35. *Measurement of Changes in Magnetic Susceptibility of Igneous Rocks with Temperature in a Weak Magnetic Field.**

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1. Introduction.

In his previous paper,[1] the writer described the magnetic properties of volcanic rocks ejected from a few of the volcanoes in Japan, dealing especially with their magnetization curve, initial susceptibility, natural remanent magnetism, and thermo-remanent magnetism. There is, however, another fundamental property of the rock's magnetism which it is necessary to examine before we can analyze the magnetic constitution of igneous rocks and ascertain its possible relation to local geomagnetic changes. This is the change in susceptibility of rock with temperature variation, especially in a weak magnetic field.

In the writer's opinion, the remarkable magnetization of natural effusive rocks is in most cases due to the presence of permanent magnetization, which is usually called "natural remanent magnetization." The intensity of this permanent magnetization is generally larger, relatively speaking, than that of magnetization induced by the geomagnetic field. Sometimes, the former is so large that, compared with it, the latter is negligible. Hence, so long as we are concerned only with the magnetization of effusive rocks from the standpoint of its relation to a conspicuous geomagnetic anomaly, the intensity of magnetization directly induced by the present geomagnetic field seems to be less important than that of the permanent component.

It has been proved,[2] on the other hand, that the natural remanent magnetization is chiefly due to the residual permanent magnetization that is produced during cooling in the geomagnetic field, the mode of its causation being given by

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* Dedicated to the late Professor Mishio Ishimoto.

1) T. NAGATA, *Bull. Earthq. Res. Inst.*, **18** (1940), 102; 281; **19** (1941), 49; 304.

2) T. NAGATA, *Bull. Earthq. Res. Inst.*, **19** (1941), 49.

$$\vec{J}_{t_i, H}(t) = \vec{H} \cdot \int_t^{t_i} P(t)\,dt \quad (t_i > t). \tag{1}$$

Eq. (1) gives the thermo-remanent magnetization caused during cooling from t_i to t in a constant magnetic field of H, while $P(t)$ in the equation is its characteristic function of temperature, the form of which depends on the characteristics of the particular rock specimen. It is believed, however, that the form of $P(t)$ is closely related to or subject to the mode of change in magnetic susceptibility with temperature. Putting aside this close relation of form $P(t)$ to thermo-remanent magnetism, the mode of change in magnetic susceptibility with temperature also seems to show a fundamental characteristic of the magnetic property of rock, since the Curie-point temperature of a rock is directly related to the physical mechanism of causation of its magnetism.

The reason for the necessity of studying the thermal change in magnetic susceptibility of rocks will now be clear. A number of illuminating papers on the problem stated here have already been published by R. Chevallier,[3] and others.[4] Of these, Chevallier's work gives a fairly clear relation between the Curie-point temperature and the constitution of the rock, although his experiments were made by means of the magnetometric method in a rather strong magnetic field (about 150 Oersteds), which greatly exceeds the intensity of our geomagnetic field. Here, we shall study the mode of thermal change of magnetic susceptibility of various kinds of rock, especially in a weak magnetic field. Moreover, the writer's experiments were conducted under the conception that the total apparent magnetization of a rock specimen thermally agitated in a magnetic field is given by linear addition of the thermo-remanent magnetization to the induced magnetization, that is,

$$\vec{J}(t) = \vec{H} \cdot \chi(t) + \vec{J}_{t_i, H}(t), \tag{2}$$

where $\chi(t)$ denotes the magnetic susceptibility at temperature t. That relation (2) holds at ordinary room temperature was experimentally proved, while the contingency that it holds at any temperature was also examined by means of the magnetometric method, the result of the examination showing that it holds, at any rate, approximately.[5]

Hence, in the present study, the induced magnetization $\vec{H} \cdot \chi(t)$,

3) R. CHEVALLIER et J. PIERE, *Ann. de Phys.*, **18** (1932), 383.
4) Y. KATO, *Rep. Col. Sci. Tôhoku Imp. Univ.*, **27** (1938), 91.
5) T. NAGATA, *loc. cit.*

from which the susceptibility is derived, is rigidly separated from the permanent componet $\vec{J}_{t_i,H}(t)$, which depends on the history of the temperature change in the specimen in a magnetic field. Under these conditions, several typical specimens of Japanese volcanic rocks were examined. The method used and the results of the experiment will now be discussed.

2. Measuring Apparatus.

Since the intensity of thermo-remanent magnetization is usally larger than the induced magnetism in a weak magnetic field, it is difficult to determine accurately the intensity of the induced part alone by means of the usual magnetometric method, in which only the intensity of total magnetization is observable. This is because the induced magnetization, which is to be given as the residual after subtracting the permanent component from the observed total magnetization, so far as eq. (2) holds, is usually accompanied by large errors.

Hence, for the measuring apparatus in the present study we adopted the ballistic method, in which we measured the e. m. f. due to the electro-magnetic induction between two coils containing a rock specimen as a core. Since the magnetic susceptibility of rocks is usually small, (less than 3×10^{-3} in its specific value), several technical improvements were required in order to be able to determine the magnitude of susceptibility in a weak magnetic field with an error smaller than a few percent. The principle and details of the measuring apparatus now follow.

(i) *General electric circuit.*

The general electric circuit in the ballistic method is shown in Fig. 1, where M_1, M_2, and M_3 denote mutual inductance. In the axis line of M_1, which consists of two circular coils, the rock specimen to be examined is set as a core, while the compensating coils M_2 is exactly the same as M_1 in their forms. M_3 is the mutual inductance for calibrating sensitivity. The ballistic galvanometer G assumes its critical-damping condition with the aid of resistances r_1 and r_2. In measuring, the electric current I in the primary circuit is turned to $-I$ with the aid of a mercury switch C, when the induced charge Q in the secondery circuit is

$$Q=2k(M_1I\mu-M_2I\mu_0), \qquad (3)$$

where k is a constant value depending on the characteristics of the ballistic galvanometer and the resistance in the secondery electric circuit, while μ and μ_0 are permeabilities in M_1 and M_2 respectively, that is,

$$\mu=1+4\pi CS\kappa/A, \quad \mu_0=1, \tag{4}$$

where κ and S denote the magnetic susceptibility of the rock specimen inserted in M_1 and the area of its cross section respectively, while a constant, C, results from the condition that the rock specimen having κ had not sufficient length; that is, $CS\kappa/A$ gives the effective susceptibility of the whole space inside the secondary coil M_1. If M_2 is suitably adjusted to equal M_1, we get from eqs, (1) and (2),

$$Q=8\pi kM_1ICS\kappa/A. \tag{5}$$

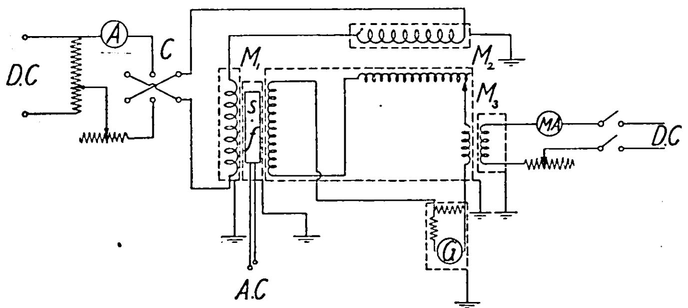

Fig. 1. Electric circuit in the apparatus for measuring susceptibility at high temperature.

M_1, M_2, mutual inductances,
M_3, mutual inductance for sensitivity test,
s, specimen,
f, non-inductive electric furnace.

Since the deflection of the ballistic galvanometer θ is proportional to Q, that is, $Q=c\theta$, we get.

$$\theta=K\kappa I, \tag{6}$$

where $K=8\pi kM_1CS/Ac$.

While, on the other hand, the intensity of magnetic field H, produced by the primary coil of M_1 and M_2, is proportional to I, i. e. $H=\frac{8}{5\sqrt{5}}\frac{N}{R}I=k'I$, we finally get

$$\kappa=\frac{\theta}{KI}=\frac{\theta}{K'H}, \tag{7}$$

where $K'=8\pi kM_1CS/Ack'$.

Thus magnetic susceptibility κ, corresponding to magnetic field H, can be determined by the observable quantities θ and I, and by the given constants K and C.

(ii). *The M_1 and M_2 coils.*

The primary coil of mutual inductance M_1 is a Helmholtz's coil of 35 cm radius and 150 turns of wire, the intensity of magnetic field at the centre of the coil being 3·85 Oe./amp. corresponding to unit electric current through the coil. The magnetic field inside the co-axial cylindrical space, 25 cm long and 20 cm in diameter ($\pm$10 cm along the the axis line and 10 cm in radial direction from the centre of the coil), is uniform with an error of less than 0·1 percent —an error sufficiently small for the present purpose of measurement. The secondary coil of M_1, which is a cylindrical solenoid, set coaxially with Helmholtz's coil, is 9·0 cm long and 6·7 cm in diameter, fine wire being wound on the outside of a double pyrex glass tube. The total number of turns and the electric resistance of the secondary coil are about 43000 and 45 KΩ respectively. Through the gap between the outer and inner glass tubes, water was always made to flow in order to absorb the heat from the furnace, as also to maintain the secondery solenoid at constant ordinary room temperature (10°C in winter and 25°C in summer).

As already mentioned, the primary and secondery coils of M_2 were constructed exactly like those of M_1. Since the turns of the secondery solenoid of M_2, however, can be varied from 40000 to 46000 with every two turns with the aid of four lever switches, mutual inductance M_2 can be equalized to M_1 with an error of only $2/43000 \simeq 5 \times 10^{-4}$. These two coil system M_1 and M_2 were set perpendicular to and 1·5 m apart from each other.

(iii). *The rock specimen and the heater.*

The rock specimen to be examined was pulverized into small grains of 0·1 *mm*, mean diameter, and poured into a tube of fuzed silica, 1·62 *cm* in its inner diameter and 10·0 *cm* long. The temperature at the centre of the specimen was determined by means of a $P_t \sim P_t \cdot Rh$ thermo-junction, which was shielded in a thin silica tube, as shown in Fig. 2. A vacuum electric furnace was also made with a fuzed silica tube and platinum

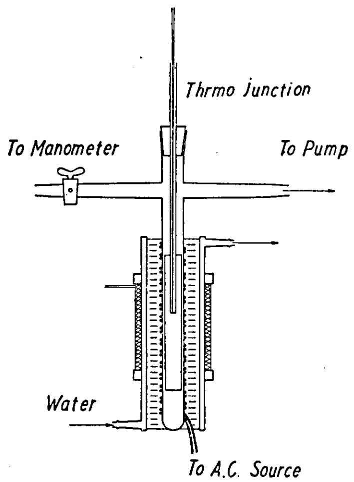

Fig. 2. Non-magnetic and non-inductive vacuum furnace in the apparatus.

wire, which last was wound non-inductively on the silica tube, while the air in the furnace was pumped out with the aid of a rotary pump, the air pressure being always kept at few *mm* of mercury. The furnace was held in the secondery coil, the gap between them being filled with pure asbestos. Needless to say, the materials inserted in the secondary coil of M_1 were almost non-magnetic ($\kappa < 10^{-5}$). The rotary pump was placed more than 2·5 m away from the coil systems M_1 and M_2 in order to avoid heterogeneity of and variations in the magnetic field in M_1 and M_2 due to the pump and the electric motor. The axes of the specimen, furnace, and secondary coil were set coaxially with that of the Helmholtz's coil, the magnetic field produced by which was sufficiently uniform in that space occupied by the secondary coil as well as by the specimen.

It may be worth noting here that all the parts mentioned above were sufficiently isolated, electrically, and that every part was shielded perfectly from the other by means of plates of conducters connected to earth.

(iv). *Sensitivity and its stability against temperature change.*

The sensitivity of the apparatus depends first on the dimensions of the specimen, that is, S and C in eq. (2), and next on the electric arrangement of the secondary circuit. Although it is desirable that the length of the specimen shall exceed three times that of the secondary solenoid, and that the diameter of the latter shall be the nearest possible to that of the former, for the purpose of determining absolutely the magnitude of the true susceptibility of the specimen, these conditions could hardly be satisfied in our apparatus, since the presence of the heater surrounding the specimen and the requirements in regard to uniformity of temperature in it prevented these conditions from being filled. In our case, moreover, a theoretical determination of the magnitudes of S and C seems to be difficult, and not accurate even if it could be done, seeing that the shapes of the specimens were rather irregular, for which reason the sensitivity of the whole measuring system was calibrated experimentally by testing the various specimens, the susceptibilities of which at ordinary room temperature have already been determined. The constants K and K' were thus determined experimentally. Strictly speaking, however, C is not a constant quantity, since it varies with various values of susceptibility κ of the inserted specimen, although the amount of change should be small, negligible in the present case, where the susceptibility itself is very small, usually of the order of 10^{-3} c. g. s. e. m. u., or less.

On the other hand, the sensitivity and stability of the secondary circuit, including the galvanometer, was checked by means of mutual inductance M_3. Since c/k usually varies slightly with weather conditions, especially with temperature and humidity, the check by means of M_3 was made both before and after every observation. The amount of variation, however, was always smaller than 0·5 percent throughout the the four seasons.

(v). *Errors in measurment.*

Uniformity in temperature of the specimen was examined at various temperatures. Actually, the distribution of temperature along the axis line was examined, an example of it being shown in Fig. 4, from which it may be said that the temperature of a specimen was uniform with

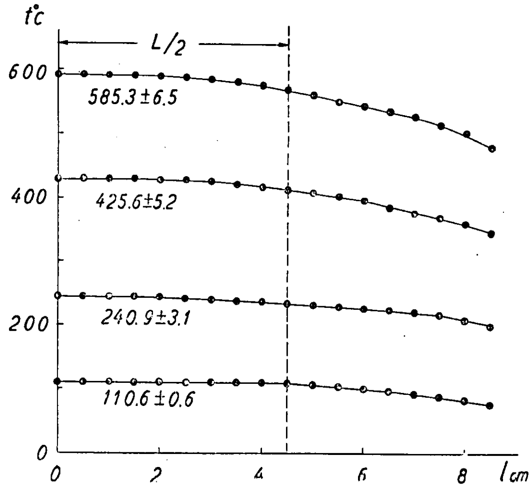

Fig. 4. Temperature distribution in the furnace. L denotes the length of specimen. (Heating velocity=2 degree/min.)

an error less than 10° in a temperature range of from 0°C to 650°C.

Since it was not possible to make M_1 exactly equal to M_2 in our apparatus, the former being adjustable only with a finite interval of 5×10^{-4} in $\varDelta M_2/M_2$, equation (6) does not quite hold, but we have the relation

$$\theta=KI\kappa+\frac{2kI\mu_0\varDelta M_2}{c}=K\kappa I+\theta_0,$$

where, as will be seen from the above equation, θ_0 is a constant value, so long as I is constant, so that in the actual measurement, substituting $\theta-\theta_0$ for θ in eq. (6), it was possible to determine κ with the aid of the relation

$$\kappa=\frac{\theta-\theta_0}{KI}=\frac{\theta-\theta_0}{K'H}. \tag{9}$$

Compared with θ, θ_0 was usually very small, the magnitude of the former corresponding to about 10^{-4} of the susceptibility of the inserted specimen. Although it would be very desirable to measure the change in susceptibility with temperature variation in a weak magnetic field nearly the same as the geomagnetic field, say 0·5 Oersteds, this was not possible in our case, seeing that we required an observational accuracy of 10^{-5} c. g. s. e. m. u. in the value of susceptibility, with the result that the intensity of the applied magnetic field, which is produced by the primary coils of M_1 and M_2, was always about 2 Oersteds, except the case in which the susceptibility of magnetite was examined.

While on the other hand, variation in θ usually fluctuated, probably due to a slight leakage current from the *A. C.* in the electric furnace, or from other sources, to the secondary circuit, which fluctuation depends on the temperature in the furnace, the higher the temperature the greater was the fluctuation. The observed values of $\theta-\theta_0$ at various temperatures, when $\mu=\mu_0$, that is, when the specimen vessel is empty, are as follows.

Temperature	$\Delta\kappa$	Temperature	$\Delta\kappa$
0~350°C	$(0{\cdot}0\pm1{\cdot}6)\times10^{-5}$	400~700°C	$(0{\cdot}0\pm2{\cdot}7)\times10^{-5}$

The quantities on the right-hand side in the Table are given in terms of magnitude of susceptibility of the specimen corresponding to the observed value of $\theta-\theta_0$.

Since this fluctuation was the largest source of observational errors, the error in our experiment throughout the whole temperature range from 0°C to 700°C in the term $\Delta\kappa$ was less than 3×10^{-5}. This observational error, however, is independent of the magnitude of the susceptibility of the inserted specimen, so that if the susceptibility of the specimen is larger, the error is relatively smaller. For example, an observed value of susceptibility of about 10^{-3} is expected to contain an error of 3 percent.

3. The results of experiment.

Several typical specimens of basaltic and andesitic rocks were examined with the aid of the present instrument, namely, six from the ejecta of Huzi (Fuji) Volcano, three from those of Miyake-sima Volcano, and a magnetite from Manchuria. According to H. Tsuya, these rocks are[6]

No. 1 (S–N–17), Huzi, the lava of Hôei explosion crater, olivine-basalt,

No. 2 (S–N–20), Huzi, Makuiwa lava, olivine-basalt,

No. 3 (S–N–23), Huzi, Makuiwa lava, two-pyroxene-bearing olivine-basalt,

No. 4 (S–N–21), Huzi, Makuiwa lava, augite-bearing olivine-basalt,

No. 5 (S–N–18), Huzi, Makuiwa lava, hypersthene-augite-olivine-basalt,

No, 6 (S–N–22), Huzi, ejecta from Hôei crater, augite-bearing olivine-basalt,

No. 7 (S–N–59), Miyake-sima, Akabakkyo lava, olivine-hypersthene-pyroxene-basaltic-andesite,

No. 8 (S–N–60), Miyake-sima, Yoridaisawa lava, olivine-hypersthene-pyroxene-basaltic-andesite,

No. 9 (S–N–75), Miyake-sima, ejecta of the central cone, olivine-two-pyroxene-basaltic andesite,

No. 10 magnetite.

6) The chemical composition of specimens Nos. (1), (2), (3), (4), (5), and (6) are as shown in the following table. (Due to H. Tsuya, *Bull. Earthq. Res. Inst.*, **15** (1937), 307)

Chemical composition of Huzi ejecta.

	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.
SiO	49·60	50·28	50·64	50·66	51·05	51·09
Al_2O_3	16·96	18·30	18·58	18·25	18·35	17·62
Fe_2O_3	5·40	4·50	3·04	4·78	2·76	2·64
FeO_3	6·65	6·89	7·29	5·72	7·72	8·42
MgO	5·92	3·80	5·58	4·94	4·63	5·09
CaO	10·03	9·76	10·00	9·98	9·90	9·68
Na_2O	2·48	2·87	2·64	2·78	2·81	2·80
K_2O	0·58	0·94	0·61	0·77	0·81	0·76
H_2O+	0·50	0·20	0·20	0·38	0·40	0·28
H_2O-	0·12	0·08	0·06	0·13	0·11	0·06
TiO_2	1·40	1·78	1·15	1·38	1·41	1·38
P_2O_5	0·20	0·34	0·16	0·25	0·24	0·26
MnO	0·21	0·20	0·17	0·17	0·18	0·21
Total	100·05	99·94	100·12	100·19	100·37	100·29
Q	3·78	3·96	1·98	4·14	2·34	2·04
Or	3·34	5·57	3·34	4·45	5·01	4·45
Ab	20·97	24·14	22·55	23·59	23·59	23·59
An	33·38	34·49	36·99	35·05	35·05	33·38
Wo	6·50	5·11	4·88	5·34	5·23	5·46
En	14·76	9·43	13·85	12·34	11·54	12·65
Fs	5·80	6·47	9.24	4·62	9·89	11·35
Mt	7·87	6·48	4·40	6·93	3·94	3·94
Il	2·73	3·34	2·12	2·58	2·73	2·58
Ap	0·33	0·65	0·33	0·65	0·65	0·65

Table I. Specific susceptibility of volcanic rocks at various temperatures.
(H, Heating process; C, Cooling process.)

Specimen / Temperature	(No. 1.) S—N 17 H=1·54 Oe.		(No. 2.) S—N 20 (1) H=1·93		(No. 2.) S—N 20 (2) H_2=1·93		(No. 3.) S—N 23 H=2·13		(No. 4.) S—N 21 H=2·14		(No. 5.) S—N 18 H=2·14		(No. 6.) S—N 22 H=2·19		(No. 7.) S—N 59 H=2·20	
	H	C	H_1	C_1	H_2	C_2	H	C	H	C	H	C	H	C	H	C
25°C	2·25	2·25	1·29	1·27	1·28	1·27	1·30	1·28	1·62	1·63	1·42	1·41	0·72	0·70	1·35	1·41
40	2·28	2·25	1·29		1·28		1·30	1·29	1·62	1·64	1·44	1·45	0·75	0·74	1·53	1·57
60	2·28	2·26	1·29		1·30	1·26	1·28	1·29	1·64	1·65	1·48	1·48	0·80	0·78	1·61	1·74
80	2·31	2·28	1·31		1·33		1·32	1·30	1·66	1·66	1·57	1·50	0·87	0·84	1·73	1·86
100	2·31	2·30	1·32		1·31		1·32	1·31	1·70	1·67	1·63	1·59	0·91	0·91	1·88	1·97
120	2·34	2·32	1·32		1·32	1·27	1·35	1·31	1·71	1·69	1·79	1·76	0·96	0·96	1·97	2·08
140	2·38	2·35	1·36		1·31		1·37	1·32	1·74	1·70	1·87	1·83	1·01	1·01	2·03	2·18
160	2·44	2·36	1·36		1·30		1·37	1·32	1·75	1·70	1·94	1·88	1·09	1·03	2·12	2·23
180	2·47	2·39	1·37		1·31	1·29	1·38	1·32	1·77	1·72	2·03	1·93	1·10	1·05	2·23	2·30
200	2·51	2·41	1·37		1·31		1·40	1·34	1·78	1·73	2·16	1·97	1·11	1·03	2·20	2·34
220	2·52	2·42	1·42	1·32	1·33		1·41	1·36	1·82	1·75	2·16	1·89	1·02	1·02	2·03	2·35
240	2·57	2·46	1·41		1·31	1·29	1·42	1·37	1·84	1·76	1·98	1·74	0·93	0·93	1·90	2·36
260	2·60	2·44	1·43		1·31		1·44	1·39	1·87	1·77	1·79	1·46	0·80	0·77	1·76	2·31
280	2·62	2·47	1·41		1·30		1·46	1·39	1·87	1·78	1·43	1·15	0·68	0·64	1·54	2·20
300	2·64	2·47	1·44	1·34	1·30	1·29	1·49	1·38	1·91	1·78	0·98	0·79	0·55	0·52	1·01	2·10
320	2·63	2·42	1·47	1·35	1·30	1·30	1·51	1·39	1·93	1·78	0·57	0·58	0·49	0·45	0·59	1·85
340	2·48	2·32	1·44	1·35	1·29	1·30	1·50	1·37	1·95	1·79	0·54	0·49	0·41	0·38	0·30	1·60
360	2·32	2·25	1·47	1·35	1·29	1·31	1·52	1·38	1·98	1·80	0·51	0·46	0·40	0·35	0·23	1·24
380	2·22	2·10	1·47	1·34	1·27	1·28	1·52	1·38	2·02	1·82	0·50	0·42	0·37	0·33	0·24	0·98
400	2·14	1·93	1·49	1·30	1·28	1·29	1·54	1·34	2·03	1·82	0·50	0·41	0·35	0·30	0·31	0·78
420	1·96	1·57	1·47	1·29	1·26	1·27	1·49	1·23	2·04	1·77	0·46	0·39	0·33	0·28	0·37	0·56
440	1·40	1·18	1·37	1·20	1·19	1·23	1·34	1·13	2·03	1·62	0·40	0·39	0·30	0·25	0·45	0·46
460	0·90	0·80	1·20	1·03	1·06	1·06	1·05	0·96	1·89	1·51	0·38	0·36	0·23	0·21	0·40	0·37
480	0·57	0·53	0·99	0·85	0·65	0·79	0·83	0·71	1·61	1·25	0·35	0·33	0·21	0·18	0·32	0·26
500	0·36	0·31	0·60	0·60	0·41	0·57	0·54	0·42	1·21	0·92	0·30	0·28	0·18	0·15	0·19	0·22
520	0·15	0·17	0·41	0·39	0·30	0·38	0·34	0·25	0·78	0·58	4·22	0·18	0·14	0·11	0·13	0·13
540	0·11	0·13	0·23	0·22	0·16	0·20	0·21	0·15	0·37	0·34	0·13	0·15	0·06	0·07	0·10	0·09
560	0·05	0·04	0·11	0·11	0·07	0·08	0·09	0·07	0·21	0·19	0·05	0·06	0·02	0·03	0·04	0·03
580	0·00	−0·01	0·00	0·01	0·01	0·01	0·03	0·03	0·05	0·07	−0·01	0·01	0·01	−0·01	0·00	0·00
600	0·00	0·00	0·01	0·02	−0·01	0·00	0·00	−0·01	0·00	0·02	0·00	0·00	0·00	0·01	−0·01	0·00
620	0·01	−0·01	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	−0·01	0·00	0·00	0·00	−0·02
640	0·00	0·00	−0·02	−0·01	−0·01	−0·01	0·00	−0·01	0·00	0·01	0·00	−0·01	−0·01	0·00	0·01	−0·02
660	0·00	0·00	−0·01	−0·01	−0·01	−0·01	−0·01	−0·01	0·00	0·00	−0·01	0·00	0·01	0·00	−0·01	0·00

Unit=10^{-3} e.m.u.

Of the results of measuring susceptibility of these specimens, those of the ejecta from Miyake-sima were already described in the writer's previous paper,[7] so that we shall here deal with the other rock specimens. The observed values of magnetic susceptibility of these rocks at various temperatures from 20°C to 700°C are given in Table I and in Figs. 5 ~12. In these figures, the scale of the ordinate gives the specific value of magnetic susceptibility, (I) and (II) denote the heating and cooling processes respectively, while (III) and (IV) in Fig. 6 show the second heating and cooling processes respectively. As will be clearly seen from

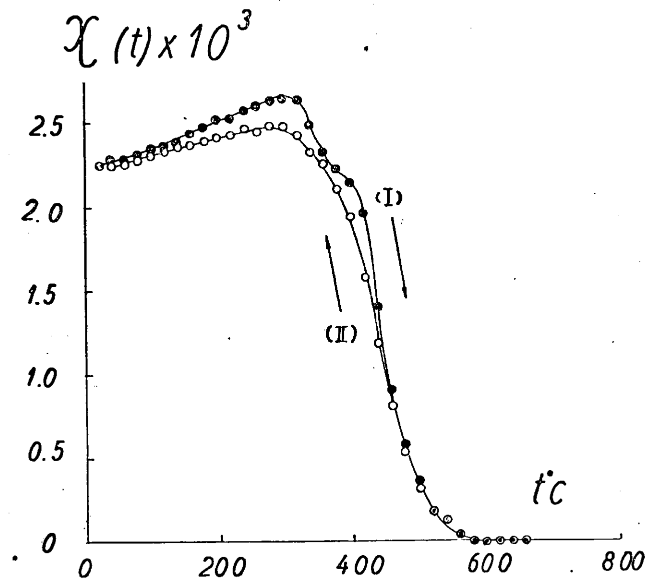

Fig. 5. Change in susceptibility with temperature, No. 1. (S—N 17) H=1·54 Oe.

these results, the $\chi(t) \sim t$ curves of the rock specimens are not always monotonic. Sometimes, the susceptibility changes stepwise with temperature, for example, those shown in Fig. 9~11. In some of the specimens, however, the thermal changes in magnetization have a fairly simple character, like those given in Fig. 6~8, in which the mode of change in susceptibility with temperature is nearly the same as those of ordinary ferromagnetic materials; that is, the susceptibility gradually decreases with temperature, the ferromagnetism disappearing at a critical temperature. Actually, the intensity of magnetization at temperature higher than the critical point could not be estimated by the present instrument, since its magnitude was much smaller than the observational error, with

7) T. NAGATA, *Bull. Earthq. Res. Inst.*, **19** (1941), 304.

the result that, practically speaking, the magnitude of susceptibility in the temperature range above the critical point is taken as zero.

It will be noticed that the susceptibility of these specimens slowly increases with temperature from 0°C, at any rate in the process of initial heating, to about 400°C in specimen No. 1, while it decreases rather abruptly from that point. Comparing the $\chi(t)\sim t$ relations in the heating (I) and cooling (II) processes, it will be said that they are nearly similar, excepting the slight difference that the susceptibility in the cooling process is usually slightly less than that in the heating process. While those in processes (III) and (IV) are nearly the same, they also nearly agree in process (II).

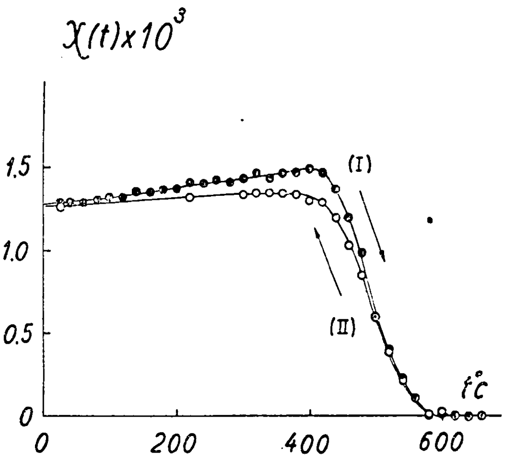

Fig. 6. (a) Change in susceptibility with temperature.
No. 2. (S—N 20) H=1·93 Oe.

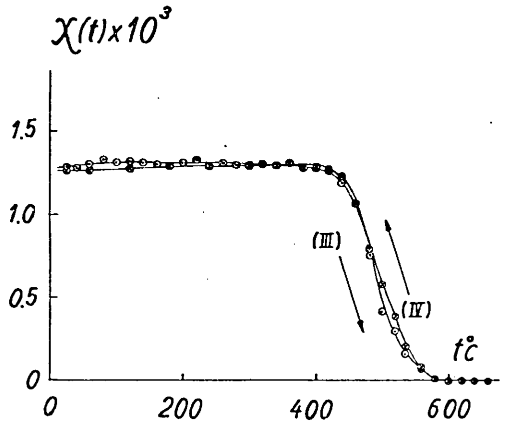

Fig. 6. (b) Change in susceptibility with temperature.
No. 2. (S—N 20) H=1·93 Oe.

This type of mode of change in susceptibility with temperature, as just mentioned, we shall call "the standard type" of rock. In the $\chi(t)\sim t$ relation of the standard type rock specimen, its susceptibility becomes approximately zero at critical temperature, at which the ferro magnetism of the rock specimen is believed to disappear. If we take this critical temperature as the apparent Curie-point of the rock specimen, the value of the standard type rock almost agrees with that of pure magnetite, namely, from 580°C to 600°C. However, since the temperature at which the rate of change in susceptibility with respect to temperature is maximum does not agree with the citical point, the former usually being slightly lower than the latter, by taking into consideration that the ferromagnetic minerals in the rocks must be composed not of pure magnetite alone, but also of solid solutions of Fe_2O_3, FeO, TiO_2, and other elements in various phases, it may be presumed that the Curie-point temperature of the rock will not be given uniquely, but instead, as a band of finite width with respect to temperature. For these reasons, we take here the temperature at which $\partial\chi/\partial t$ is maximum as the mean Curie-point of a rock specimen, denoting it by $\bar{\theta}$. The critical temperature at which the ferromagnetism of a rock specimen disappears may then be interpreted as the upper limit of the band of Curie-point temperatures, which point will correspond to the Curie-point temperature of that part of the total ferromagnetic minerals in the rock that has the composition of pure magnetite, which point is denoted here by θ. The actual values of $\bar{\theta}$ and θ are given in Table II.

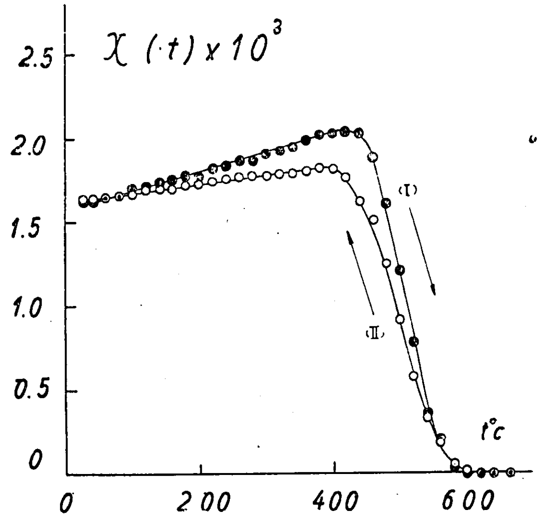

Fig. 7. Change in susceptibility with temperature.
No. 3. (S—N 23) H=2·13 Oe.

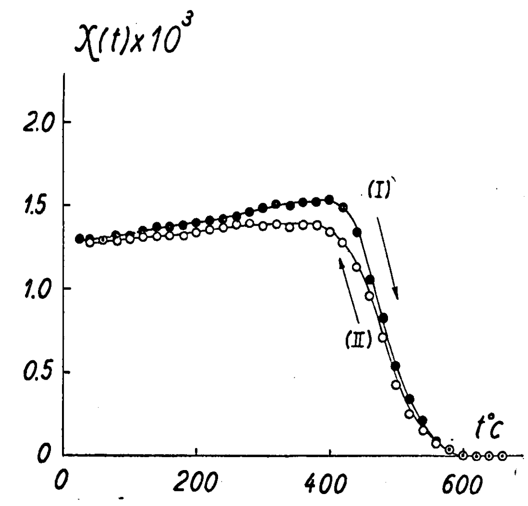

Fig. 8. Change in susceptibility with temperature.
No. 4. (S—N 21) H=2.14 Oe.

In contrast to this, those rock specimens of no standard type of character change in susceptibility with temperature in various ways. As to the curves of rock samples whose susceptibilities change stepwise with temperature, they may be regarded as the result of superposition of two fundamental curves of $\chi(t)$, the mean Curie-point temperatures of which are $\bar{\theta}_1$ and $\bar{\theta}_2$, while the upper limits of the band of Curie-point temperatures of each of the two curves separated from $\chi(t)$ are θ_1 and θ_2 respectively. Here, the fundamental curve of $\chi(t)$ is defined as the curve, the mode of which is similar to the standard curve, that is, it changes monotonically with temperature, having only one mean Curie-point temperature, but its θ does not necessarily agree with the Curie-point of magnetite, namely, θ_M. The observed valuesof $\bar{\theta}_1$, $\bar{\theta}_2$, θ_1, and θ_2 are given in Table II, where it will be seen that their θ_2 agrees well with the θ of the standard type curve, as with θ_M. Hence, it may be said that one of the elemental curves composing the $\chi(t)$ curve of stepwise change type is of standard type.

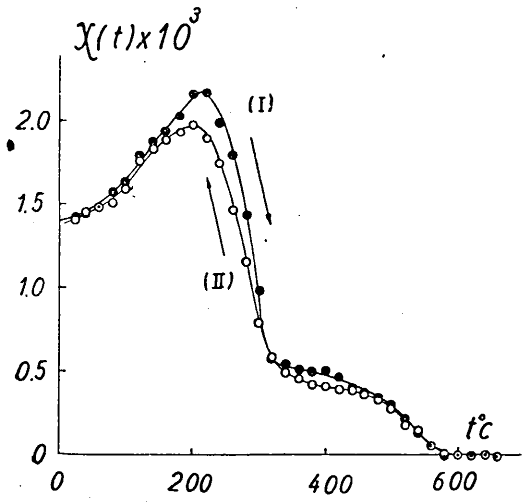

Fig. 9. Change in susceptibility with temperature.
No. 5. (S-N 18) H=2·14 Oe.

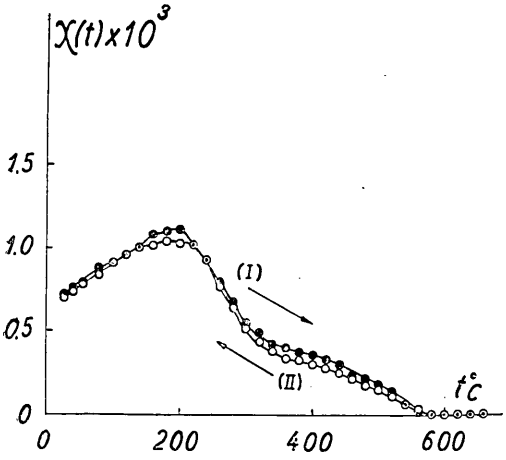

Fig. 10. Change in susceptibility with temperature.
No. 6. (S—N 22) H=2·19 Oe.

Generally speaking, it may be possible that a $\chi(t)$ curve is composed of two or more fundamental curves, the mean Curie-point temperatures of which are not alike.[8] Thus, generally,

$$\chi(t)=\sum_j \chi_j(t).$$

In all these examples mentioned above, the susceptibility at any temperature in the process of heating and cooling is nearly the same, there

Table II.

Specimen	Locality	Rock	$(\chi_0)_{t=0}$	$\bar{\theta}$	θ	C_{Mt}
No. 1. (S—N 17)	Huzi	olivine-basalt	$2{\cdot}25\times10^{-3}$	460°C	575°	7·87 %
No. 2. (S—N 20)	Huzi	olivine-basalt	$1{\cdot}28\times10^{-3}$	500	580	6·48
No. 3. (S—N 23)	Huzi	two-pyroxene-bearing olivine-basalt	$1{\cdot}29\times10^{-3}$	495	590	4·40
No. 4. (S—N 21)	Huzi	augite-bearing olivine-basalt	$1{\cdot}55\times10^{-3}$	520	590	6·95
No. 5. (S—N 18)	Huzi	hypersthene-augite-olivine-basalt	$1{\cdot}31\times10^{-3}$	$\bar{\theta}_1=270$ $\bar{\theta}_2=520$	$\theta_1=320$ $\theta_2=580$	3·94
No. 6. (S—N 22)	Huzi	augite-bearing olivine-basalt	$0{\cdot}70\times10^{-3}$	$\bar{\theta}_1=280$ $\bar{\theta}_2=510$	$\theta_1=310$ $\theta_2=580$	3·94
No. 7. (S—N 59)	Miyake-sima	olivine-hypersthene-pyroxene-basaltic-andesite	$1{\cdot}31\times10^{-3}$	H $\bar{\theta}_1=320$ H $\bar{\theta}_2=520$ C $\bar{\theta}=360$	$\theta_1=380$ $\theta_2=580$ $\theta=580$	

being slight differences between them, as already described in the case of the standard type specimen. In other words, the susceptibilities of rock specimens, Nos. 1 to 6, are almost reversible with respect to temperature, regardless of whether it belongs to the standard type or not.

On the other hand, we have an example in which the change in susceptibility is irreversible with respect to temperature. It is shown in Fig. 11, where the susceptibility changes stepwise with temperature, $\bar{\theta}_1$, $\bar{\theta}_2$, θ_1, and θ_2 being 270°C, 500°C, 360°C, and 580° C respectively during heating, while in cooling it changes rather monotonically, $\bar{\theta}$ being 360°C, although θ is 580°C in this case also.

In all these examples, where the lower mean Curie-point temperature $\bar{\theta}_1$ is fairly smaller than that of pure magnetite, it is a common character that the rate of increase of susceptibility with temperature in a certain initial range from 0°C is much larger than that of the standard type rock, amounting to from 0·2 to 0·5 percent/degree. In such samples, the susceptibility at that temperature where it takes the largest value amounts to from 1·5 to 1·8 times that at oridinary room temperature. Since this phenomenon of increase of magnetic susceptibility with temperature could not be seen in the $\chi(t)\sim t$ relations in a magnetic field of from about 120 to 150 Oersteds, in the result of study

8) Specimen No. 1, (shown in Fig. 5) seems to be intermediate in type between standard and stepwise change.

by Chevallier and Piere, it is believed that this phenomenon is peculiar to the rock in a weak magnetic field.

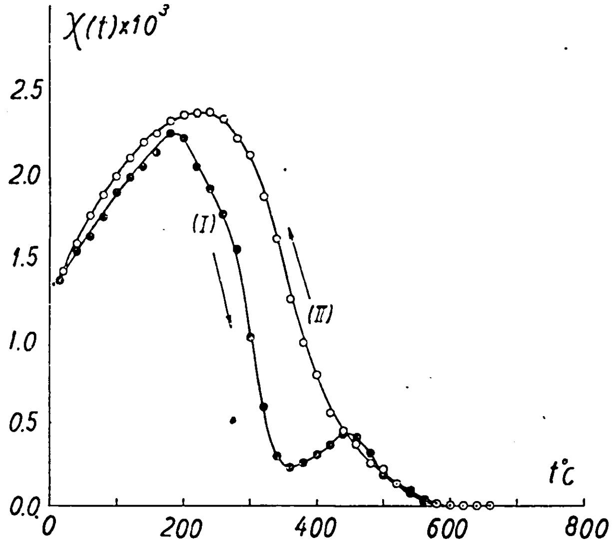

Fig. 11. Change in magnetic susceptibility with temperature (irreversible type). No. 7 (S—N 59) H=2·20 gauss.

Next, the fact that the susceptibilities of some rock specimens change stepwise with temperature shows that the ferromagnetic minerals contained in them consists of a few groups of different mineralogical characters, the number of these groups corresponding to that of $\overline{\theta}_j$.

For example, specimen No. 5, shown in Fig. 9, contains two different groups of forromagnetic minerals, one of which is nearly the same as pure magnetite, corresponding to the part of $\chi_2(t)$, (component of standard type), while the other differs greatly from pure magnetite, since θ_1, which corresponds to $\chi_1(t)$, is clearly much lower than θ_M. Further details of the relation between the mode of thermal change in the susceptibility of rocks and their petrological composition, as well as its relation to the mode of causation of thermo-remanent magnetism in a weak magnetic field, will be discussed in future papers. It may however be worth while to note here the fact that, according to microscopic observations of the Huzi ejecta by Tsuya, the groundmasses of specimens Nos. 1, 3, and 5 are clearly more crystalline than those of Nos. 2 and 4, which fact may correspond to our result in which the mode of change in susceptibility with temperature of the former specimens is of the standard type, while that of the latter is not.

Lastly, for comparison, the result of the same examination of a specimen of magnetite is given in Fig. 12. That its mode of change differs slightly from that of pure magnetite must be chiefly because it contains impurities.

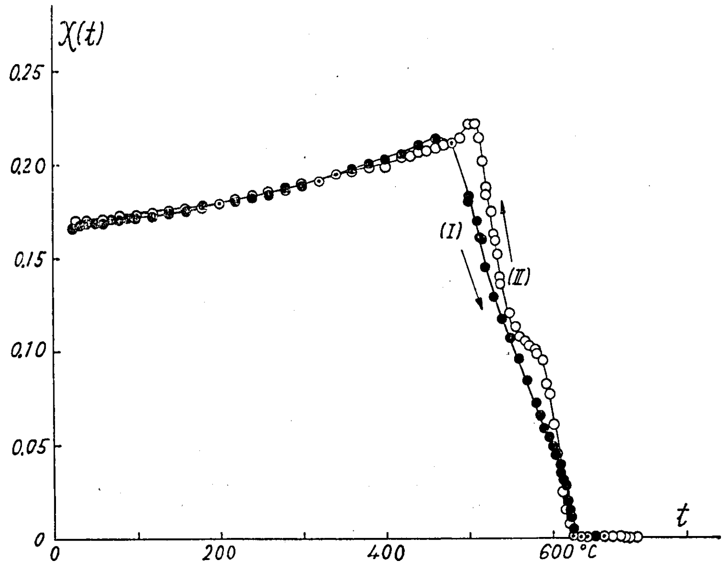

Fig. 12. Magnetite grains. H=1·54 Oe.

4. Conclusion.

In this paper, the writer describes the method of measuring the change in magnetic susceptibility of rocks with temperature in a weak magnetic field, and gives several typical examples of the result alone, without any physical and petrological interpretation of these results. It is evident from the results of the present examination that the magnetization of these rocks, which is chiefly due to the ferromagnetic minerals present in them, changes markedly with temperature, exactly in the same manner as the usual ferromagnetic materials, although the mode of change in the former is usually much more complex than that of the latter. This phenomenon would be a contributive cause in the change in magnetization of the earth's crust, provided there were a a certain temperaturc change. There is, however, no such conspicuous increase of susceptibility in a weak magnetic field as that in the case of iron, usually known as "Hopkinson effect," so far as our experiment went. It is believed that the Hopkinson effect will not appear in a rock, even if the applied magnetic field were as small as 0·1 to 0·5 Oersteds, a field much weaker than that in the present case, since the demagnetizing factor of the ferromagnetic minerals in the rock is usually very large, namely, 3 or 4, regardless of the smallness of the apparent demagnetizing factor of the whole specimen as a rock. Hence, the mode of change in susceptibility with temperature shown in Figs. 4 ～11 is believed to be general with all igneous rocks.

In conclusion, the writer wishes to express his sincere thanks to Prof. H. Tsuya for his interest and kind advices from the petrological point of view, and to Prof. C. Tsuboi for his continued encouragement in the writer's geomagnetic study of the earth's crust. His hearty thanks are also due, for grants received, to the Department of Education and to the Hattori Hôkô Kai.

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35. 岩石の帶磁率の溫度に因る變化の測定

地震研究所 永田 武

岩石の帶磁率の溫度による變化を知る事は地殼の磁性を論ずるには是非共必要な事である．岩石が磁場内で溫度變化を爲す時は一般に熱殘留磁氣の生成，消滅が起きるので，この影響をさける爲に磁場逆轉に依る彈動法を用ひて，帶磁率の溫度による變化の測定を爲した．種々の測定誤差が伴ふので，結局の測定誤差は比帶磁率の絕對値に於いて最高 3×10^{-5} である．從つて 10^{-3} の比帶磁率の測定には 3％ の誤差を伴ふ．但し測定に用ひた磁場の强さは 1·5 乃至 2·2 Oersted である．然しこの樣な測定の結果に於いても，岩石の帶磁率の溫度による變化をかなり詳しく求める事が出來た．

測定した岩石試料のすべてに於いて，それ等の帶磁率は 580°C 乃至 600°C の溫度で 0 になる．この溫度は磁鐵鑛の磁氣變態點にほぼ一致する．然し帶磁率と溫度との關係は必ずしも單調でなく本文第 9 圖乃至第 11 圖に示す如く，300°C 附近で著しい變化を示す岩石もある．又溫度變化に對して帶磁率がほぼ可逆的に變化する場合と，著しい非可逆性を示す場合とがある．更に室溫からある溫度迄は溫度の增加と共に帶磁率は一般に若干增加する傾向（但し 1·5～2·2 Oersted の磁場に於いて）が明らかに見られる．この報告では主として測定裝置，及び測定結果の數例を報告するにとどめた．猶ほこの研究は文部省科學研究費，及び服部報公會の研究援助によつて遂行されたものである．兩當事者に對し厚く感謝の意を表する．

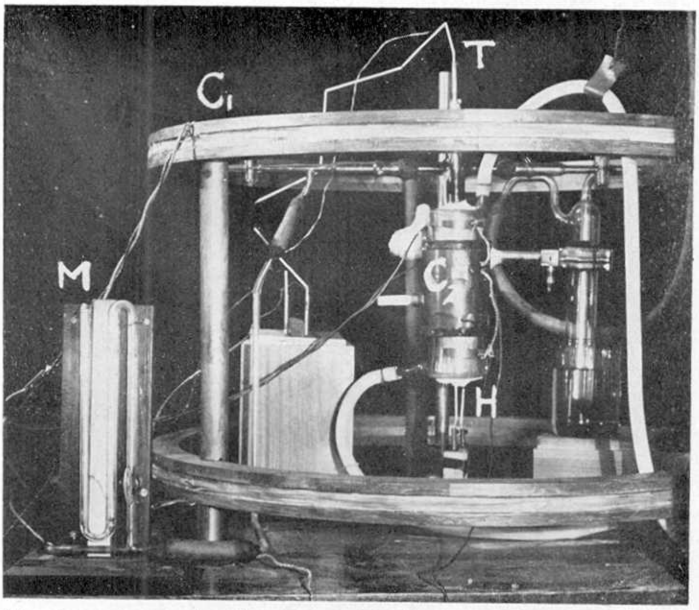

Fig. 3 a. Apparatus for measuring the magnetic susceptibility at high temperature.

C_1, primary coil, C_2, secondary coil,
H, plutinum heater, M, manometer,
T, thermo-junction.

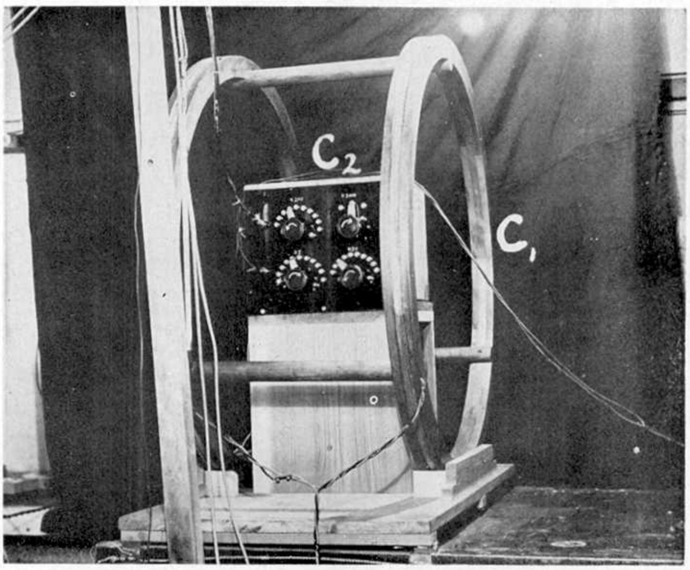

Fig. 3 b. Compensating equipment.
C_1, primary coil, C_2, variable secondary coil.