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6. *Studies of the Thermal State of the Earth. The Seventh Paper: A Sea Bottom Thermogradmeter.*

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Summary

An apparatus for measuring the geothermal gradient in the sea bottom, or a sea bottom thermogradmeter, has been constructed. The apparatus consists of a probe containing two pairs of thermistors and a recorder set in a pressure tight and water proof steel container. Each of the pairs of the thermistors forms the two arms of an A.C. bridge. The other two arms of the bridge comprise a continuous potentiometer. Signals from the two A.C. bridges consisting of two pairs of thermistors and two potentiometers are separately amplified through amplifiers X and Y.

As the potentiometers rotate coaxially at the same speed as the recording drum, the phase angle of the output signal of the amplifier changes 180° when the potentiometer passes its balancing position. Therefore, as far as the phase angle is concerned, the output signal can be represented logically. It is the same for the output signal of the other amplifier. The output signals of the amplifiers X and Y are fed to an "and" gate circuit. The output signals of the gate circuit trigger the relay, and the contact of the relay makes or breakes when the potentiometers pass through their balancing positions, which give marks on the facsimile paper on the drum. Two pairs of thermistors give the temperature differences between the bottom and the top, and between the bottom and the middle point of the probe. The temperature differences ranging from 0°~2°C can be recorded on the paper with an accuracy of 0.001°C for about 2.5 hours.

Some preliminary experiments indicated that the apparatus will serve for determining the terrestrial heat flow through the sea bottom.

1. Introduction

Measurement of the terrestrial heat flow through the ocean floor has been carried out both in the Atlantic and Pacific Oceans[1),2),3)]. The pioneering work by Bullard, Maxwell and Revelle showed that the heat flow in the oceanic area is almost equal in amount to that in the continental area. This result, being in sharp disagreement with general expectations, seems to indicate that the mantle beneath the oceans may be quite different thermally from the mantle beneath the continents. More spectacular results have been reported by Herzen recently. Herzen's results for the south-eastern part of the Pacific showed a remarkable geographical distribution of the heat flow for which the only reasonable explanation appears to be the existence of thermal convection in the mantle[3),4)].

The Japanese Islands form one of the most active parts of the island arcs around the Pacific Ocean with regard to seismicity, volcanicity and recent orogenesis. In the hope of contributing to the clarification of the mechanism of these activities, we have conducted measuring activities of the terrestrial heat flow over the Japanese Islands since 1958[5),6),7)]. We have also wished to take measurements in the oceanic area surrounding Japan. Recently, the m.s. "Ryofu Maru" of the Japan Meteorological Agency has been equipped with a 13,000 m long tapered wire with a powerful winch and the Deep-Sea Research Committee has been organized by the Japan Society for the Promotion of Science[8)]. The Committee plans to measure the heat flow through the ocean floor as a part of its research project. The work was started in 1960 with the construction of the necessary instruments. The present report gives an account of thermogradmeter built to this end.

[1)] E. C. BULLARD, *Proc. Roy. Soc. A*, **222** (1954), 408.

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

[3)] R. von. HERZEN, *Nature*, **183** (1959), 882.

[4)] T. RIKITAKE and K. HÔRAI, *Bull. Earthq. Res. Inst.*, **38** (1960), 403.

[5)] R. UYEDA, T. YUKUTAKE and I. TANAOKA, *Bull. Earthq. Res. Inst.*, **37** (1958), 251.

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

[7)] S. UYEDA and K. HÔRAI, *Bull. Earthq. Res. Inst.*, **38** (1960), 421.

[8)] K. TERADA and H. FUTI, *Reports of Japanese Expeditions of Deep-Sea*, **1** (1960): *Oceanogr. Mag.* **11** (1960), 145.

2. General Description

The terrestrial heat flow, Q, may be obtained from measurements of the geothermal gradient, $\Delta T/\Delta h$, and the thermal conductivity, K, of the strata concerned, namely,

$$Q=K\cdot\Delta T/\Delta h \qquad (Q \text{ in cal/cm}^2\text{sec}, K \text{ in cal/cm sec deg. C}, T \text{ in deg. C and the depth } h \text{ in cm.})$$

The quantity $\Delta T/\Delta h$ at the sea bottom can be measured by thermistors placed in the tube penetrating vertically into the bottom. The constancy of the temperature at deep bottom[9] enables us to measure $\Delta T/\Delta h$ at the surface of the sea bottom, whereas $\Delta T/\Delta h$ on land has to be measured fairly

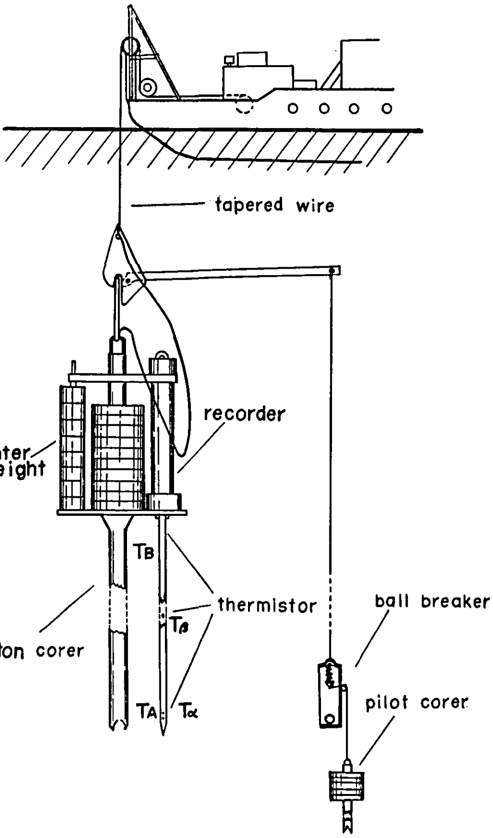

Fig. 1. Schematic diagram showing the operation of apparatus R. 1.

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[9] J. Masuzawa, *presented at the annual meeting of Japan Oceanographical Society, November*, 1960 or W. S. Wooster and G. H. Volkmann, *Jour. Geophys. Res.*, **65** (1960), 1239.

deep below the surface. K is measured in laboratory by usual method[10] from the specimens of the bottom sediments obtained by a core-sampler.

The general layout of apparatus No. 1 (R. 1) is as shown in Fig. 1. The probe and the recorder are attachable to a piston-core-sampler, so that the core specimens can be obtained right on the spot, where the thermal gradient is measured, in one operation. To help in the penetration of the probe and the corer, the whole apparatus is allowed to fall freely for several meters when the pilot corer touches the bottom and unhooks the apparatus by a lever device. For the detail of the operation of unhooking and penetrating the probe readers are referred to the papers[11),12)]. The whole system weighs approximately 800 kg : the core-sampler 550 kg, the thermogradmeter 100 kg, and the counter weight 150 kg. The length of the probes are 1.5 m, 3 m and 4.5 m. Probes of different lengths are used for different conditions of the sea bottom. Two pairs of thermistors $T_A - T_B$, $T_\alpha - T_\beta$ are placed in the probe, each forming the two arms of an A.C. bridge, to give the temperature difference between the bottom and the top of the probe and that between the bottom and the middle point. Fig. 2 shows these component parts assembled aboard the m.s. " Ryofu Maru ".


Fig. 2. Assembling apparatus R. 1. aboard the " Ryofu Maru ".

3. The Probe and Pressure-Tight Container

The steel probe and the container of the recorder are as shown in Figs. 3 and 4. The inner and outer diameter of the probe is 15 mm and 25 mm respectively. It has a flange A (Fig. 3) at the top which presses the rubber packing B against the lid C. In order to accomplish

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[10] *loc. cit.*, (1) and (5).

[11] *loc. cit.*, (1).

[12] *loc. cit.*, (2).

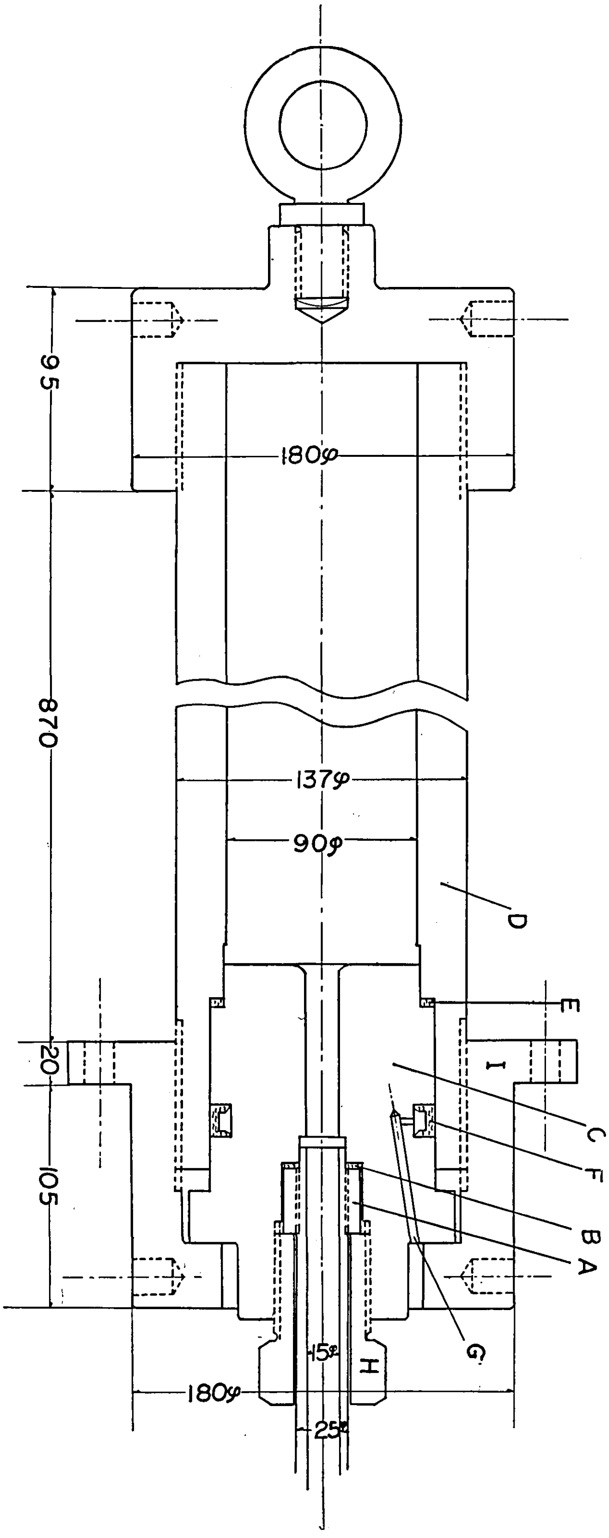

Fig. 3. Plan of the pressure-tight container of apparatus R. 1.

a better thermal contact the thermistors are immersed in fluidal paraphin which fills the tube. To make the container pressure-tight, packing E and F are placed between the lid C and the main container D whose thickness is 23.5 mm. The hole G is open to the outer space so that the external water pressure can push the packing F from inside to make the contact tighter as the apparatus sinks deeper into the sea. The probe and the lid are mannually pressed by means of the screws H and I. The container and the probe are to stand the external hydrostatic pressure of 1,000 bars safely. On our actual tests to date, the apparatus has been successfully sunk to the depths of 3,000 m, 5,040 m and 5,400 m.

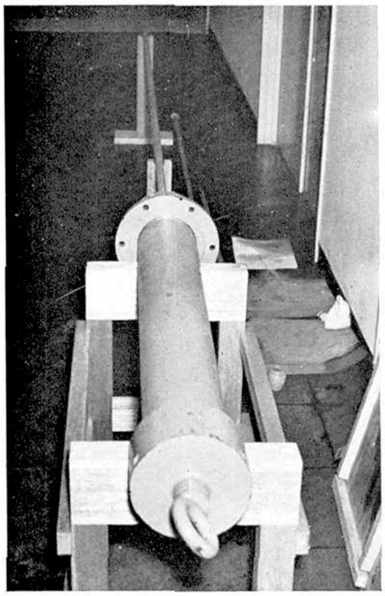

Fig. 4. The probe and container of apparatus R. 1.

4. Recorder

The block and circuit diagrams of the measuring system in apparatus R. 1. are shown in Figs. 5, 6 and 7. The two independent A.C. bridges, including the thermistors in the probe T_A, T_B and T_α, T_β are fed with a 400 c/s A.C. voltage from a single CR oscillator. Pairs of thermistors, having the same $\Delta R/\Delta T$ characteristics in the temperature range from 0°C to 4°C, were selected from a number of thermistors D 13 manufactured by the Nihon Electrical Company. The said temperature range is considered to include deep ocean temperatures: it has been reported that in the western Pacific the temperature at 5,000 m depth is 1.55 ± 0.10°C almost everywhere[13]. Fig. 7 shows the examples of the resistance-temperature characteristics of the thermistors used. The thermistors (52, 11), (12, 04), (03, 14), (05, 13) were used in pairs. The constant difference in the absolute values of resistance was roughly compensated by an additional carbon resistor connected in series. The resistance of all the temperature sensitive arms of the bridge was thus adjusted to about 3.0 kΩ at 0°C. A continuous potentiometer of 100 Ω is connected between the two ends

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[13] *loc. cit.*, (9).

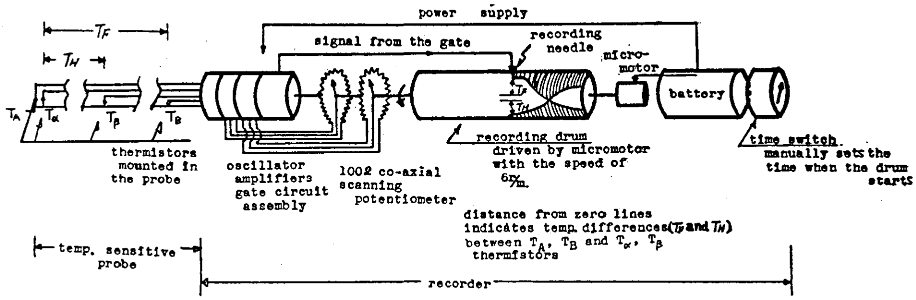

Fig. 5. Schematic diagram of the recorder of apparatus R. 1.

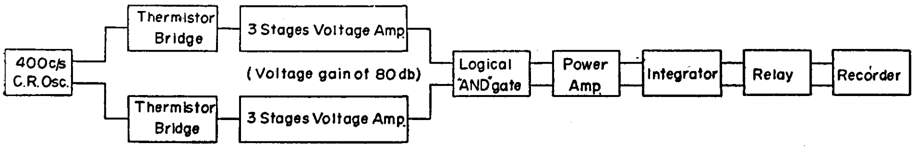

Fig. 6. Simplified block diagram of the recorder of apparatus R. 1.

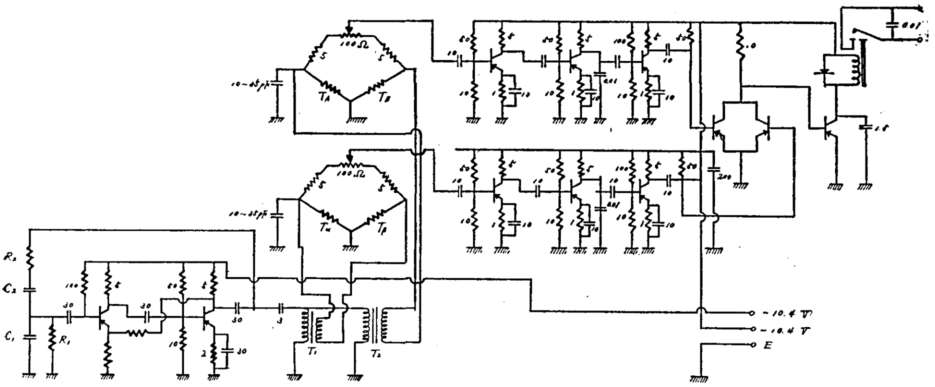

Fig. 7. Circuit diagram of the recorder of apparatus R. 1.

of the fixed arms of 5 kΩ (or 2.5 kΩ) of the bridge. This potentiometer rotates at the same rate of revolution as the recording drum. The unbalance output A.C. voltage from the two bridges are independently amplified through transitorized amplifiers with a voltage gain of 80 db. The phase angle of the output signal of the amplifier changes 180° when the potentiometer passes its balancing position, therefore as far as the phase angle is concerned the behaviour of the amplifier can be represented logically, namely "yes" or "no" or "1" or "0". The logical output signal X of the amplifier changes from "0" to "1" at the instance when the potentiometer passes through its balancing point. It is the same for the other amplifier the logical output signal of which is indicated by Y. The output signal of the logical "and" gate is shown in Table 1. The recording signal is sent forth when the output signal of the "and" gate is "1". The recording is performed on facsimile paper wound on the drum, the two balancing points of the two potentiometers which correspond to the temperature difference of $T_A - T_B$ and $T_\alpha - T_\beta$ respectively can be interpreted as both ends of a black line on the paper. It may be said that the signals from the two bridges serve mutually as the reference signal in the "and" gate. For the 1.5 m long probe, sometimes only a pair of thermistors, T_A and T_B, are used, the other pair of thermistors being replaced by proper carbon resistors so that the bridge works only as the source of the reference signal. Figs. 8 and 9 are the photographs of the instrument. The drum and two continuous potentiometers, driven by a micromotor, rotate once per 10 seconds and the pitch of the recording needle is either 0.5 mm or 0.25 mm for one revolution. The effective length of the drum being 20 cm, the apparatus

Table. 1.

Y \ X	0	1
0	0	0
1	0	1

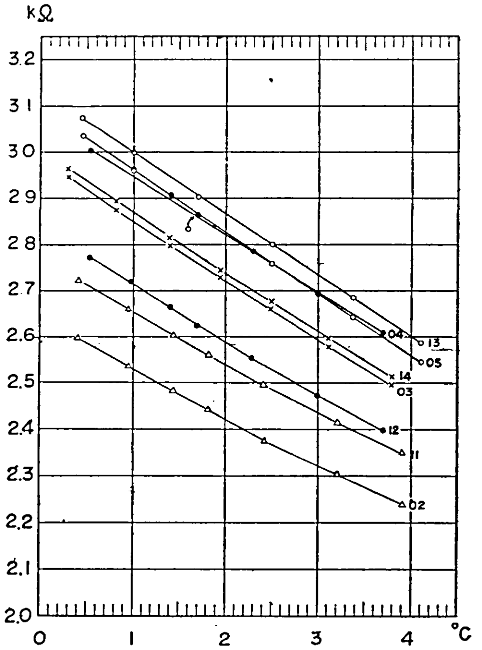

Fig. 8. Examples of the temperature-resistance characteristics of the thermistors used. Numbers attached to each curve are the thermistor numbers.

keeps working for about 1.25 hours or 2.5 hours, depending on the pitch just mentioned. The starting time of recording is set by a time-switch before setting the apparatus into the container. The over-all sensitivity of the apparatus can be changed by altering the value of the fixed resistance in the bridges. The fixed resistance was, in our apparatus,

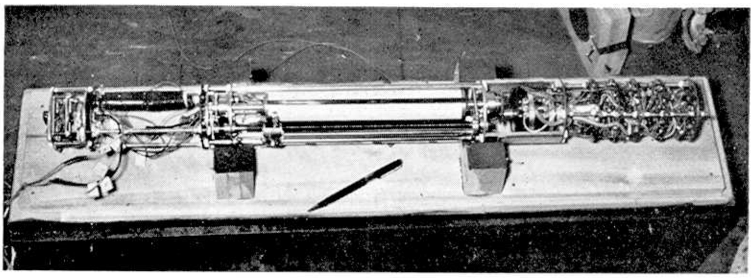

Fig. 9. The recorder for apparatus R. 1. (Batteries unlaoded.)

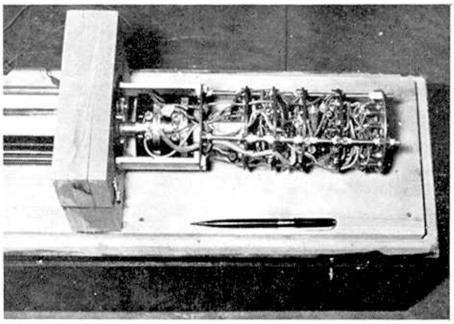

Fig. 10. Electronic part of the recorder.

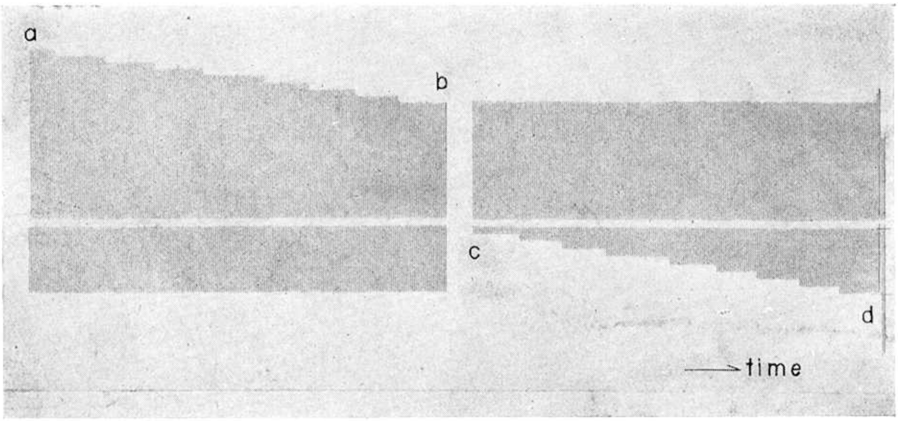

Fig. 11. Sensitivity calibration recording of the apparatus R. 1.

either 5 kΩ or 2.5 kΩ. Fig. 11 is an example of the records of calibration tests, obtained by inserting 3 kΩ carbon resistors in place of thermistors, and altering stepwise the resistance of a helical potentiometer connected as shown in Fig. 12. In Fig. 11, between a and b, the stepwise change was made in the bridge for T_A and T_B, while keeping the state of affairs in the bridge for T_α and T_β unchanged. Between c and d the stepwise change was made in the bridge for T_α and T_β, keeping the other bridge untouched. The step (~1.5 mm) in the record corresponds to the stepwise change of 2 Ω which is equivalent to the temperature difference of about 0.02°C for the thermistors used. The width of the recording paper being 93 mm, the maximum recordable temperature difference in this case is about 1.24°C. Fig. 13 is an example of the laboratory recording tests for the pairs of thermistors (08–18) and (09–17) when they were immersed into a water bath in which the temperature was controlled at *ca* 0.3°C. The envelopes T_H and T_F represent the time variation in the temperature differences in eash bridge, the asymptotic values indicated by dotted lines being the zero-lines.

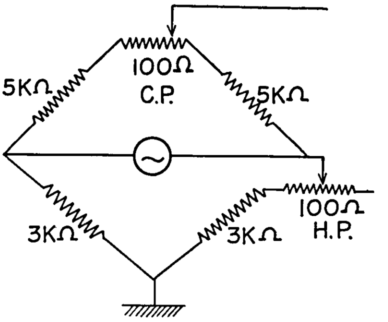

Fig. 12. Sensitivity calibration.
C. P.....continuous potentiometer
H. P.....helical potentiometer.

Owing to the fact that the resistance-temperature characteristics of thermistors forming a pair are not exactly identical, the position of the zero-line on the record depends on the ambient temperature. The shift of the zero-line due to 1°C change in the ambient temperature for the present pairs of thermistors was found to be equivalent to the temperature difference of the order of 0.01°C. As it can not be expected that the ambient temperature at the bottom of oceans will always be known, it would not be worthwhile to carry out the tedious work of predetermining the zero-line at various temperatures for each pair of thermistors. The precise position of the zero-line would be more conveniently determined in situ: it is planned that the zero-line will be easily determined on each measurement by keeping the whole apparatus just above the sea bottom for say 30 minutes and by starting the recording some time, say 10 minutes, before the probe is allowed to penetrate into the bottom. The vertical temperature gradient in the water near the bottom of the deep sea is extremely small, and as shown from the actual observation on the time constant of the probe, the

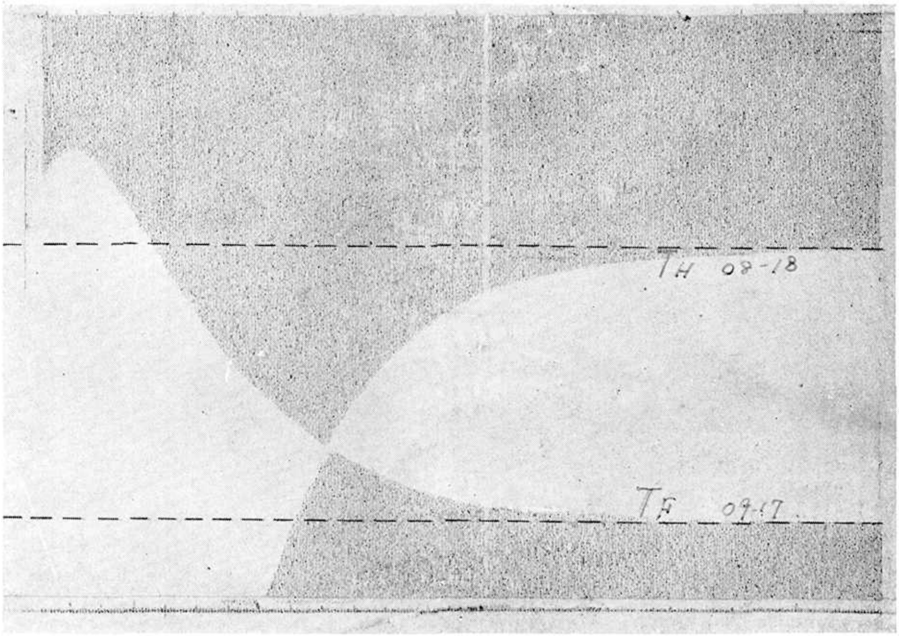

Fig. 13. Example of recording tests.

thermistors in the probe reach a nearly perfect thermal equiliblium with the water oustide in 30 minutes. Therefore the record obtained during the said period when the apparatus is just above the sea bottom will show the zero-line for that measurement. The continuous potentiometers and the drum are driven by a small D.C. motor. A set of batteries, i.e. a 10.4 volt mercury cell for the ampifier, and the oscillator and a 5.2 volt mercury cell for the micromotor and a 67.5 volt dry cell for the recorder are able to keep the apparatus working for two complete runs.

A flash bulb inclinometer as used in the equipment of the Scripps Institution of Oceanography[14] is attached to the recorder. Some preliminary tests in the Pacific proved that the apparatus works well in the sea bottom at depths of 5,040 m and 5,400 m.

5. Apparatus to be used on Board

When the depth is not great as in the continental shelf or lakes, it may be possible to sink the probe only and take the measurements

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[14] R. von. HERZEN, private communication

aboard by using an electric cable connecting the probe and the recorder. It will be useful especially when the ship does not have a powerful winch. A couple of handy apparatuses (named S. 1.) were made for the purpose of measuring heat flow at the sea bottom shallower than, say 1500 m. The probe shown in Fig. 14 (a)~(b) is made of a steel tube whose outer and inner diameters are 2.6 cm and 2.2 cm respectively. In order to facilitate the penetration of the probe a 25 kg weight made of steel was attached at an end of the probe. The connector between the thermistors and the cable is placed in a space made inside the weight and sealed by means of an O-ring. When necessary, additional weights with fins can be attached as observed in Fig. 14(b). The electrical circuit diagram of the handy thermogradmeter is shown in Fig. 15. In this

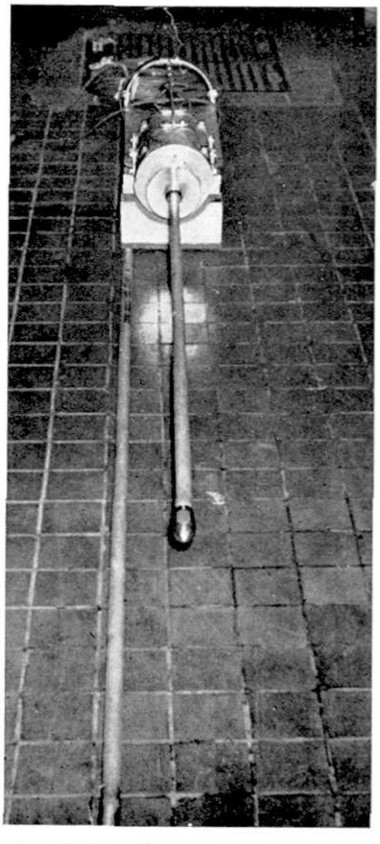

Fig. 14(a). The probe for the apparatus S. 1.

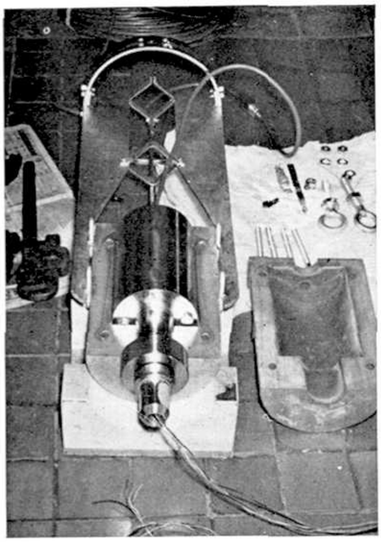

Fig. 14(b). The weight and the junction-container of the apparatus S. 1.

instrument, a helical potentiometer is used in the reference arms of the bridge. The temperature difference is read by the scale of the helical potentiometer which is manipulated to find the null position in the microammeter. Fig. 16 is the photograph of the instruments. Since 0.1 Ω can be read on the scale of the potentiometer, in the bridge used in the present case the unbalance resistance of 0.12 Ω of the thermistors can easily be detected : for the bridge as shown in Fig. 17, the relation between the change in R_2, (ΔR_2), to nullify the unbalance caused by the change in, say, R_{T_B}, (ΔR_{T_B}), is given as

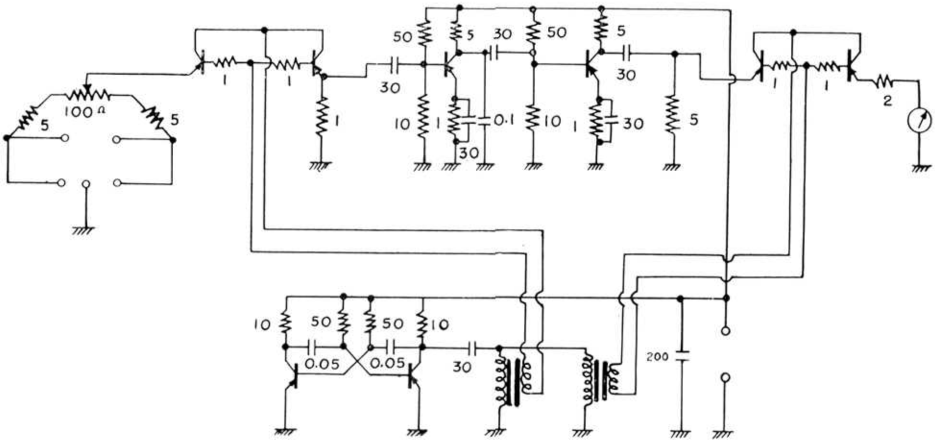

Fig. 15. Circuit diagram of the apparatus S. 1.

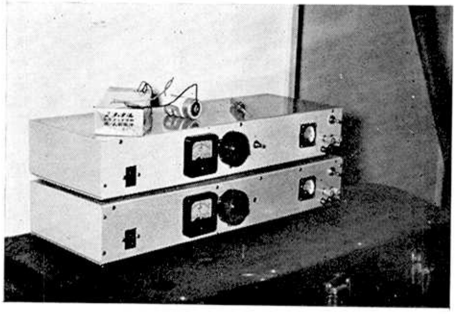

Fig. 16. Apparatus S. 1.

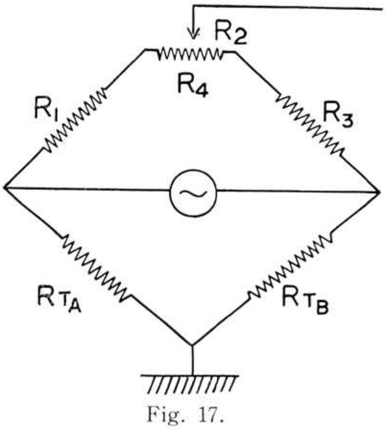

Fig. 17.

$$\Delta R_{T_B}=\frac{R_{T_A}+R_{T_B}}{R_1+(R_4-R_2-\Delta R_2)}\Delta R_2 .$$

For the present case, $R_{T_A} \fallingdotseq R_{T_B} \fallingdotseq 3\,\mathrm{k}\Omega$, $R_1 = R_3 = 5\,\mathrm{k}\Omega$, $R_4 = 100\,\Omega$

$$\therefore \Delta R_{T_B} \fallingdotseq 6/5\,\Delta R_2 .$$

This means that the sensitivity of the apparatus is of the order of 0.001°C, using the present thermistors.

6. Time Constants

It is expected that it takes some length of time after penetration for the thermistors in the probe to attain thermal equilibrium with the sea bottom. When the probe penetrates into the bottom, there will be some heating due to the friction between the probe and the bottom material. This problem has been thoroughly worked out by Bullard[15] for a similar type of probe as is used in our apparatus.

Steel being a good thermal conductor the thermal time-constant of the thermistors in the probe is largely controlled by the paraphin filling inside the tube. At the centre of the cylinder of paraphin, the time necessary for attaining 90% of a given sudden change in external temperature can be estimated[16] as 6 min (tube with 1.5 cm inner diameter)

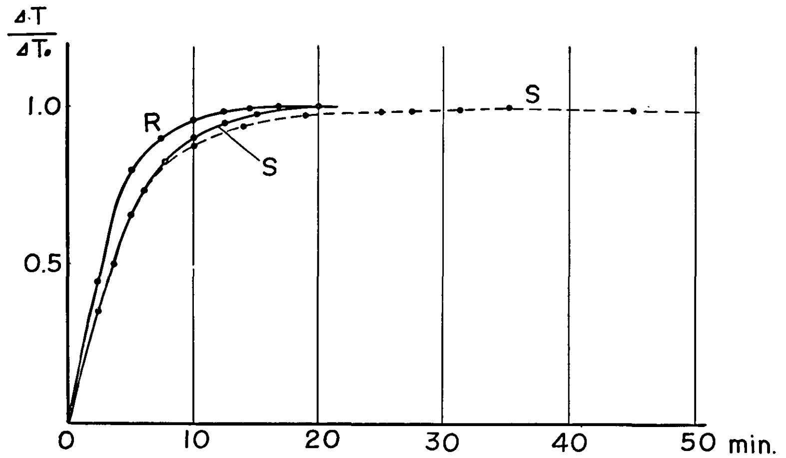

Fig. 18. Changes in the temperature of probes when the external temperature is suddenly changed by submersion into a water-bath (full lines), and by penetrating into the sea bottom (broken line).
R....probe for the apparatus R. 1.
S....probe for the apparatus R. 1.

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[15] *loc. cit.* (1).

[16] H. S. CARSLAW and J. C. JAEGER, *Conduction of Heat in Solids, 2nd ed.*, (1959), 199, Oxford.

and 12 min (tube with 2.2 cm inner diameter). These values were found to be almost correct by experiment: in Fig. 18, the full curves show the process of attainment to thermal equilibrium with the surrounding water.

As described by Bullard, the attainment of thermal equilibrium in bottom material will be slower owing to the poorer diffusivity of the bottom material. This was found to be the case as the broken curve, taken when the probe was driven into the sea-bottom, shows. For these reasons, at least half an hour seems to be necessary for the probe to stay in the sea-bottom to give useful data.

In actual operation, it is frequently found difficult to keep the probe still in the bottom for such a long time, because of, for instance, the drift of the ship. To avoid this drawback, in the instrument used by the Lamont Geological Observatory, thermistors are sealed in a small probe, having a short time constant, attached to the core-sampler. The present authors also are experimenting with the said system. Some of the preliminary tests made are as follows. Outside the core-sampler with a 2 inch diameter, 3 small probes, 5 mm and 8 mm in the inner and outer diameters, were attached as shown in Fig. 19. Each of the probes as well as the corer were equipped with an electric heater wound outside. After keeping the system in the sea-bottom for a long time, heating current was supplied to these heaters for a short time and the temperature change caused by it was measured. Figs. 20 and 21 summarize the results. The time variations in the temperature due to heating by the heaters attached to the small probes are shown in Fig. 20. This shows that the time-constant of the small probes in the sea bottom is very short: the disturbance decays more than 90% within a few minutes. The effect of heating by a heater wound on the corer varies much more slowly as shown in Fig. 21. Fig. 21 also assures that keeping the probe 10 cm away from the corer, the heating disturbance from the corer is not practically perceptible at least until one hour later. From these observations, it is concluded that using probes such as No. 3 in Fig. 19, the time required for measurement will be greatly lessened.

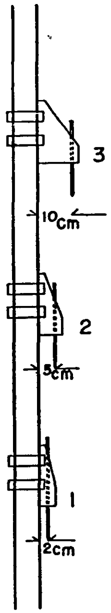

Fig. 19. Thermistor probes attached to the core-sampler.

In our apparatus No. 2 (R. 2), which is now under construction, we adopted this system.

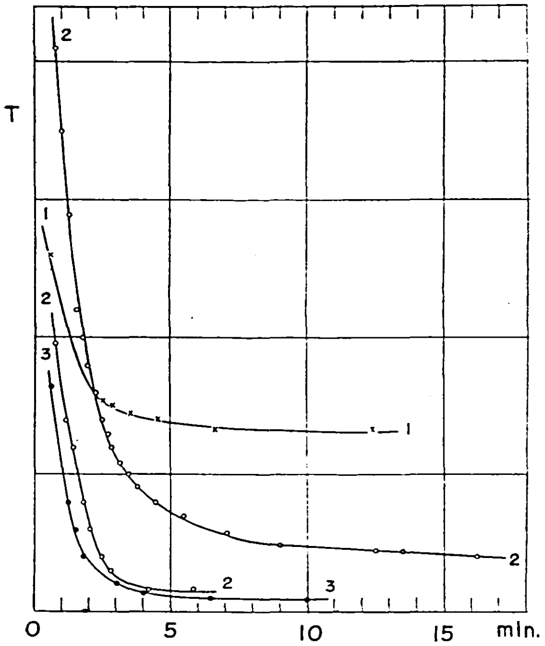

Fig. 20. Temperature variations with time after instantaneous heating by a heater attached to the probes.

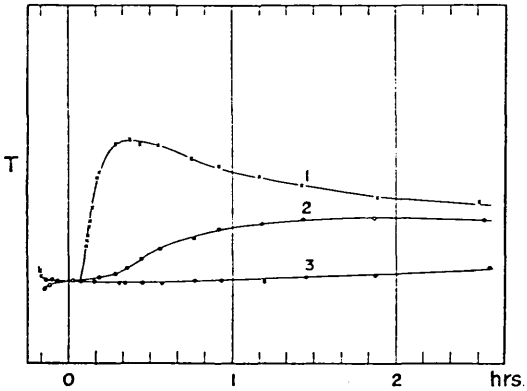

Fig. 21. Temperature variations with time after 5 minute heating by a heater attached to the core-sampler.

7. Concluding Remarks

The work of determining the terrestrial heat flow through the ocean floor has only been set about recently in Japan. So far, we have only built the apparatus for this purpose, and the actual measurements will be taken in the forthcoming years. The authors thank Drs. T. Rikitake, and N. Nasu, Tokyo University and Dr. K. Terada, Japan Meteorological Agency, for their encouragement and supervision. In designing the apparatus, kind advice was given to the authors from colleagues of the institutes having experience in this work. In particular, the authors wish to acknowledge the information given by Sir Edward Bullard, Department of Geodesy and Geophysics, University of Cambridge, Dr. R. von Herzen, Scripps Institution of Oceanography, University of California, and Drs. M. Langseth, and S. Gerard, Lamont Geological Observatory, Columbia University. Thanks are also due to the staff of the Sokkisha Company, Tokyo and the Rigosha Company, Tokyo for their wholehearted cooperation in the construction of the apparatus. Kind assistance rendered by the crew of the m.s. Ryofu Maru throughout the sea work is also gratefully acknowledged.

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6. 地球熱学 (第7報) 海底地温勾配測定装置

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金森博雄}

気象庁 淵秀隆

日本列島をとりかこむ海域において地殻熱流量の実測を行なう目的のため，船より吊り下げ海底地層に貫入せしめて，海底での地温勾配を測定記録する装置を試作した．サーミスタを用いた交流ブリッヂ法を用い，0°～2°C 程度の温度差が，0.001°C の精度で自動記録されるもので，その概要は本文第5図の通りである．全装置は耐圧容器に収められる．浅海測定用には，測定器を船上に留め感熱部のみを海底に突差す方式を採用した．太平洋上での試験結果はおおむね良好で，今後は実測を行なう予定である．なお，本研究は，科学技術庁特別調整費，文部省科学研究費によつて行なわれた．