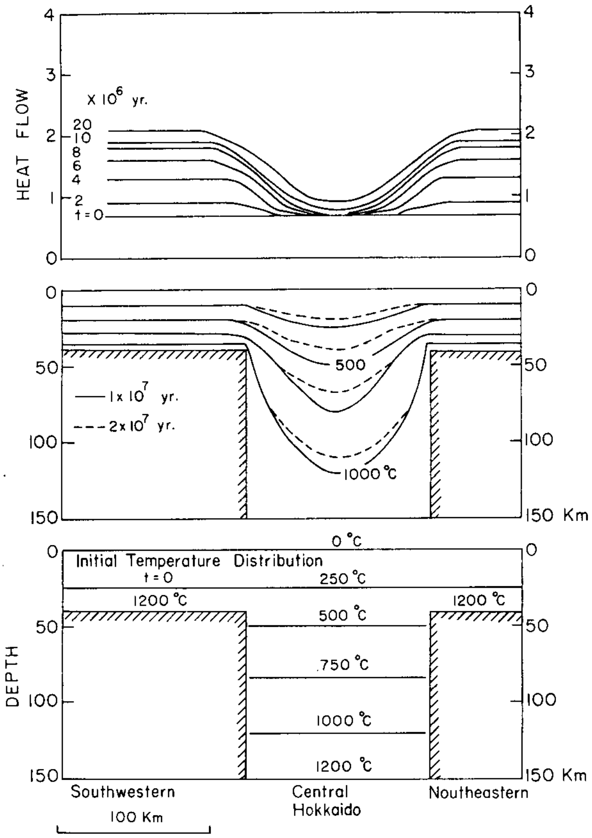


Fig. 14. Variation of surface heat flow and temperature distribution in the crust and upper mantle with time.

strikes of the island arcs as shown in Fig. 15. If the high heat flow values observed at the island arc and the marginal sea are interpreted as the effect of frictional heating of the downgoing plate, the high heat flow values should be observed in the central Hokkaido. However, near the junction of the Northeastern Japanese Arc and the Kurile Arc, there is a metamorphic zone, Hidaka range, by which the geothermal activities characteristic of the island arc structure are interrupted.

On the other hand, the inclined seismic zone, which is regarded as one of the valid evidences for the plate tectonics hypothesis, exists beneath the central Hokkaido. A narrow belt of the Mesozoic metamorphic formation extending from Sakhalin to the central Hokkaido, may have resulted in the

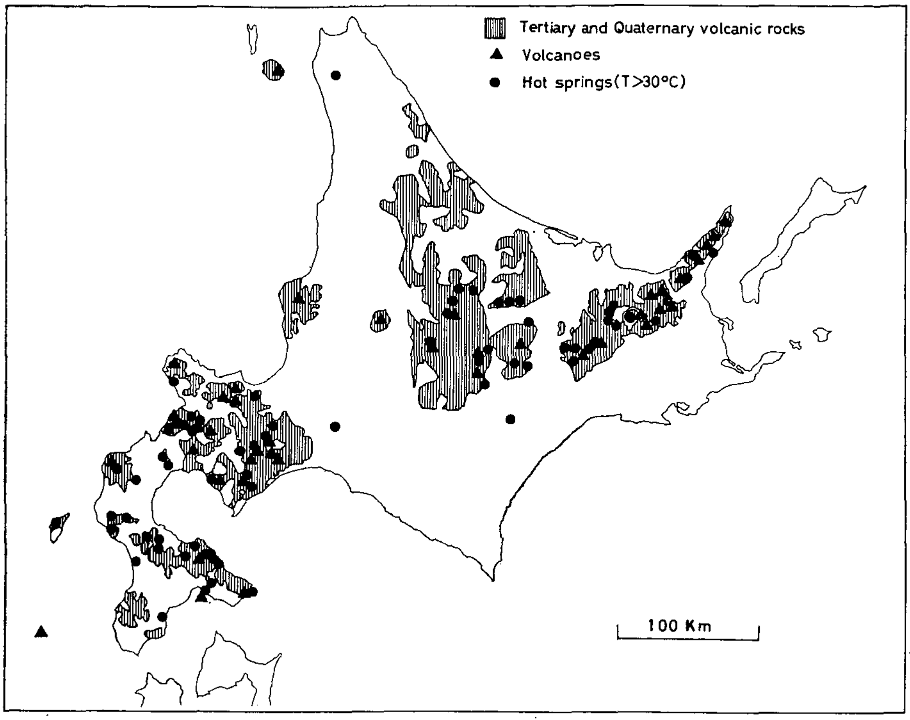


Fig. 15. Geographycal distribution of Tertiary and Quaternary volcanic rocks, volcanoes and hot springs in Hokkaido.

low heat flow activities there because the formation is older than the surroundings.

Besides, the causes of the exceptionally low heat flow in the central Hokkaido, may be the low heat production by radioactive heat sources in the thick sedimentaly layer (amounting to 3~9 km) reported by Kametani and Yoshiyama[18] or in the lower crust, the underground endothermic reactions as examined by Uyeda and Horai,[4] or low mantle heat flow.

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