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26. *Studies of the Thermal State of the Earth. The Sixth Paper: Terrestrial Heat Flow at Innai Oil Field, Akita Prefecture and at Three Localities in Kanto-District, Japan.*

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Summary

Values of terrestrial heat flow have been determined at four localities in Honshu, the Main Island of Japan, for deep wells penetrating sedimentary layers. The sedimentary strata being saturated with water in situ, thermal conductivity of the cores was measured in the saturated state. The heat flow values are, each in the unit of 10^{-6} cal/cm^2sec, 1.49 at Innai Oil Field, Akita Prefecture, 0.74 at Tokyo University, Tokyo, 0.76 at Kashima, Ibaraki Pref. and 0.91 at Katsuta, Ibaraki Pref. As far as the eastern part of Japan is concerned, the data so far obtained seem to suggest that the heat flow is smaller on the Pacific coast side than inland and on the Japan Sea side. Repeated temperature measurements in the wells at Kashima and Katsuta showed that the temperature data obtained immediately after the end of boring are not correct except near the bottom.

1. Introduction

The present report forms a part of the authors' attempt to determine the distribution of the terrestrial heat flow in and around the Japanese Islands. The results, reported already in this Bulletin[1),2)], are summarized in Table 1 and Fig. 1. Though the data are very insufficient, it may be suspected that the terrestrial heat flow values in

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[1)] S. UYEDA, T. YUKUTAKE and I. TANAOKA, *Bull. Earthq. Res. Inst.*, **36** (1958), 251.

[2)] K. HÔRAI, *Bull. Earthq. Res. Inst.*, **37** (1959), 571.

Honshu, the main Island of Japan, are somewhat greater than the world's average ($1.2-1.4\times10^{-6}$ *cal/cm²sec*). On the Pacific coast side, however, rather small values were obtained at Hitachi Mine ($0.63-0.90\times10^{-6}$ *cal/cm²sec*).

In the present work, it is intended to obtain the heat flow values

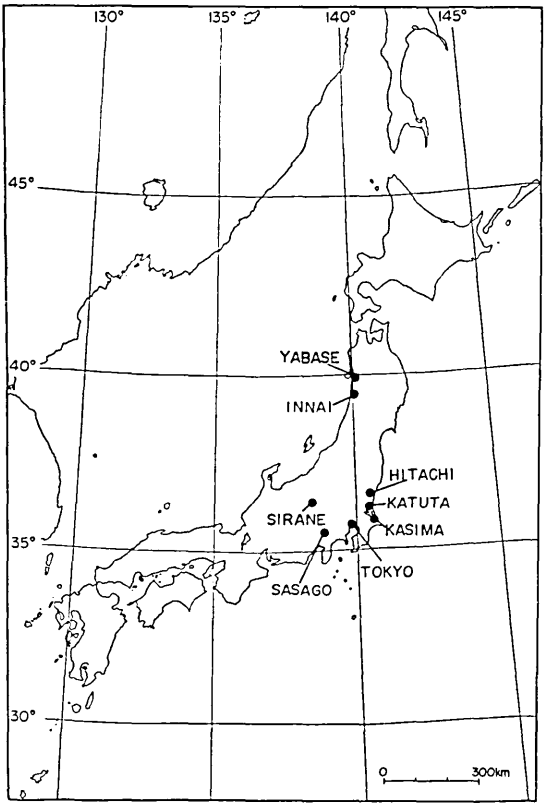

Fig. 1. Map of Japan, indicating the localities where heat flow study has been made.

Table 1. Terrestrial heat flow in Japan already reported.

Locality	Latitude	Longitude	Heat flow (10^{-6} *cal/cm² sec*)
Yabase Oil Field	39°44′N	140°06′E	2.01
Sasago Tunnel	35°37′N	138°48′E	2.06
Hitachi Mine	36°38′N	140°36′E	0.63-0.67 (northern part) 0.78-0.90 (southern part)
Sirane Thermal Area	36°37′N	138°34′E	10.8

for some deep wells: one in Innai Oil Field, Akita Prefecture, two in Ibaraki Prefecture and one in Tokyo University, Tokyo (Fig. 1). The geothermal gradient in these wells were obtained from the already existing data of temperature measurements. The common features of these wells are that the strata penetrated by them are all rather soft sedimentary layers with varied grain size and that the layers are considered to be saturated with water in situ. It was, therefore, not possible to utilize the temperature data of these wells for estimating the heat flow values until the effect of water content on thermal conductivity of sediments was quantitatively elucidated as reported in our preceding communication[3], of which the outline summary is as follows: the thermal conductivity of sediments increases with water content when one adds water to a dry specimen and this increase continues until water saturates the pore of the specimen. With more addition of water, i.e., in the oversaturated state, the thermal conductivity decreases with increase of water content and finally approaches the conductivity of pure water, which is a good deal smaller than that of ordinary rock-forming minerals. An example of the experiments showing the variation of thermal conductivity with water content is reproduced in Fig. 2, in which it is observed that the conductivity takes a maximum value at

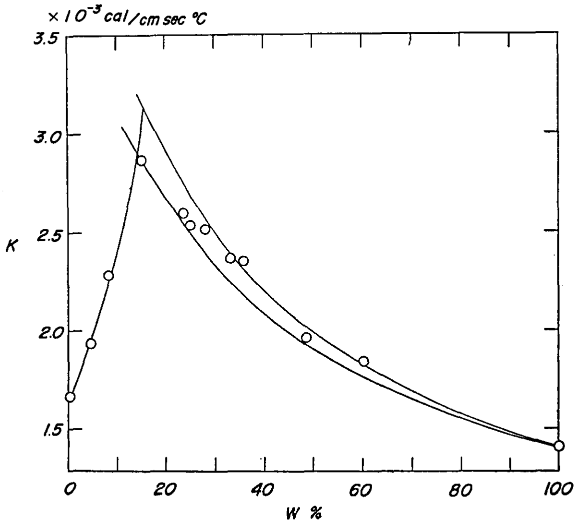

Fig. 2. Relation between thermal conductivity and water content (weight percentage): Lower Sasaoka Bed (IN VIII).

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[3] K. Hôrai and S. Uyeda, *Bull. Earthq. Res. Inst.*, **38** (1960), 217.

the water content by weight of some 18 per cent. It was shown also that, on an experimental as well as a theoretical basis, this water content should be the saturation water content of the specimen. Following the method by Bullard et al.,[4] a simple theoretical explanation was also given to the above mentioned effect of water content on thermal conductivity and *the* maximum thermal conductivity, i.e., the conductivity at the saturation point was expressed as

$$K_{\max}=k_w\frac{3-2v_p(1-k/_wk_s)}{3k_w/k_s+v_p(1-k_w/k_s)}\,, \qquad (1)$$

where k_w, k_s and v_p stand for the thermal conductivity of water and of the mineral grains and the porosity of the specimen. It seems, therefore, legitimate that in estimating the terrestrial heat flow in the cases where the strata concerned are saturated with water in situ to use *the* maximum thermal conductivity of the specimens. In the present work, therefore, we have obtained *the* maximum thermal conductivity for each sedimentary specimens by the same procedures as in 3) and regarded it as the thermal conductivity relevant for the heat flow estimation.

2. Innai Oil Field, Akita Prefecture

Innai (30°16′N, 139°58′E) is one of the oil fields distributed on the Japan Sea coast of north-eastern Japan as shown in Fig. 1. These oil-fields are situated on sedimentary layers of shale, siltstone and tuff of Quarternary and Tertiary ages, forming the Mizuho-Fossa Magna Folded Belt. Of these oil-fields, some temperature data were made available by the courtesy of the Teikoku Oil Company as listed in our previous communication[5]. The temperature-depth data for Innai Oil Field is reproduced in Fig. 3 together with simplified geologic column. Circles in the figure are the results of bottom temperature measurements for the wells with various depths in the oil-field. The measurements were usually made on finishing the drilling, after leaving the wells for at least 20 hours. As will be stated later, there are reasons for regarding the bottom temperature thus measured as the true temperatures. The mean geothermal gradient is estimated as 4.3°*C*/100 *m*. Some cores of the strata were given to the authors by the Teikoku Oil Company; they

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4) E. C. BULLARD, A. E. MAXWELL and R. REVELLE, *Adv. Geophys., III* (1956), 153.

5) S. UYEDA, T. YUKUTAKE and I. TANAOKA, *loc. cit.*

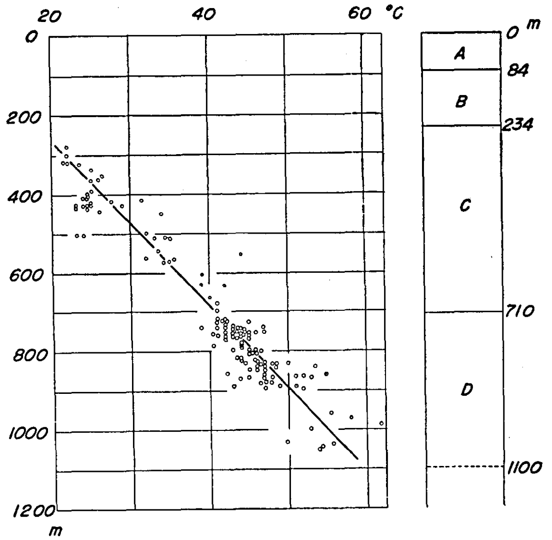

Fig. 3. Underground temperature in Innai Oil Field, Akita Prefecture, and the geologic column:
A....Magurogawa bed,
B....Upper Sasaoka bed,
C....Lower Sasaoka bed,
D....Tentokuzi bed.

Table 2. Thermal conductivity in water-saturated state of the core samples studied.

Locality	Sample No.	Depth (*m*)	Material	Apparent density (dry) (*gr/cc*)	Water-content by weight (%)	Thermal conductivity (10^{-3} *cal/cm sec deg*)	Temperature during measurement (*deg °C*)
Innai	IN VI	449	sandy silt	1.72	15.5	3.18	36.1
	IN VIII	635	sandy silt	1.67	15.2	2.87	22.2
	IN X	827	silty sand	1.48	14.3	3.14	31.5
	IN XIV	1019	silt	1.53	15.3	3.13	34.8
Tokyo Univ.	TU I	64-68	sandy clay	1.73	14.2	3.49	33.1
	TU II	183-192	sandy clay	1.68	15.3	2.95	32.4
	TU III	251-261	clay	1.75	12.6	3.65	30.1
Kashima	KS II	203-205	sandy silt	1.56	14.1	2.90	32.5
	KS III	322-324	sandy silt	1.61	15.7	3.65	32.2
	KS VII	555-558	sand	1.71	12.4	4.49	32.5
	KS VIII	655-658	silt	1.61	19.8	3.22	32.9
Katsuta	KT I	345	silt	1.58	19.7	2.75	34.8
	KT II	503	silt	1.65	17.2	2.67	33.1
	KT III	755	sandy silt	1.90	12.4	3.29	33.9
	KT IV	905	sandy silt	1.97	12.2	3.38	34.5

are all rather soft shale which are easily powdered. By the procedures stated already, the thermal conductivity of these shales in the water-saturated state was obtained as listed in Table 2. Since the geothermal gradient appears to be roughly constant all through the depth (Fig. 3) and so does the thermal conductivity, it may be permissible to take the simple mean value (3.11×10^{-3} *cal/sec cm deg*) from Table 2 as the representative thermal conductivity. Thus the heat flow at Innai Oil-field is estimated to be 1.49×10^{-6} *cal/cm²sec*. Compared with the heat flow value 2.01×10^{-6} *cal/cm²sec* at Yabase Oil-field, situated some 60 *km* north of Innai, it is considerably small. There seems to be a need for more determinations before establishing the exact average heat flow in this part of Japan.

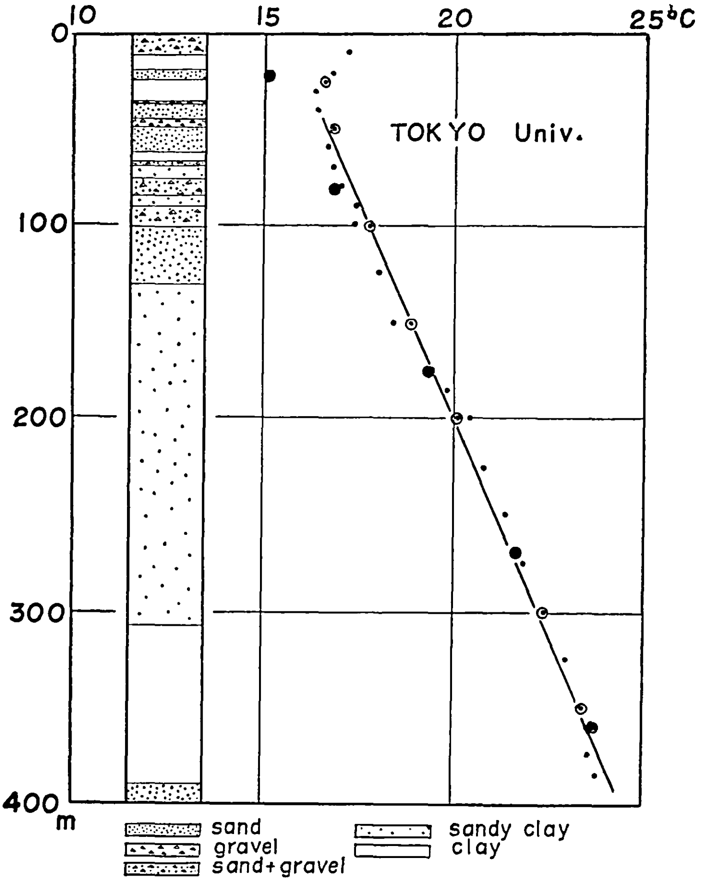

Fig. 4. Temperature-depth curve in the well at Tokyo University.

3. The Deep Well in Tokyo University, Tokyo

The temperature-depth curve for the deep well (35°42′N, 139°46′E) in Tokyo University is as shown in Fig. 4. The well was drilled in the period 1894–1898 by Shinsai Yobo Chosakai (Imperial Earthquake Investigation Committee)[6]. The temperature data shown by double circles are by A. Tanakadate[6] for the period 1901–1903, and those by large and small full circles are by us in 1957[7]. The geothermal gradient is $2.20°C/100\,m$. The strata penetrated by the well are the Quaternary marine sediments of the Kanto Structural Basin that has subsided since late Miocene. The specimens collected in the course of drilling have been preserved. They, however, are all dried clay, sandy clay, sand and gravel. The authors selected three specimens of clay and sandy clay at the depths of 65–81 *m*, 183–192 *m* and 251–261 *m* for the thermal conductivity measurement in the water-saturated state. The results are listed in Table 2. At the present stage of the accuracy of information, it was decided to take the simple mean value (3.36×10^{-3} *cal/cm sec deg*) of the individual thermal conductivity values for the representative thermal conductivity. As for the heat flow value, thus, $0.74 \times 10^{-6}\,cal/cm^2sec$ was obtained.

4. Two Deep Wells in Ibaraki Prefecture

For natural underground gas development, test boring at several localities in Kanto District has been conducted. Temperature-depth relations and core specimens were supplied to the authors by the Geological Survey for two survey holes in Ibaraki Prefecture owned by Nitto Chemical Industry, Tokyo: one is an 888.8 *m* deep hole at Kashima (KT-1) and the other is a 906.9 *m* deep hole at Katsuta (TR-1). The locality maps for these wells are in Fig. 5, a, b and Fig. 6, a, b. Their positions are 35°57′N, 140°41′E and 36°24′N, 140°30′E respectively.

Kashima well is located on the eastern marginal area of the Kanto Structural Basin and the core specimens belong to Quaternary (upper 50 *m*) and Tertiary (below 50 *m*) sediments. The thermal conductivity of the sediments in the water-saturated state is listed in Table 2, giving the mean value of 3.57×10^{-3} *cal/cm sec deg.* Katsuta is situated on the southern end of the thick Tertiary beds occupying the southern marginal area of Abukuma Plateau along Tanakura Sheared Zone. The

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[6] A. TANAKADATE, *Rep. Imp. Earthq. Invest. Committ.*, **45** (1903), 17.

[7] S. UYEDA, T. YUKUTAKE, and I. TANAOKA, *loc. cit.*

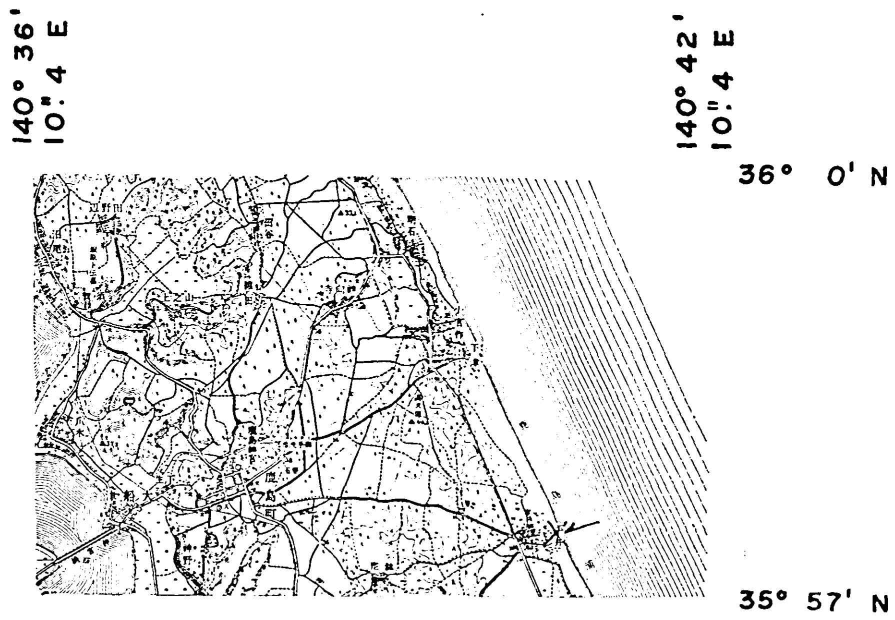

Fig. 5, a. Locality map of Kashima well.

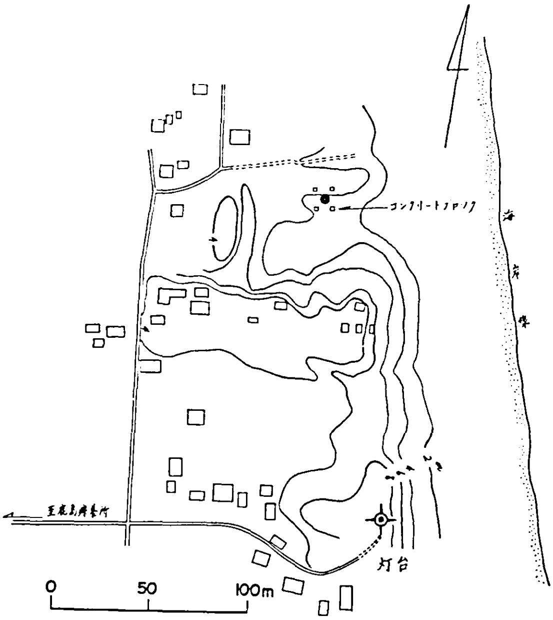

Fig. 5, b. Sketch map of Kashima well.

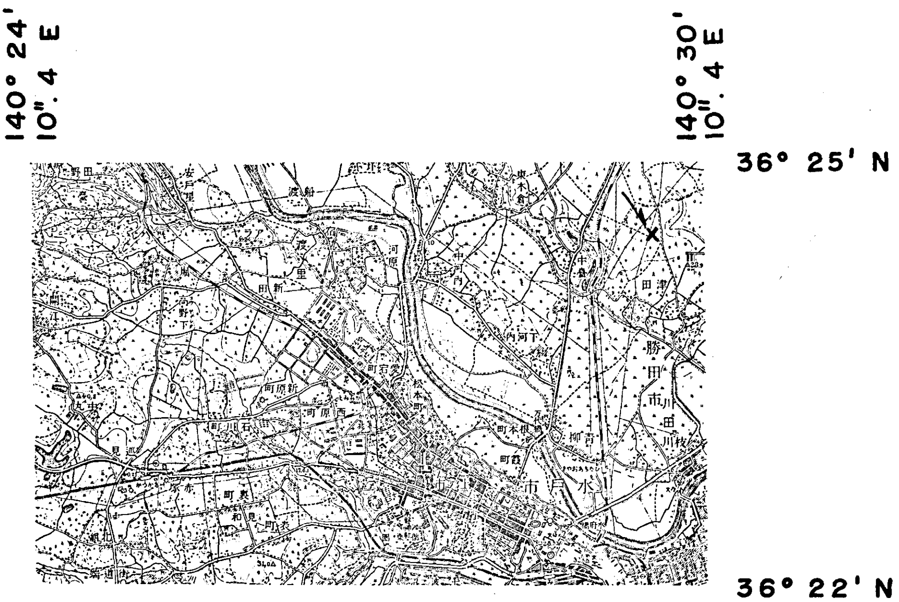

Fig. 6, a. Locality map of Katsuta well.

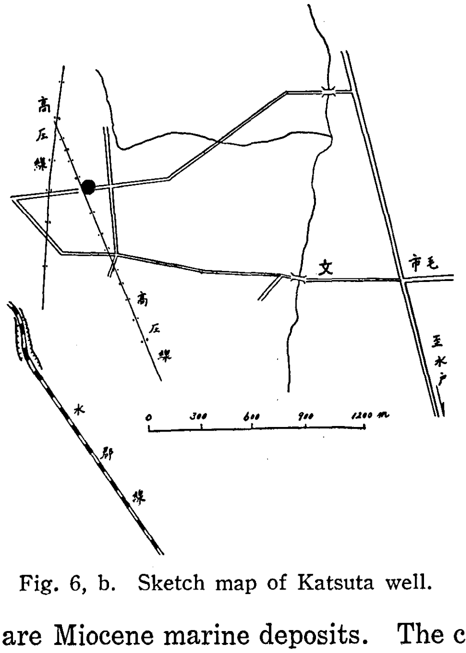

Fig. 6, b. Sketch map of Katsuta well.

strata below 50 *m* are Miocene marine deposits. The conductivity values for water-saturated state are again in Table 2: mean value being 3.02×10^{-3} *cal/cm sec deg*. The temperature-depth relation in these wells obtained by the Geological Survey are shown in Figs. 7 and 8 by thin lines: the data are the results of continuous recording of temperature by a Ni-Mn bridge as the Ni-resistor was lowered with a speed of 5-10 *m/min*. The temperature of the resistor was known to follow about 80% of sudden change in ambient temperature within 7 seconds. The temperature measurement was made one or two days after electrical

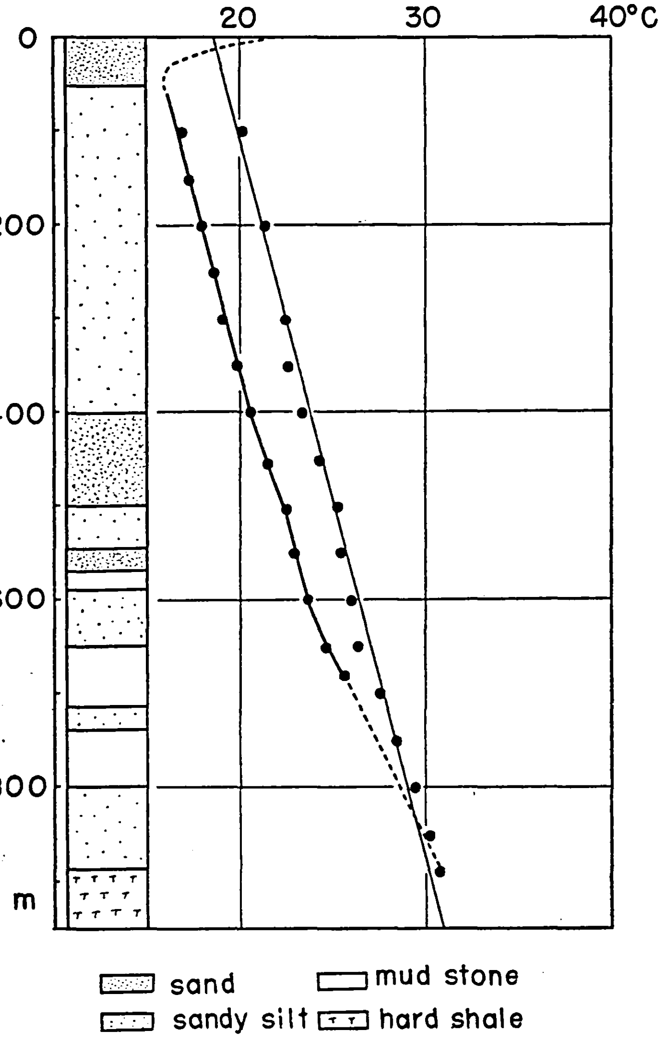

Fig. 7. Temperature-depth curves for Kashima well and the geologic column:
thin line.....measurement immediately after drilling,
thick line....measurement at 20 months after drilling.

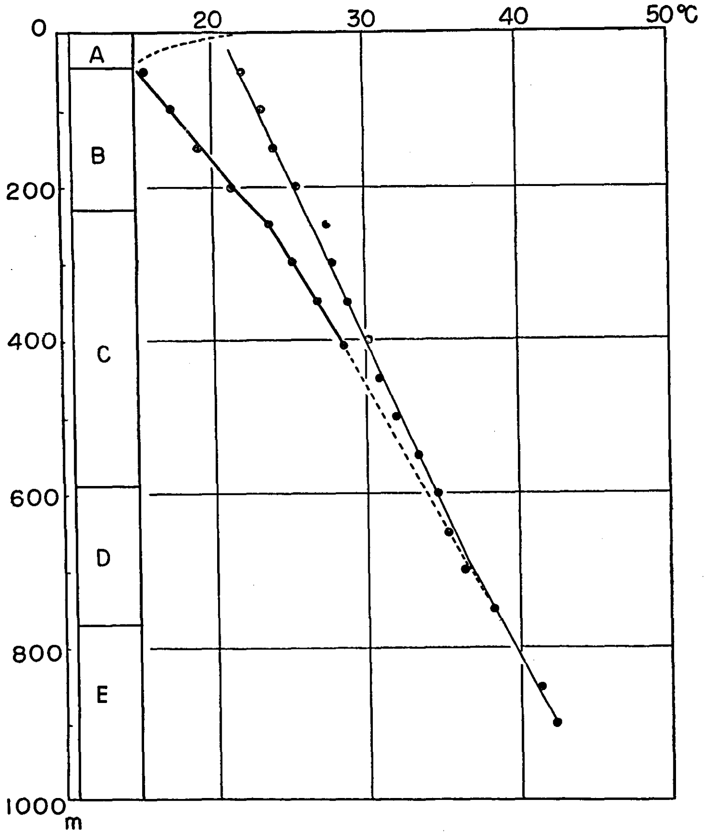

Fig. 8. Temperature-depth curves for Katsuta well, and the geologic column:
A....Kamiichi gravel,
B....Genjigawa bed,
C....Zuiryu bed,
D....Daiman bed,
E....Sionokusa bed,
thin line.....measurement immediately after drilling,
thick line....measurement at 9 months after drilling.

Table 3. Drilling schedule of Kashima and Katsuta wells.

	Kashima (KT-1)	Katsuta (TR-1)
Start	Sept. 1, 1958	Aug. 28, 1959
End	Oct. 10, 1958 at 891 m	Oct. 9, 1959 at 906 m
Electrical Logging	Oct. 13, 1958	Oct. 15, 1959
Temperature Logging	Oct. 15, 1959	Oct. 16, 1959

logging which immediately followed the completion of drilling. The dates of the drilling work for these wells, according to the Nitto Chemical Industry, are as shown in Table 3.

Although the above continuous run may be considered as having recorded the actual temperature nearly correctly, there still remained a fair possibility that the actual temperature then was already seriously affected by the effect of drilling. Bullard some time ago discussed the problem of the temperature disturbances due to drilling[8]: disturbance by heat generation due to the tool is smaller than that by circulation of drilling fluid which results in heating at the upper part of the hole and cooling at the lower part. Considering that the heat capacity of the fluid standing in the hole is so small that the change in temperature after the bore is finished can be neglected, the disturbance at any depth was assumed to be caused by the difference in the temperature of the virgin stratum and that of the fluid and this disturbing condition holds from the moment when the hole passes that depth ($t=0$) and lasts until the bore is finished, ($t=t_1$). Then the disturbance temperature at a time t ($t>t_1$) was found to be expressed by, after some simplifying assumptions,

$$\frac{T}{T_0}=-\frac{\{Ei(-r^2/4kt_2)-Ei(-r^2/4kt)\}}{Ei(-a^2/4kt_1)}\,, \tag{2}$$

where

$$-Ei(-z)=\int_z^\infty \frac{e^{-z}}{z}dz\,,$$

and

T=disturbance temperature at a point r from the axis of the hole,
T_0=disturbance temperature at the wall of the hole at $t=t_1$.
k=thermal diffusivity of the stratum,
$t_2=t-t_1$, and a=radius of the hole.

When $r^2/4kt$ is small, (2) can be approximated by,

$$T/T_0=\log(1+t_1/t_2)/(\log 4kt_1/a^2-0.577)\,. \tag{3}$$

From these Bullard calculated, as a function of t_1, the value of t_2/t_1, needed to reduce the disturbance to 1 per cent of its initial value, for extreme values of $a^2/4k$ likely to be encountered in practice. His results are as shown in Table 4.

In the present cases, the diameters are 7.7 inches and $6\frac{3}{4}$ inches for

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[8] E. C. BULLARD, *Mon. Not. Roy. Astr. Soc., Geophys. Suppl.*, **5** (1947) 127.

Table 4. Time necessary to leave the bore to make the disturbance less than a per cent (after E. C. Bullard).

t_1	0.1	1	10	100	in days
t_2/t_1	14	11	8.3	7.4	for $a^2/4k=58$
t_2/t_1	51	28	18	13	for $a^2/4k=38,000$

the Kashima and Katsuta holes respectively. Taking 10 *cm* for a, 0.005 for k, we get the approximate value of $a^2/4k$ for the present cases as 5000, which is well between the above extreme cases. The records of the drilling operation in Table 3 show that t_1 in our cases is about 30 days for the upper part of the holes. Consequently, in order of obtain true temperatures at the upper part, one may have to leave the hole for some 300 days. For the lower part, however, t_1 is small. Fig. 9 shows the records of drilling of the Kashima and Katsuta holes for the last ca 100 *m*. From this diagram, it may be observed that the last few

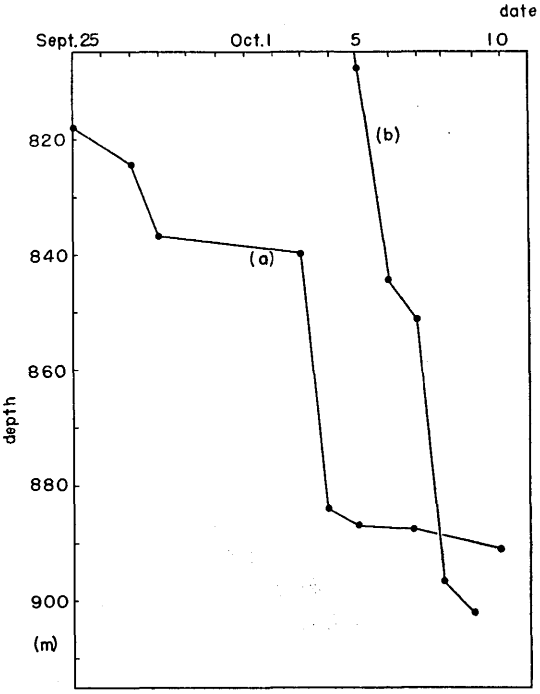

Fig. 9. Diagram showing the depth of the bores at final stage of drilling:
(a)....Kashima well, (b)....Katsuta well.

meters were drilled in a time which is a fraction of a day, and therefore the measurement at one or two days after the bore was finished would give very nearly the true temperature for the bottom. Such a fact has recently been reported by Cooper and Jones[9]. Moreover, in the actual drilling of these wells, water supply being insufficient and the drilling fluid being expensive, circulations of the fluid was made in such a way that fluid coming up from the bottom was recovered and filtered to be used as many times as possible. This, in fact, resulted in a rise of the temperature of the circulating fluid, both by heating at the bottom part and by heating on the sunlit surface, nearly to the bottom temperature. Therefore, as for the thermal disturbance, the cooling at the bottom must have been much smaller than the heating near the top.

Recently, the Nitto Chemical Industry has kindly allowed the authors to re-measure the temperatures in these wells. The measurements were made on June 24 and 25, 1960 for Kashima and Katsuta wells respectively. Unfortunately, owing to various difficulties, the depths covered were only 680 *m* and 410 *m* and the results are shown in Fig. 7 and 8 by thick lines. Considering the length of the time during which the wells have been left untouched since the first measurement, it is highly probable that the new data will give the true temperature in the wells. It is interesting to note that the extrapolation of the new data coincides well with the bottom temperatures of the old data. This may be a proof for the above argument for the correctness of bottom temperature measured soon after drilling.

The information about the thermal conductivity of the strata concerned is limited. As stated above, only three cores were measured for each holes. This situation makes it rather worthless to try to correlate the observed changes with depth of the geothermal gradient and thermal conductivity. For Kashima well, it seems best to use the average of the measured conductivity, 3.57×10^{-3} *cal/cm sec deg* as the representative one. The value of heat flow at Kashima, then, may be obtained as follows; The mean geothermal gradients based on the old and new data are 1.28°*C*/100 *m* and 1.50°*C*/100 *m* giving the heat flow values of 0.46×10^{-6} *cal/cm²sec* and 0.56×10^{-6} *cal/cm²sec* respectively. Of these two values, the first one is too small because the gradient is underestimated, and the second one may be closer to the true value. Below 600 *m*, (Fig. 8), the temperature data lie well on the line which passes through the

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[9] L. R. COOPER and C. JONES, *Geophys. Journ. Roy. Astr. Soc.*, **2** (1959), 116.

bottom temperature of the old data. On account of the possible correctness of the bottom temperature, the gradient below 600 *m* seems to be 2.6°*C*/100 *m* giving the heat flow value of 0.96×10^{-6} *cal*/*cm*^{2}*sec*. This is the highest value from the data available at present. Considering the above stated situation, the terrestrial heat flow at Kashima may be safely estimated to be about $0.56\sim0.96\times10^{-6}$ *cal*/*cm*^{2}*sec*, the mean value being 0.76×10^{-6} *cal*/*cm*^{2}*sec*. For Katsuta well, the average conductivity being 3.02×10^{-3}*cal*/*cm sec deg*, the old data of temperature give geothermal gradient and the heat flow as 2.40°*C*/100 *m* and 0.73×10^{-6} *cal*/*cm*^{2}*sec*. The new data clearly show (Fig. 9) a kink in temperature-depth curve at about 250 *m*. As no conductivity data are available above 250 *m*, we take, from the new data, the gradient between 400 *m* and 250 *m* which is 3.12°*C*/100 *m*. This gives the heat flow value as 0.94×10^{-6} *cal*/*cm*^{2}*sec*. In this case, the extrapolation to the old bottom temperature gives the gradient of 2.90°*C*/100 *m* and the heat flow of 0.88×10^{-6} *cal*/*cm*^{2}*sec*. From these three values, the first being definitely underestimatimad we may be able to state that the terrestrial heat flow at Katsuta is around 0.88 and 0.94×10^{-6} *cal*/*cm*^{2}*sec*, their mean value being 0.91×10^{-6} *cal*/*cm*^{2}*sec*.

Conclusion and Acknowledgments

Values of terrestrial heat flow obtained in the present work are, 1.49×10^{-6} *cal*/*cm*^{2}*sec* at Innai Oil-field, Akita Prefecture, 0.74×10^{-6} *cal*/*cm*^{2}*sec* at Tokyo University, Tokyo, 0.76×10^{-6} *cal*/*cm*^{2}*sec* at Kashima, Ibaraki Prefecture, and 0.91×10^{-6} *cal*/*cm*^{2}*sec* at Katsuta, Ibaraki Prefecture. Combining these data with those obtained previously (Table 1), it may be concluded with some reserve that the heat flow is consistently smaller on the Pacific side of the Japanese Island. These small values are even less than the world average. Considering that the Japanese Islands are very active in seismicity and other geophysical and geological events, these small values of heat flow may seem strange. It may, however, not necessarily be surprising if one assumes that some convective movements prevails in the mantle beneath Japan in such a way that the Pacific side of the Japanese Island is located on the sinking part of the convective cell. Existence of the Japan Trench off coast may, if the same pattern of oceanic heat flow should exist as was found in the south-eastern Pacific by Herzen10), incorporate this hypothesis.

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10) R. von HERZEN, *Nature*, **183** (1959), 882.

Many more reliable determinations of terrestrial heat flow all over Japan as well as in the Pacific Ocean are undoubtedly required to establish this premature speculation.

In concluding, the authors wish to express their sincere thanks to Dr. T. Rikitake for his encouragement. They are also grateful to Prof. C. Tsuboi and Prof. T. Nagata for their interest in the present work. Kind offices of the staff of the Teikoku Oil Company, Nitto Chemical Industry, and Japan Geological Survey, especially Messrs. Y. Izumibe, J. Suyama and Y. Ono are cordially acknowledged.

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26. 地球熱学 (第6報) 秋田県院内油田，および，関東地方三地点における地殻熱流量

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第五報に報告したように，堆積岩の熱伝導度は，水による飽和状態において最大値を有する．油田，ガス田等の深井では，地層は，飽和状態にあると考えられるので，そのような場所での地殻熱流量の推定には上記の最大熱伝導度が用いられるべきである．このような考えに従つて，本州内四地点での地殻熱流量をもとめた．結果は，秋田県院内油田において 1.49×10^{-6} *cal/cm*^{2}*sec*，東京大学において 0.74×10^{-6} *cal/cm*^{2}*sec*，茨城県鹿島において 0.76×10^{-6} *cal/cm*^{2}*sec*，および同県勝田において 0.91×10^{-6} *cal/cm*^{2}*sec* である．従来得られた結果と照合すると，東北日本に関する限り，太平洋側では，地殻熱流量は，世界的平均より更に低いようである．更に測点を増し，この傾向を確めることが望まれる．また，ボーリングに伴う地中温度の擾乱の程度，およびこの擾乱の恢復について有用な測定が，鹿島，勝田のガス井について行なわれた．