6. The Mode of Causation of Thermo-Remanent Magnetism in Igneous Rocks. Preliminary Note.

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1. Introduction.

Since the discovery of the fact that the igneous rocks, especially the effusive ones, are permanently magnetized in their natural state, a number of investigators[1] have studied the characteristics of this permanent magnetism. This permanent magnetism in igneous rocks, which is usually called natural remanent magnetism, is generally much larger than the intensity of the magnetism that is induced in the same rocks by the present geomagnetic field. Since it had been experimentally proved[2] that this natural remanent magnetism is chiefly due to the magnetization that remains after the rock has cooled from the state of high temperature (in an external magnetic field), and that the direction of the residual magnetization agrees with that of the applied magnetic field, many investigators[1] have attempted to estimate the direction of the earth's magnetic force in remote times when the remanent

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1) G. FOLGHERAITER, *Rend. Ac. Lincei. Roma.* **3~2** (1894), 53; **4~1** (1895), 203; **4~2** (1895), 78.
P. MERCANTON, *C. R. Acad. Sci. Paris.* **182** (1926), 859, 1231; **194** (1932), 1371; *C. R. Soc. Suisse. Geophys. Meteor. Astro.* (1926), 345.
F. POCKELS, *Phys. Z. S.*, **2** (1901), 306.
P. DAVID, *C. R. Acad. Sci. Paris.* **138** (1904), 41.
R. CHEVALLIER, *Ann. Phys. Paris.* **4** (1925), 5.
B. BRUNHES, *Journ. Phys. Paris.* **5** (1906), 705.
E. THELLIER, *C. R. Acad. Sci. Paris.* **197** (1933), 232, 1399; **203** (1636), 743; **204** (1937), 876.
A. F. HALLIMOND and E. F. HERROUN, *Rroc. Roy. Soc. London*, A., **141** (1933), 302.
J. G. KÖNIGSBERGER, *Z. S. Geophys.* **6** (1930), 190; *Gerl. Beitr. Geophys.* **35** (1932), 151.

2) J. G. KÖNIGSBERGER, *Z. S. Geophys.* **6** (1930), 190; **8** (1932), 322; *Gerl. Beitr. Geophys.* **35** (1932), 204; **38** (1933), 47; *Beitr. Angew. Geophys.* **5** 19 5), 193.
G. E. ALLEN, *Phil. Mag.* **7** (1904), 45; **17** (1909), 572.
S. NAKAMURA and S. KIKUCHI, *Proc. Phys. Math. Soc. Japan.* **6** (1912), 268.
T. NAGATA, *Bull. Earthq. Res. Inst.*, **18** (1940), 281; *Zisin.* **12** (1940), 285, 544.

magnetization originally came into existence, assuming that the direction of the remanent magnization in rocks, upon cooling and solidifying, agrees with the geomagnetic direction, so long as the rock mass had not moved after completion of the cooling. Such studies were also made by M. Matuyama[3] and others[4] with certain Japanese igneous rocks. This method of presuming the geomagnetic direction in remote times, having been applied also to the remanent magnetization of certain kinds of baked earths, we have at present a number of papers[5] on this subject.

Our present knowledge of the characteristics of thermo-remanent magnetism, that is, the residual permanent magnetism that results when the igneous rock is cooled from high temperature in a weak magnetic field, however, is largely the result of the comprehensive experimental work of J. G. Königsberger.[6] According to this investigator, cooling of ferromagnetic minerals in rocks in a magnetic field from Curie-temperature may produce certain results, depending on the change in the coercive force with temperature and on the demagnetizing force at near Curie-point, the effect finally resulting in thermo-remanent magnetism. He further presumed that the effect just mentioned was due to the lattice-change in the magnetite, which might be caused by escape of the Fe_2O_3.

The main object of these investigators, including Königsberger, seems to have been in discovering the character of natural remanent magnetism and its relation to the geomagnetic field in remote geological times. We have, however, another interesting phenomenon of geophysics that seems to be closely related to the causation of thermo-remanent magnetism in nature. It is the local anomalous variation in geomagnetism that follows severe volcanic activity. To illustrate, in a recent expedition that we made to Miyake island,[7] we observed by means of both magnetograph records and absolute measurements that the geomagnetic dip at a point about two *km* north of a region in which severe volcanic eruptions had occurred, made a total change of about 25 minutes during

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[3] M. MATSUYAMA, *Proc. Imp. Acad. Japan.* **5** (1932), 113; *Proc. Fourth Pacific Sc. Congress* (Java), (1929), 567.

[4] S. NAKAMURA and S. KIKUCHI, *loc. cit.*
T. NAGATA, *loc. cit.*

[5] P. MERCANTON, *C. R. Acad. Sci. Paris.* **143** (1906), 138; **166** (1918), 681.
E. THELLIER, *Ann. Inst. Phys. Globe.* **10** (1932), 113; **16** (1238), 157; *C. R. Acad. Sci. Paris.* **197** (1933), 1399.

[6] J. G. KÖNIGSBERGER, *loc. cit.*
The results of his studies are summarized in his paper, "Natural Residual Magnetism of Eruptive Rocks" (*Terr. Mag.* **43** (1938), 119, 299.)

[7] H. TSUYA, R. TAKAHASI, T. HAGIWARA, T. MINAKAMI, T. NAGATA, and others. "Report of Volcanic Eruption of Miyakesima-Island, July 1940." *Zisin.* **12** (1940), 435~533. (In Japanese).

twenty days after the volcanic activity began. Seeing that the ejected lava flow and bombs (already cooled to ordinary temperature) showed a natural remanent magnetism of $5 \times 10^{-3} \sim 3 \times 10^{-2}$ in its specific intensity, while their specific susceptibility in ordinary temperature amounted only to $0{\cdot}6 \times 10^{-3} \sim 1{\cdot}2 \times 10^{-3}$, it may be concluded that much of the observed geomagnetic change might be due to the change in the thermo-remanent magnetism of the subterranean magma rather than to the temperature change in its susceptibility. Although in the cases of activities of other volcanoes, local geomagnetic changes were also observed by means of magnetographs,[8] the magnitude of the variation in these cases was smaller than that observed in Miyake island, while according to S. T. Nakamura,[9] who analysed the results of intermittent re-surveys of geomagnetic dip (with the aid of the dip-circle), secular geomagnetic variation seems to be related to volcanic activity.

Hence, our keen interest is in the causation of thermo-remanent magnetism and its disappearance, seeing that these phenomena can be presumed to occur in the earth's crust accompanying changes in temperature and sometimes accompanying changes in stress distribution. If it can be physically established that the magnetic condition of the igneous rocks is influenced by temperature, the external magnetic field, and pressure, we should then be able to form some idea of the physical conditions and their changes in the earth's crust by measuring the anomalous distribution of the geomagnetic field on the earth's surface and its changes. For this purpose, it is necessary to examine experimentally the characteristics of the thermo-remanent magnetism as well as the magnetic susceptibility of rocks due to temperature changes. The physical aspect of the causes that gave rise to thermo-remanence will especially be interesting both from the geophysical standpoint just mentioned and from the standpoint of the physics of the magnetism of such aggregate of complex solid solutions and crystals that we call rocks.

We shall however deal here only with the general phenomenological aspect of the causation of thermo-remanence as suggested by our experimental studies with a few basic volcanic rocks.

2. Thermo-Remanent Magnetism.

As mentioned in the introduction, the residual permanent magnetism

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[8] T. Nagata, *Zisin.*, **10** (1938); Read before the 148 th (1939) and 163 rd (1940) meetings of the *E. R. I.* (Not yet published).

T. Minakami, *Bull. Earthq. Res. Inst.*, **13** (1935), 799.

[9] S. T. Nakamura, *Proc. Imp. Acad. Japan.*, **11** (1935), 102.

that remains after the sample is cooled from temperature t to zero in a uniform magnetic field of H, we shall call thermo-remanent magnetism, indicated here by J_{tH} for unit mass of sample. Since the intensities of the remanent magnetism that is produced by cooling from t°C to 0°C and that to the ordinary room temperature (about 20°C) are practically the same, the remanent magnetism produced in the latter case will frequently be taken as J_{tH}. The apparatus for measuring the thermo-remanent magnetism in the present study is, in outline, as follows. A non-inductive electric furnace, 22 cm large and 2·5 cm in its inner diameter, is set coaxially in the centre of a large Helmholtz's coil of 25 cm radius, the axes of the furnace and of the coil being, obviously, perpendicular to the geomagnetic meridian. The resistance wire in the furnace is pure nichrome wire of magnetic susceptibility smaller than 1×10^{-4}. The specimen to be measured was pulverized into small grains, 0·5∼1·0 mm in their mean diameter, and a silica tube, 11 cm long and 1·8 cm in its inner diameter, was filled with this powder. The tube containing the rock grains was placed in the centre of the furnace coaxially. In the space occupied by the tube, the magnetic field supplied by the Helmholtz's coil was thus nearly uniform, with an error of less than 0·1 percent. The temperature of the specimen was measured at its centre with Pt, Pt–Rh thermo-junction, the temperature throughout the sample being uniform, with an error of less than 5°C, provided the heating or cooling velocity did not exceed 0·05 degrees per second. The intensity of the thermo-remanent magnetism produced in the apparatus was measured by means of another instrument by a ballistic method, already described in the previous paper.[10]

In measuring the J_{tH} of various values of t successively, the J_{tH} obtained in the first experiment was purposely nullified by heating the specimen to a temperature higher than t and cooling it in a non-magnetic space, before proceeding with the next experiment. Thus in every treatment, the sample was in standard condition. In this way, the intensity of the thermo-remanent magnetism of various values of t in a constant magnetic field was measured. The direction of the thermo-remanence always agreed with the direction of the external magnetic field applied. Several typical examples of the observed data are given in Table I, as also Fig. 1, where the intensity of the applied magnetic field was 0·458 Gauss for all the examples.

As will be seen from these results, J_{tH} in a constant magnetic field H increases with increase of temperature t, and reaches maximum value

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[10] T. NAGATA, *Bull. Earthq. Res. Inst.*, **18** (1940), 102.

Table I. Specific Intensity of Thermo-remanent Magnetism.

t	$J_{t.H}$ ($H=0{\cdot}458$ Gauss)					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
20°C	$0{\cdot}00\times10^{-3}$	$0{\cdot}00\times10^{-3}$	$0{\cdot}00\times10^{-3}$	$0{\cdot}00\times10^{-3}$	$0{\cdot}00\times10^{-3}$	$0{\cdot}00\times10^{-3}$
200	0·65	0·20	0·62	2·85	0·30	0·56
300	0·96	0·75	2·36	6·50	0·45	2·17
350				9·77		
400		4·21	6·18	15·35	1·22	5·63
450	2·84	8·80	7·95	20·95	3·97	6·28
500	3·75				8·58	6·70
550	4·81	11·32	9·86	26·45	16·45	
600	5·30				21·20	6·68
650		11·60	9·87	27·25		
700	5·70				22·10	
750				27·35	21·95	
800	5·65					

No. 1.	Volcano Mihara Somma lava.	No. 4.	Volcano Mihara Bomb.
No. 2.	〃 〃 Bomb.	No. 5.	Miyakesima Volcano Lava flow.
No. 3.	〃 〃 Bomb.	No. 6.	〃 〃 Bomb.

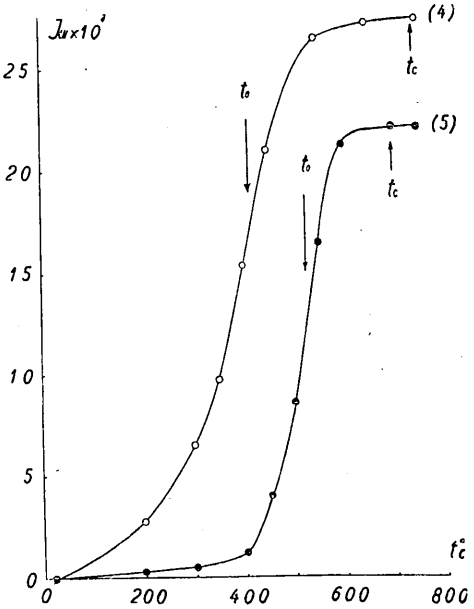

Fig. 1 (a). Intensity of thermo-remanent magnetism ($H=0{\cdot}458$ Gauss)

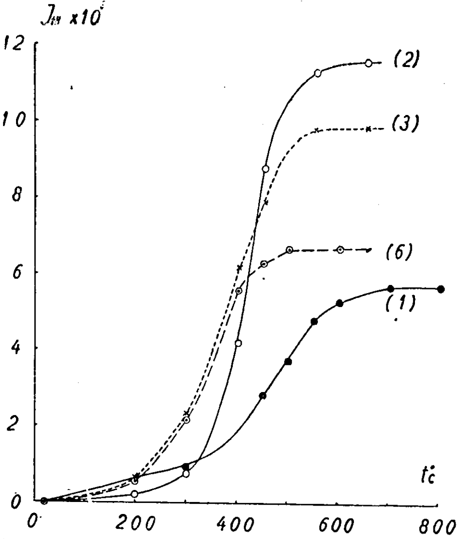

Fig. 1 (b). Intensity of thermo-remanent magnetism ($H=0{\cdot}458$ Gauss)

at t_c, a J_{tH} of higher temperature than t_c being always constant and equal to $J_{t_c H}$. The intensity of the *saturated thermo-remanent magnetism* of volcanic rocks is then in most cases larger than the intensity of the induced magnetism $H\cdot\chi$ at ordinary room temperature in the same magnetic field H, where χ denotes the specific magnetic susceptibility of the same specimen. It is notable that the $J_{t_c H}$ of basic rocks, basalt or basaltic andesite, is frequently much larger than its $H\cdot\chi$, the ratio of $J_{t_c H}$ to χH in them sometimes amounting to one hundred. The observed values of $J_{t_c H}$ and χ of several typical specimens are given in Table VII, where Q_t[11] denotes the ratio $J_{t_c H}/\chi H$, and is called here the *coefficient of the thermo-remanent magnetism.* Qualitatively speaking, the magnitude of Q_t seems to be given not only by the chemical composition and crystal structure of the ferromagnetic minerals in the rocks, but also by the size of those grains; that is to say, the ferromagnetic minerals that are scattered as microcrystals in the groundmass occupy a larger percentage of the total ferromagnetic component of the rock the larger the value of Q_t. In other words, the Q_t of such a rock in which the larger part of the ferromagnetic component in it consists of phenocrysts, seems to be comparatively small. This conclusion, however, is only the qualitative result of microscopic observations of thin sections of these rocks. A more quantitative solution of this problem will be discussed in a future report.

It will be seen from Fig. 1 that the differential coefficient of the curve for $J_{t,H}$ with respect to temperature is largest at t_0, and that $\partial^2 J_{tH}/\partial t^2$ is positive for the range at temperatures lower than t_0, whereas it is negative at temperatures higher than t_0, so that temperature t_0 may be taken as a transcendental point of thermo-remanence, while t_c would have another important physical meaning in its causation.

Next, the intensity of the saturated thermo-remanent magnetism in various external magnetic fields was measured, although, at present, we have only the experimental data obtained in a weak magnetic field, that is, smaller than 1·7 Gauss. A number of the observed results are given in Table II and Fig. 2.

Table II (a).

H	$J_{t_c H}$	$J_{t_c}=J_{t_c H}/H$	H	$J_{t_c H}$	$J_{t_c}=J_{t_c H}/H$
0 Gauss	$0{\cdot}00\times10^{-2}$	$\sim$	0·98 Gauss	$4{\cdot}07\times10^{-2}$	$4{\cdot}2\times10^{-2}$
0·27	1·21	$4{\cdot}5\times10^{-2}$	1·34	5·62	4·2
0·63	2·78	4·4	1·70	6·68	4·1

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[11] J. G. Königsberger has already proposed certain notations for the various characteristics of thermo-remanent magnetism, and used them for a long time. In this paper, we shall follow his notations as far as possible.

Table II (b).

H	$J_{t_c H}$	J_{t_c}	H	$J_{t_c \cdot H}$	J_{t_c}
0 Gauss	$0{\cdot}00 \times 10^{-2}$		0·82 Gauss	$5{\cdot}90 \times 10^{-2}$	7·2
0·14	0·96	6·9	1·00	7·20	7·2
0·28	2·10	7·5	1·36	9·22	6·8
0·46	3·53	7·6	1·72	11·33	6·6
0·64	5·07	7·9			

Since, as will be seen from these results, $J_{t_c \cdot H}$ is nearly proportional to H, if H is not large, we may write the relation in the case of a weak magnetic field

$$J_{t_c \cdot H} = F(H) \cdot J_{t_c},$$

$$F(H) \fallingdotseq H, \qquad (1)$$

where $F(H)$ denotes a function of H alone. On the other hand, from the relation between $J_{t \cdot H}$ and t in two different values of H are given in Table III and Fig. 3, we get the relation

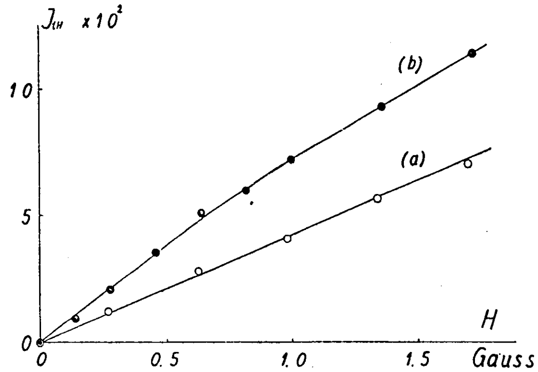

Fig. 2. Intensity of saturated thermo-remanent magnetism in various magnetic fields.

$$\frac{J_{t \cdot H_1}}{J_{t \cdot H_2}} = \frac{H_1}{H_2}. \qquad (2)$$

Extending the results obtained with eqs. (1) and (2), we may say that generally,

$$J_{t \cdot H} = H \cdot J_t, \qquad (3)$$

so long as H is not very much larger than 1 Gauss; or more generally

$$J_{t \cdot H} = F(H) \cdot J_t. \qquad (3')$$

In the above expressions, J_t is a function of temperature only, and does not include H. Thus, the effect of the external magnetic field on the rise of thermo-remanence is, apparently at any rate, separated from the temperature effect, and the intensity of the saturated thermo-remanence produced in a magnetic field of unit intensity will be taken as a parameter in order to show the character of the thermo-remanence of the materials, because J_{t_c} which is independent fo H, is a constant peculiar to the rock specimen. Should relation (3) be established, the coefficient of the thermo-remanence Q_t may also be taken as a characteristic quantity of the material, because

$$Q_t = \frac{J_{t_c \cdot H}}{\chi \cdot H} = \frac{J_{t_c}'}{\chi}. \qquad (4)$$

It will be presumed, however, that $F(H)$ is not always equal to H for every value of H, for the reason that the maximum intensity of the remanent magnetization is expected to be limited to a value that is smaller than its saturated magnetization (in the magnetization curve), owing to the fact that the magnetic properties of the rocks is due to the ferromagnetic minerals in them, particularly as these rocks show the characters of ferromagnetism, for example, the hysteresis phenomenon in the magnetization curve. A more definite expression for $F(H)$ must be sought by further studies. Here, we shall accept eqs. (1), (2), and (3) that were established within the limits of a weak magnetic field:

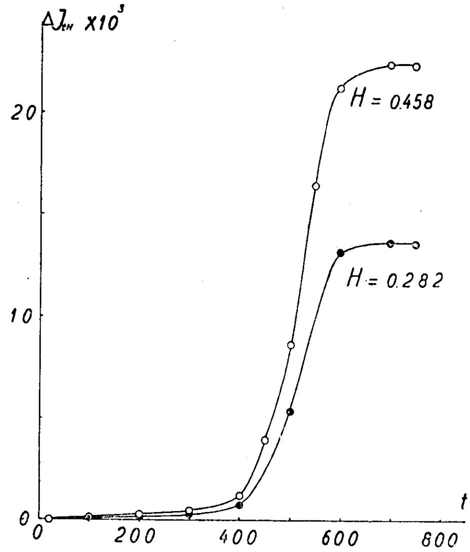

Fig. 3 (a). Intensity of thermo-remanent magnetism in different magnetic fields.

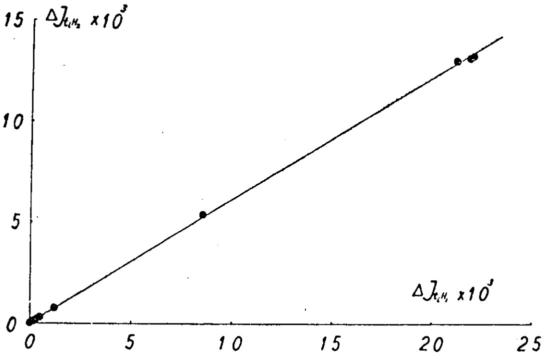

Fig. 3 (b). The relation between $\Delta J_{t_i \cdot H_1}$ and $\Delta J_{t_i \cdot H_2}$. The straight line gives $\Delta J_{t_i \cdot H_2}/\Delta J_{t_i \cdot H_1} = H_1/H_2 = 1{\cdot}62$.

Table III.

t_i	$\Delta J_{t_i \cdot H_1}$ $(H_1 = 0{\cdot}458)$	$\Delta J_{t_i \cdot H_2}$ $(H_2 = 0{\cdot}282)$	$\Delta J_{t_i \cdot H_1}/\Delta J_{t_i \cdot H_2}$
20	$0{\cdot}00 \times 10^{-3}$	$0{\cdot}00 \times 10^{-3}$	—
100	0·15	0·10	1·5

(to be continued.)

Table III. (*continued.*)

t_i	$\Delta J_{t_i\cdot H_1}$ $(H_1=0{\cdot}458)$	$\Delta J_{t_i\cdot H_2}$ $(H_2=0{\cdot}282)$	$\Delta J_{t_i\cdot H_1}/\Delta J_{t_i\cdot H_2}$
200°C	$0{\cdot}30\times10^{-3}$	$0{\cdot}18\times10^{-3}$	1·7
300	0·45	0·28	1·6
400	1·22	0·75	1·65
450	3·97	—	—
500	8·58	5·40	1·59
550	16·45	—	—
600	21·20	13·15	1·61
700	22·10	13·45	1·64
750	21·95	13·35	1·64

3. Partial Magnetization during Cooling.

The relation between J_t and t were obtained in the preceding paragraph. This characteristic of J_t seems to be common to every one of the twenty specimens of igneous rocks that the writer studied. There remains, however, the fundamental question in what manner does thermo-remanent magnetism arise in the process of cooling from a high temperature. Although the dynamical mechanism of the causation of J_t may be a difficult problem, some of the phenomenological and kinematical features could be seen in the results of the following experiment.

First, we examined the effect of *partial magnetization during cooling*. That is, in the cooling of the specimen, the magnetic field of H was applied only in the temperature range of from t_{i+1} to t_i, while in other temperature ranges, higher than t_{i+1} and lower than t_i, the external magnetic field applied was kept always at zero. The specimen which was then cooled to 0°C also showed residual permanent magnetism. We shall call this permanent magnetism the partial magnetism during cooling, and refer to it as $\Delta J_{t_i\cdot H}$, while $\Delta t=t_{i+1}-t_i$. The experiment for bringing about partial magnetism during cooling was made with the same apparatus as that for producing thermo-remanence, and its intensity was measured also by the ballistic instrument. Tests were made before each experiment in order to see that the intensity of the permanent magnetic component of the specimen was zero in its initial state.

Thus, the $\Delta J_{t_i\cdot H}$ for various successive values of t_i was measured, the temperature range $\Delta t=t_{i+1}-t_i$ being kept constant during every experiment. The values, for example, of $\Delta J_{t_i\cdot H}$ for $\Delta t=50$°C are shown in Fig. 4 and Table IV. As will be seen from Fig. 4, $\Delta J_{t_i\cdot H}$ is very small, nearly zero, in the temperature range lower than 100°C, and also zero in the range higher than the critical temperature t'_c, while it has maximum value at temperature t'_0 below t'_c. Comparing the relation between $\Delta J_{t\cdot H}$ and t with that between $J_{t\cdot H}$ and t of the same specimen, we get

$$t'_c = t_c, \quad t'_o = t_o, \tag{5}$$

provided we neglect small quantities of the order of observational errors.

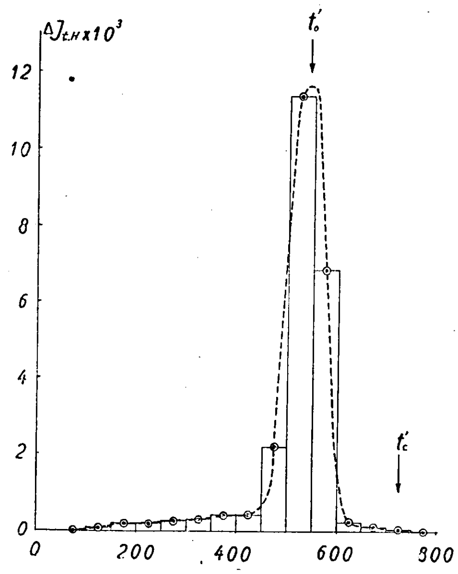

Fig. 4 (a). Partial magnetism during cooling at various temperatures. (Δt $=50$°C, $H=0{\cdot}458$ Gauss). Specimen No. 5.

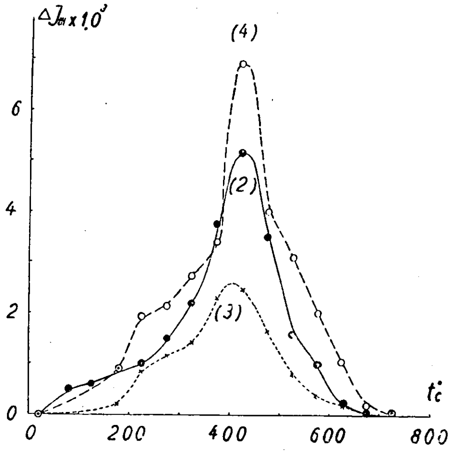

Fig. 4 (b). Partial magnetism during cooling at various temperatures. (H $=0{\cdot}458$ Gauss).

Table IV. Specific Intensity of Partial Magnetism during Cooling.

Δt	$\Delta J_{t\cdot H}$ ($H=0{\cdot}458$ Gauss)			
	No. 2	No. 3	No. 4	No. 5
150 → 100°C	$0{\cdot}63\times10^{-3}$	—	—	$0{\cdot}07\times10^{-3}$
200 → 150	0·90	$0{\cdot}22\times10^{-3}$	$0{\cdot}88\times10^{-3}$	0·21
250 → 200	0·99	0·86	1·94	0·21
300 → 250	1·51	1·15	2·15	0·26
350 → 300	2·22	1·42	2·76	0·32
400 → 350	3·78	2·32	3·38	0·43
450 → 400	5·14	2·47	6·90	0·44

(to be continued.)

Table IV. (*continued.*)

Δt	$\Delta J_{t\,H}$ ($H=0{\cdot}458$ Gauss)			
	No. 2	No. 3	No. 4	No. 5
500 → 450°C	$3{\cdot}52\times10^{-3}$	$1{\cdot}64\times10^{-3}$	$3{\cdot}97\times10^{-3}$	$2{\cdot}20\times10^{-3}$
550 → 500	1·58	0·79	3·12	11·40
600 → 600	0·99	0·40	2·02	6·86
650 → 600	0·24	0·20	1·03	0·25
700 → 650	0·09	0·03	0·21	0·14
750 → 700	0·01		0·04	0·08

As shown in Table V and in Fig. 5, the sum of the $\Delta J_{t\,H}$ of the whole range of 0 to t, that is, the sum of $\Delta J_{t_i H}$ from $t_i=0$ to $t_i=t-\Delta t$, is always nearly equal to the amount of $J_{t\,H}$, the thermo-remanence caused by cooling from t to 0 in the same magnetic field H. This rela-

Table V (a). Specimen, No. 4.

Δt	$\Delta J_{t\,H}$	$\frac{\partial}{\partial t}J_{t\,H}\times\Delta t$	$\sum\Delta J_{t\,H}$	$J_{t\,H}$	t
				0·00	20°C
200 → 150°C	$0{\cdot}88\times10^{-3}$	$1{\cdot}20\times10^{-3}$	$0{\cdot}88\times10^{-3}$	$2{\cdot}85\times10^{-3}$	200
250 → 200	1·94	1·60	2·82		250
300 → 250	2·15	2·05	4·97	6·50	300
350 → 300	2·76	3·27	7·73	9·77	350
400 → 350	3·38	5·20	11·11	15·35	400
450 → 400	6·90	5·98	18·01	20·95	450
500 → 450	3·97	3·40	21·98		500
550 → 500	3·12	2·10	25·10	26·45	550
600 → 550	2·02	0·60	27·12		600
650 → 600	1·03	0·20	28·15	27·25	650
700 → 650	0·21	0·10	28·36		700
750 → 700	0·04	0·00	28·40	27·35	750

Table V (b). Specimen, No. 5.

Δt	$\Delta J_{t\,H}$	$\frac{\partial}{\partial t}J_{t\,H}\times\Delta t$	$\sum\Delta J_{t\,H}$	$J_{t\,H}$	t
		$0{\cdot}10\times10^{-3}$		$0{\cdot}00\times10^{-3}$	20°C
150 → 100°C	$0{\cdot}07\times10^{-3}$	0·10	$0{\cdot}07\times10^{-3}$		150
200 → 150	0·21	0·10	0·28	0·30	200
250 → 200	0·21	0·10	0·49		250
300 → 250	0·26	0·20	0·75	0·45	300

(*to be continued.*)

Table V (b). (*continued.*)

Δt	$\Delta J_{t\,H}$	$\frac{\partial}{\partial t}J_{t\cdot H}\times\Delta t$	$\sum\Delta J_{t\,H}$	$J_{t\,H}$	t
350 → 300°C	$0{\cdot}32\times10^{-3}$	$0{\cdot}32\times10^{-3}$	$1{\cdot}07\times10^{-3}$		350
400 → 350	0·43	0·45	1·56	$1{\cdot}22\times10^{-3}$	400×10^{-3}
450 → 400	0·44	2·75	1·96	3·97	450
500 → 450	2·20	4·61	4·16	8·58	500
550 → 500	11·40	7·87	15·56	16·45	550
600 → 550	6·86	4·75	22·42	21·20	600
650 → 600	0·25	0·20	22·67		650
700 → 650	0·14	0·10	22·81	22·10	700
750 → 700	0·08	−0·15	22·89	21·95	750

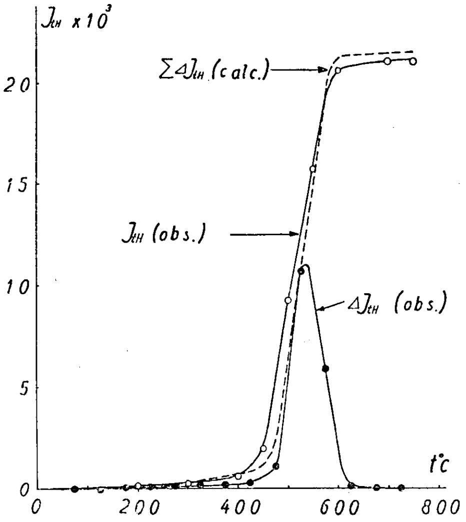

Fig. 5 (a). Comparison of $\sum\Delta J_{t\,H}$ with $J_{t\cdot H}$. ($H=0{\cdot}458$ Gauss). Specimen, No. 5.

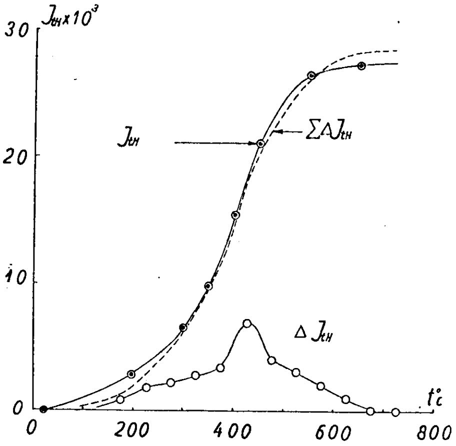

Fig. 5 (b). Comparison of $\sum\Delta J_{t\,H}$ with $J_{t\,H}$. ($H=0{\cdot}458$ Gauss). Specimen, No. 4.

tion holds for any value of t, although there is a discrepancy of a few per cent between the intensity of $J_{t\cdot H}$ and the sum of $\Delta J_{t\,H}$, while the general tendency of the $J_{t\cdot H}\sim t$ relation and that of $\sum\Delta J_{t\cdot H}\sim t$ seems always to be parallel. Neglecting the small discrepancy, seeing that it may probably be the result of experimental errors, we can establish the following relation, at any rate, as a first approximation,

$$\sum_{t_i=0}^{t_i=t-\Delta t}\Delta J_{t_i\,H}=J_{t\,H}. \tag{6}$$

Conversely, we compare $\Delta J_{t\cdot H}$ with the gradient of the $J_{t\cdot H}$ curve for the same range. The difference of $J_{t_{i+1},H} \sim J_{t_i H}$, where $t_{i+1} > t_i$ and the value of $\Delta J_{t_i H}$ of the same specimen for the temperature range $\Delta t = t_{i+1} - t_i$, are given in Fig. 6, Δt being actually taken as 50°C. Although there is also a small discrepancy in these two quantities for the same temperature range, the general tendency is identical. Hence we can write, approximately,

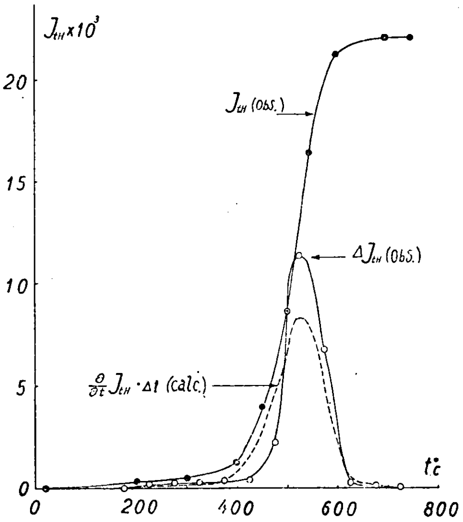

Fig. 6 (a). Comparison $\frac{\partial}{\partial t} J_{tH} \times \Delta t$ with ΔJ_{tH}. ($H = 0{\cdot}458$ Gauss).
Specimen, No. 5.

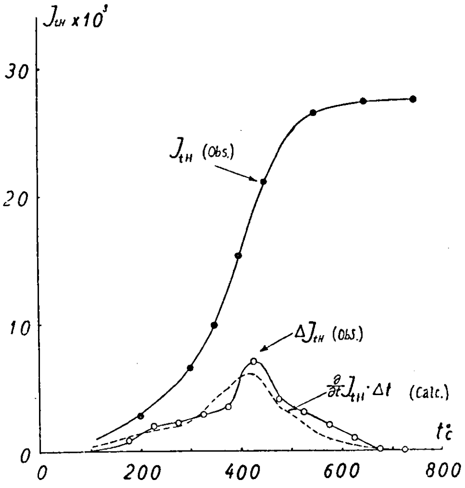

Fig. 6 (b). Comparison $\frac{\partial}{\partial t} J_{tH} \times \Delta t$ with ΔJ_{tH}. ($H = 0{\cdot}458$ Gauss).
Specimen, No. 4.

$$J_{t_{i+1} \cdot H} - J_{t_i \cdot H} = \frac{\partial}{\partial t} J_{t_i \cdot H} \cdot \Delta t = \Delta J_{t_i H}. \tag{7}$$

The fact indicated by eqs. (6) and (7) shows that the net intensity of the partial magnetism during cooling, which arises during the cooling from t_{i+1} to t_i, remains unchanged in the process of continued cooling to zero or to ordinary room temperature in non-magnetic space. Thus the partial magnetism during cooling brought about in different ranges of Δt remains unchanged and accumulates, becoming a permanent feature. The important fact shown by these equations is that the thermo-remanent magnetism of t is the total sum of the partial magnetism during coooling in the small ranges given by dividing the whole range from 0 to t, and that the difference in the J_{tH}'s varying values of t is equal to the partial magnetism during cooling in the range of its temperature difference. In other words, this is the law of composition and decomposition of thermo-remanent magnetism.

In the foregoing results the magnitude of the partial temperature range was always taken as 50°C. In the next step, the magnitude of the partial magnetism during cooling corresponds to a 25°C range. The observed results are given in Table VI and Fig. 7.

Table VI.

Δt	$\Delta' J_{t\cdot H}$	$\Delta'_1 J_{t\cdot H} + \Delta'_2 J_{t\cdot H}$	$\Sigma\Delta' J_{t\,H}$	$\Delta J_{t\cdot H}$ ($\Delta t=50$°C)	$J_{t\,H}$	t
					$0{\cdot}00\times10^{-3}$	20°C
75 → 50°C	$0{\cdot}23\times10^{-3}$	$0{\cdot}51\times10^{-3}$	$0{\cdot}23\times10^{-3}$			
100 → 75	0·28		0·51			
125 → 100	0·41	0·99	0·92			
150 → 125	0·48		1·40			
175 → 150	0·48	1·02	1·88	$0{\cdot}88\times10^{-3}$		
200 → 175	0·54		2·32		2·85	200
225 → 200	0·91	1·83	4·23	1·94		
250 → 225	0·92		5·15			
275 → 250	0·97	1·98	6·12	2·15		
300 → 275	1·01		7·13		6·50	300
325 → 300	1·17	2·28	8·30	2·76		
350 → 325	1·11		9·41		9·77	350
375 → 350	1·29	3·00	10·70	3·38		
400 → 375	1·71		12·41		15·35	400
425 → 400	3·25	7·26	15·56	6·90		
450 → 425	4·01		19·57		20·95	450
475 → 450	1·54	3·02	21·11	3·97		
500 → 475	1·48		22·59			
525 → 500	1·05	2·12	23·64	3·12		
550 → 525	1·07		24·71		26·45	550
575 → 550	1·05	1·62	25·76	2·02		
600 → 575	0·57		26·33			
625 → 600	0·57	1·04	26·90	1·03		
650 → 625	0·47		27·37		27·25	650
675 → 650	0·25	0·31	27·52	0·21		
700 → 675	0·06		27·58			
725 → 700	0·00	0·00	27·58	0·04		
750 → 725	0·00		27·58			

In this experiment, the 50°C temperature range for the preceding experiment was divided into two equal ranges of $\Delta'_1 t = \Delta'_2 t = 25$°C. The partial magnetism during cooling corresponding to $\Delta'_1 t$ and $\Delta'_2 t$ is denoted by $\Delta'_1 J_{t_i\cdot H}$ and $\Delta'_2 J_{t_i\cdot H}$ respectively, while that corresponding to Δt is $\Delta J_{t_i\cdot H}$, as already noted. Comparing, then, the results given in Fig. 6 with those in Fig. 4, we get approximately for any value of t_i,

$$\Delta'_1 J_{t_i \cdot H} + \Delta'_2 J_{t_i \cdot H} = \Delta J_{t_i \cdot H}. \qquad (8)$$

The feasibility of this relation is graphically shown in Fig. 7. In the present case, the law of composition of thermo-remanence,

$$\sum_{0}^{t-\Delta t} \Delta' J_{t_i \cdot H} = J_{t \cdot H} \qquad (8')$$

also holds approximately, as shown in Fig. 8. Since it seems difficult under present experimental limitations to calculate the differential coefficient of the $J_{t\,H}$ curve with respect to temperature for an elemental range narrower than 50°C, comparison of $\Delta' J_{t \cdot H}$ for a 25°C range with the gradient of $J_{t \cdot H}$ is omitted.

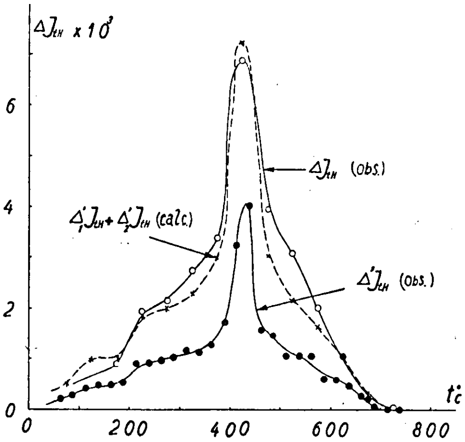

Fig. 7. Comparison of $\Delta'_1 J_{t\,H} + \Delta'_{2 t \cdot H}$ with $\Delta J_{t\,H}$. ($H = 0{\cdot}458$ Guss).
Specimen, No. 4.

Thus the laws of composition and decomposition of the thermo-remanence were established as a first approximation in our quest. As it was difficult, however, to measure quantitatively the partial magnetism during cooling for the narrower elemental temperature range by means of the present apparatus, the order of intensity of the partial magnetism during cooling $\delta J_{t \cdot H}$, corresponding to a cooling down of about 2°C at various temperatures in the same magnetic field, was measured, the results being shown in Fig. 9. Comparing these results with those of $\Delta J_{t\,H}$ and of $\Delta' J_{t \cdot H}$, we can get the relation for any temperature,

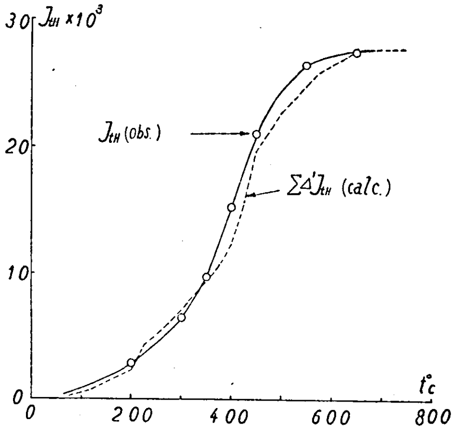

Fig. 8. Comparison of $\sum \Delta' J_{t \cdot H}$ with $J_{t \cdot H}$. ($H = 0{\cdot}458$ Gauss).
Specimen, No. 4.

$$\frac{\partial}{\partial t} J_{t\,H} \sim \frac{\Delta J_{t \cdot H}}{\Delta t} \sim \frac{\Delta' J_{t \cdot H}}{\Delta' t} \sim \frac{\delta J_{t \cdot H}}{\delta t}, \qquad (9)$$

where Δt, $\Delta' t$, and δt denote respectively 50°, 25°, and 2°C temperature range for cooling. Thus, we may conclude that the ratio of the intensity of partial magnetism during cooling to the corresponding temperature range at any temperature may have a finite value in the limiting case, namely, $\Delta t \rightarrow 0$, and that the ratio agrees with the differential coefficient of $J_{t_i \cdot H}$ with respect to temperature at t_i, that is, that $\lim\limits_{\Delta t \to 0} \frac{\Delta J_{t_i \cdot H}}{\Delta t}$ exists, and that it is a function of temperature. Expressing this conclusion by formula, we get

$$\lim_{\Delta t \to 0} \frac{\Delta J_{t_i \cdot H}}{\Delta t} = \frac{\partial}{\partial t} J_{t_i \cdot H} = P(t_i, H) \quad (10)$$

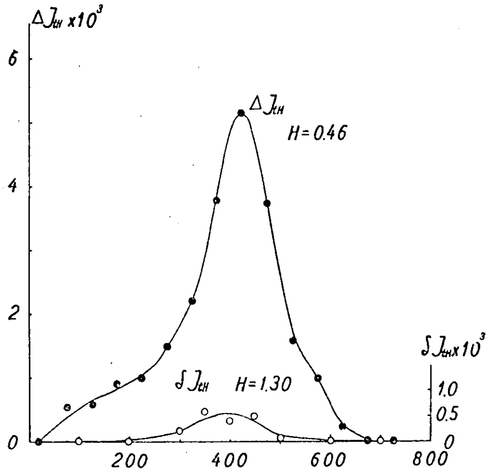

Fig. 9. Comparison of $\delta J_{t,H}$ with $\Delta J_{t \cdot H}$, where $\delta t=2$°C and $\Delta t=50$°C.
Specimen, No. 2.

In the preceding paragraph, we found that the effects of temperature cooling and of applying an external magnetic field in order to cause thermo-remanent magnetism can be expressed by their functions separated into the function of t and that of H. Since, on the other hand, thermo-remanence is given by the sum of the partial magnetism during cooling in each temperature range, obtained by dividing the whole range, through which it must cool in order to bring about thermo-remanence, the effect of the magnetic field on partial magnetism during cooling may be regarded as being quite similar to that on thermo-remanence. Consequently we get

$$\Delta J_{t\,H} = H \cdot \Delta J_t \,, \quad (11)$$

$$\sum_i \Delta J_{t_i} = J_t \,, \quad (12)$$

$$\lim_{\Delta t \to 0} \frac{\Delta J_{t\,H}}{\Delta t} = H \cdot \frac{\partial}{\partial t} J_t = H \cdot P(t). \quad (13)$$

Summarizing the facts obtained from the foregoing experiments we can establish the relation

$$\vec{J}_{t \cdot H} = \vec{H} \cdot J_t = \vec{H} \cdot \int_t^0 P(t)\,dt \,, \quad (14)$$

where the arrow means a vector quantity. And, more generally, if the residual permanent magnetism at 0°C (in the process of causation of which, magnetic field H is applied during the cooling range from t to t' alone) is denoted by $J^{(t')}_{tH}$, we get

$$\vec{J}^{(t')}_{tH}=\vec{H}\cdot\int_{t}^{t'} P(t)\,dt. \qquad (t'<t) \tag{15}$$

The general character of the function $P(t)$ in eqs. (14) and (15), is given by the curve shown in Fig. 4 (a) and (b), which has two particular points on the temperature coordinate, i.e. t_o and t_c, where

$$\left.\begin{aligned} &P(t_o)=\text{Maximum}, \\ &P(t\geqq t_c)=0 \end{aligned}\right\}.$$

On the other hand, we must examine the dependency of the magnetism during cooling on the time required for cooling. For this purpose, the intensity of ΔJ_{tH}, corresponding to the range of cooling from 400°C to 350°C in 0·458 Gauss, was measured, the cooling velocity during the range being varied. In actual treatment, the time for cooling during a 50°C range was varied from about one minute to 80 minutes. The result of the experiment is shown in Fig. 10. As will be seen from the figure, the magnitude of ΔJ_{tH} for the various periods of cooling seems to be nearly constant, the fluctuations forming only a small percentage, with a tendency for ΔJ_{tH} to become smaller, the shorter the time of cooling. It must, however, not be overlooked that the experimental error may not be small, should the time required for cooling be shorter than ten minutes, because in that case the uniformity of temperature in the specimen would be disturbed It may therefore be concluded that, as a first approximation in our quest, the causation of magnetism during cooling, and therefore of thermo-remanent magnetism, is independent of the velocity of cooling, whence we get

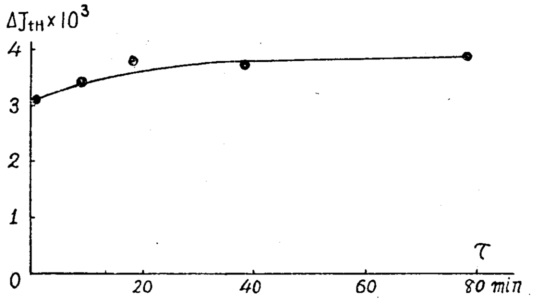

Fig. 10. Relation between ΔJ_{tH} and the cooling time (τ) through Δt.
Specimen, No. 4.

$$\frac{\partial}{\partial \tau}\Delta J_{t,H}=0. \tag{17}$$

$P(t)$ is then not a function of time τ, that is,

$$\frac{\partial}{\partial \tau}P(t)=0. \tag{18}$$

Consequently, equation (14) and (15) must be established independently of the time of cooling.

4. Magnetization during Cooling.

As the next step, the intensity of magnetization at any temperature during the heating and cooling processes in an applied external magnetic field was measured, the object being to see directly the way in which thermo-remanence, which was already determined indirectly in the preceding experiments, is caused. For this study, an astatic magnetometric method was used, the apparatus being shown in Fig. 11, in which the distance between the two magnets is 28·8 cm. Coaxially with the horizontal line perpendicular to the geomagnetic meridian through the centre of the lower magnet, two circular cylindrical solenoids are set, one of which is fixed, while the other is movable with the aid of an adjusting screw. The fixed solenoid contains an electric furnace made of non-inductively wound pure nichrome wire. Between the solenoid and the furnace, a circular double tube of hard glass is set coaxially with them, water being made to flow through the double glass tube in order to absorb the heat that would flow from the furnace to the solenoid and the magnet system.

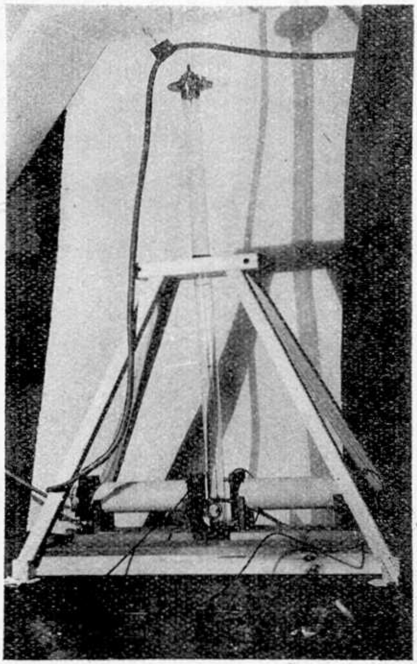
Fig. 11. Astatic magnetometer for measuring magnetism during cooling.

The specimen to be measured is set coaxially in the furnace with the axis-line of the solenoid. The movable coil is for compensating the magnetic field at the point of the lower magnet due to the fixed solenoid. Provided the whole magnetometric apparatus is well adjusted, the magnetic susceptibility of the pure nichrome wire being sufficiently small, and the heat absorption of the water cooling device adequate, the suspended magnet system scarcely deflects during the temperature change from 0°C to 800°C in the furnace, when no rock specimen there is in the furnace, that is, when it is empty. Consequently it was possible to measure the intensity of magnetization of rock specimens in the furnace with a certain degree of accuracy, provided the specific intensity exceeded 2×10^{-4} c.g.s.e.m.u.

An example of the results obtained in this experiment is given in Fig. 12 (a), (b), (c), where the values shown in (a) give the intensity of magnetization J_h of a fresh unused specimen in its initial heating process, while those in (b) give that in the cooling process, J_c, both being in the magnetic field of H; whereas (c) gives the intensity of magnetization during the process of heating in non-magnetic space, the specimen used having already, in its initial state at 0°C, the thermo-remanent magnetism caused in the process shown in (b). As is clear from (a) and (b), Fig. 12, the intensity of magnetization undergoes a marked irreversibility owing to change of temperature, that is, at temperatures below a certain value, J_c is much larger than J_h at the same temperature in the initial heating process. We shall now compare the result shown in Fig. 12 (b) with the curve showing the relation between

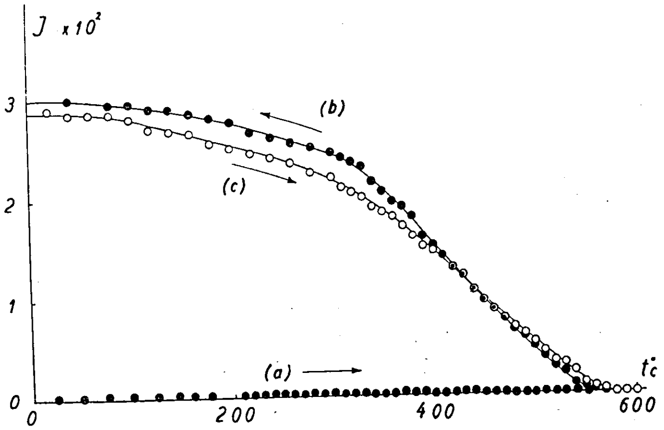

Fig. 12. Intensity of magnetization in heating and cooling processes.
(a) J_h in initial heating process. (b) J_c in cooling process.
(c) Second heating process. $H=1{\cdot}30$ Gauss.
Specimen, No. 2.

$J_{t\cdot H}$ and t of the same sample, where the magnitude of $J_{t\cdot H}$ has been corrected to $H = 1{\cdot}30$ Gauss with the aid of eq. (1). Since J_c at 0°C is nearly equal to $J_{t_c\cdot H}$, as shown in Fig. 13, it may be concluded that J_c, at any temperature, gives the approximate value of the permanent magnetism that was produced during the cooling from t_c to t. The permanent magnetism at t in the cooling process from a temperature higher than t_c, that is, the magnetism caused upon cooling from t_c to t, we shall call $J_c(t,H)$. Precisely speaking, however, magnetization J_c, given in Fig. 12 is the sum of the magnetism that was caused during the cooling and the induced magnetism $H\cdot\chi(t)$, where $\chi(t)$ is the specific susceptibility at t, that is,

$$J_c = J_c(t,H) + H\cdot\chi(t). \tag{19}$$

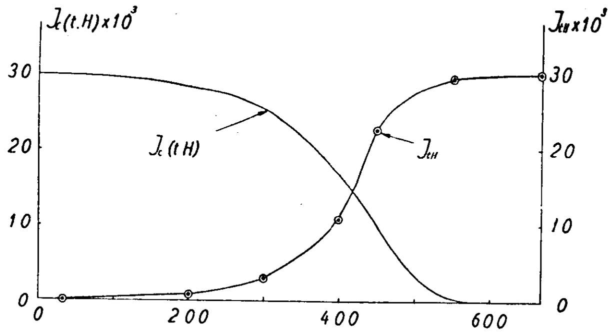

Fig. 13. Relation between $J_c\,(t,H)$ and $J_{t\cdot H}$. ($H = 1{\cdot}30$ Gauss). Specimen, No. 2.

In the case of the present example, $H\cdot\chi(t)$ seems to be negligible compared with $J_c(t,H)$ (disregarding errors of few per cent), because, J_h, which is believed to be $H\cdot\chi(t)$ in the heating process, is very small compared with J_c (see also result given in Fig. 15), so that in the present case we can put

$$J_c \doteqdot J_c(t,H). \tag{20}$$

Assuming that eq. (20) holds in the example shown in Fig. 12, we get approximately

$$J_c(0,H) = J_{t_c\cdot H}, \quad J_c(t_c\cdot H) = 0, \tag{21}$$

and

$$J_{t\cdot H} = J_c(0,H) - J_c(t,H) \tag{22}$$

If, for example, eq. (22) holds, it must result, in the equation

$$J_{t_{\frac{1}{2}}\cdot H} = \frac{1}{2}J_c(0,H) = \frac{1}{2}J_{t_c\cdot H},$$

where $$J_{t_i\cdot H}=J_c(t_i,H).$$

It will also be seen from Fig. 13 that this relation is satisfied. Fig. 14 shows that it is possible to establish the relations

$$-\frac{\partial}{\partial t}J(t_i,H)\,\Delta t\fallingdotseq\Delta J_{t_i\cdot H},\tag{23}$$

$$\sum_{t_c-\Delta t}^{t}\Delta J_{t_i\cdot H}=J(t,H).\tag{24}$$

It may be an axiomatic conclusion, however, that relations (23) and (24) are established, provided eqs. (6), (7), and (22) have been obtained.

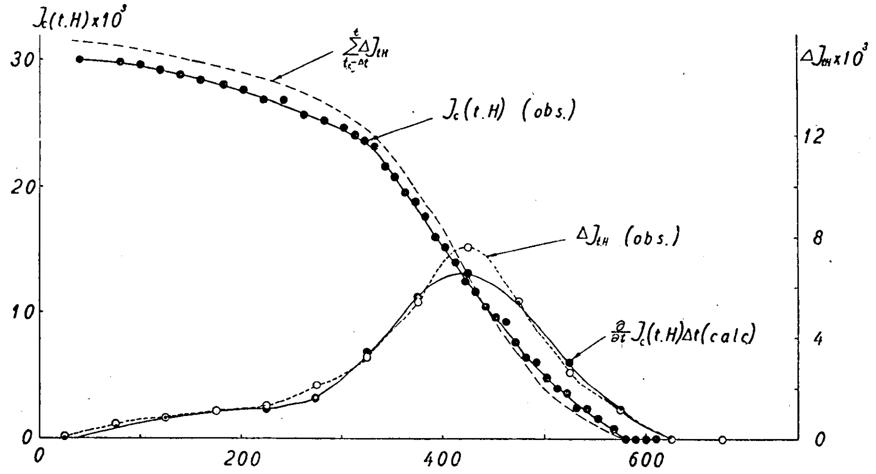

Fig. 14. Comparison of $J_c(t,H)$ with $\sum\Delta J_{t\cdot H}$, and that $\frac{\partial}{\partial t}J_c(t,\mathrm{H})\times\Delta t$ with $\Delta J_{t_i\cdot H}$.

Thus, comparing eqs. (21), (22) with eqs. (14), (15), we finally get

$$\vec{J}_c(t,H)=\vec{H}\int_{t_c}^{0}P(t)\,dt-\vec{H}\cdot\int_{t}^{0}P(t)\,dt=\vec{H}\cdot\int_{t_c}^{t}P(t)\,dt\equiv\vec{J}^{(t)}_{t_c\cdot H},\tag{25}$$

and

$$\vec{J}_c(t,H)=\vec{H}\cdot J_c(t).\tag{26}$$

The relation (25) may be additional proof that the almost net intensity of the magnetism produced during the cooling from t_c to t in H remains as permanent magnetism, undisturbed by the continued cooling from t to 0°C in non-magnetic space—a fact already referred to in paragraph (§ 3).

Next, we take into consideration that the curve (c) in Fig. 12, showing the disappearance of the thermo-remanent magnetization during the heating process in non-magnetic space, nearly agrees with that of $J_c(t,H)$, although the sense of temperature change in the two cases are the reverse of each other. In other words, the magnetism during cooling caused in any range of cooling in the magnetic field of H, vanishes when the sample is heated through that range in non-magnetic space. This fact was independently ascertained at the time it was found that the magnetism produced during the cooling from t to t' always vanished when the specimen was heated to t, and cooled again in non-magnetic space.

This result may suggest that the physical state which is capable of being permanently magnetized as $P(t_i)\Delta t$ in a magnetic field of unit intensity, corresponds to the elemental cooling range Δt at t_i, the external magnetic field affecting the initial physical state in such a way as to cause magnetization of $\vec{H}\cdot P(t_i)\Delta t$, whereas the said physical state vanishes when it corresponds to a heating of Δt at t_i, independently of $\vec{H}$, resulting in the disappearence of magnetization $\vec{H}\cdot P(t_i)\Delta t$, regardless of the magnitude of H. Putting the foregoing fact in a formula, we get

$$\frac{\partial}{\partial t}J_o=\frac{\partial}{\partial t}J_c(t,H)=-\frac{\partial}{\partial t}J_{t\cdot H}=-H\cdot P(t), \qquad (27)$$

where J_o denotes the permanent magnetism due to the thermo-remanence in H. As an example of the application of eq. (27) in practical treatment, the specimen with its thermo-remanence saturated was heated in non-magnetic space to t, and then cooled in a magnetic field of $-H$ to 0°C. The intensity of the residual magnetism after this treatment ought to be

$$J_{t_c\cdot H}+\int_0^t\frac{\partial}{\partial t}J_o dt-H\int_t^o P(t)dt=J_{t_c\cdot H}-2J_{t\cdot H}. \qquad (28)$$

From the experiments in which the foregoing treatments for various values of t, from 0 to t_c, were carried out, it was proved, as shown in Fig. 15, that relation (28) nearly holds. When eq. (28) is applied in measuring thermo-remanence, we may get a double value for $J_{t\cdot H}$ for any value of t.

Finally, in the series of experiments with the aid of the magnetometer, measurement of δJ_c, corresponding to a small cooling range δt at various temperatures t, was tried. Since quantitative measurement of the value was difficult with the present apparatus, all that can be said here is that the intensity of ∂J_c, corresponding to ∂t cooling, was negligible compared with the magnitude of $J_c(t,H)$. In this examination, the external magnetic field of $H=1{\cdot}30$ Gauss was applied only during the time it was being cooled at 2°C from t_i throughout the entire cooling range from t_c to 0°C; actually the time it was kept at about 1·5 minutes in every experiment. The magnitude of ∂J_c for various values of t_i is given in Fig. 16, where the $J_c(t,H)$ curve is also shown for comparison. As already discussed, we must interpret the magnitude of ∂J_c as being

$$\partial J_c = H\cdot\chi(t_i) + H\cdot P(t_i)\cdot\partial t.$$

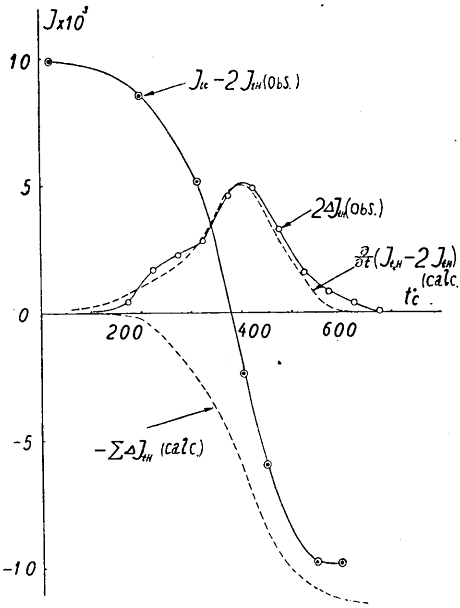

Fig. 15. Comparison of $\Delta J_{t\cdot H}$ with $\frac{\partial}{\partial t}\left(J_{t_c\cdot H}+\int_0^t \frac{\partial}{\partial t}J_{o\cdot}\ dt - H\cdot\int_t^o P(t)\,dt\right)$

Whence, we get from Fig. 15 the result that in the present example, the intensity of the induced magnetism $H\cdot\chi(t)$ in the cooling process is also negligible compared with J_c. This conclusion being already assumed in the interpretation of the result given in Fig. 11, it is possible to confirm the conclusion that partial magnetism during cooling is smaller, the smaller the cooling range (see eq. (7)).

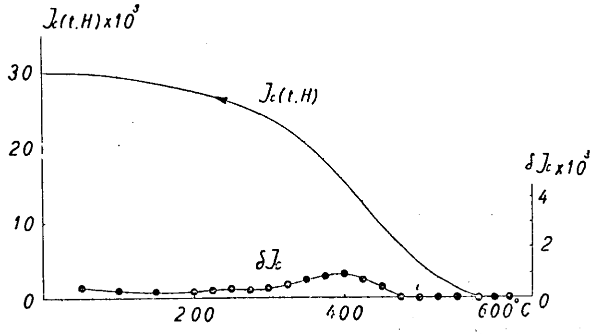

Fig. 16. Comparison of ∂J_c with $J_c(t\cdot H)$.

It must be noted here that the relation $H\cdot\chi(t)\ll J_c(t,H)$ holds only for basic rocks, which have a large Q_t value, whereas in the case of intermediate and acidic rocks, the Q_t of which is generally small, amounting to 0·5∼5·0, approximation of $J_c\simeq J_c(t,H)$ is not permissible. However, since eq. (20) is used only as an approximation to get the relation of $J_c(t,H)$ to $J_{t\cdot H}$, and to $\Delta J_{t\cdot H}$, and since the result thus obtained must be independent of this approximation, the final conclusion from eqs. (21) to (27) would also hold in the case of magnetism during cooling of intermediate and acidic rocks.

5. Examples of Actual Characteristic Values of Magnetism during Cooling, and their Application to Geophysics.

We have found in the present studies general apparent characteristics of the mode of causation of thermo-remanent magnetism, a number of the values of the characteristics being defined. They are the intensity of saturated thermo-remanent magnetism in unit magnetic field J_{t_c}, the coefficient of thermo-remanence Q_t, and two particular temperatures t_o and t_c in the characteristic function $P(t)$. As examples, the actual values of these characteristics of several basic rocks are given in Table VII. These rocks are either basalt or basaltic andesite, the chemical and normative compositions of some of them being shown in Table VIII.

As frequently mentioned, the magnitude of J_{t_c} of these basic rocks is generally very large compared with their magnetic susceptibilities, Q_t being much larger than unity. Their temperature t_o is from 300°C to 520°C, while t_c is from 580°C to 720°C, where the former is nearly equal to the Curie-temperature of pure magnetite, the latter being that of pure hematite. Whether transcendental temperature exactly agrees with the Curie-temperature of the rock is, at present, not clear. It will be presumed, however, that they are closely related to each other. Besides the quantities mentioned above, other parameters, in order to give the characteristic of the thermo-remanence, will be considered, as, for example, the magnitude of $P(t_o)$ and the sharpness of the peak of $P(t)$ around t_o. A clear example of discrepancy in the sharpness of the peak will be seen in the results shown in Fig. 4. All these characteristics of the rocks may be closely related to their petrological constitution, exactly like their susceptibilities and Curie-points. Since, in the present study, the general mode of causation of thermo-remanent magnetism has been found, although only approximately and phenomenologically, the relation of the causation of thermo-remanence to the composition of the rock wil be sought by measuring the charac-

Table VII. Numerial Values of Characteristics in Thermo-remanent Magnetism of Volcanic Rocks.

No.	Locality	Rock	J_{t_c}	χ	Q_t	t_o	t_c
1	Mihara Volcano. Somma Lava.	Hypersthene-bearing olivine-basalt.	$1{\cdot}23\times10^{-2}$	$2{\cdot}50\times10^{-3}$	5	470°C±20°C	710°C±20°C
2	Mihara Volcano. Bomb. ejec. Aug. 1940.	Basalt.	2·53	0·37	68	420 ±10	690 ±20
3	〃	Basalt.	2·16	0·85	25	405 ±10	690 ±20
4	〃	Basalt.	5·95	0·69	86	430 ±10	720 ±20
5	Miyakesima Volcano. Lava. Flow. ejec. July. 1940.	Olivine-hypersthene-augite-basaltic andesite.	4·81	1·12	43	520 ± 5	710 ±20
6	Miyakesima. Bomb. ejec. July. 1940.	Augite-olivine-basalt.	1·46	0·74	20	380 ±10	580 ±20
7	Mihara. Bomb. ejec. Aug. 1940.	Basalt.	1·81	0·34	53	400 ±10	690 ±20
8	〃	Basalt.	2·43	1·03	24	430 ±10	630 ±20
9	Mihara. An'ei Lava Flow(1778).	Hypersthene-bearing basalt.	4·19	0·56	75	420 ±10	600 ±20
10	Mihara. Meizi-Taisyo Lava (1911 ~1914).	Basalt.	3·15	0·34	93	480 ±10	700 ±20
11	Mihara. An'ei Lava Flow(1778).	Hypersthene-bearing basalt.	5·12	2·21	23	480 ±10	620 ±20
12	〃 〃	〃	2·92	0·76	38	480 ±10	—
13	Zawo Volcano. Dyke Rock.	Olivine-two-pyroxene-andesite.	0·57	0·49	12	570 ±10	605 ±10
14	Usami Volcano. Lava Flow.	Augite-hypersthene-andesite.	0·68	0·79	9	540 ±10	580 ±10
15	Usami Volcano. Lava Flow.	Hypersthene-bearing olivine-augite-andesite.	0·20	1·07	2	—	—
16	Asama Volcano. Bomb. ejec. 1940.	Andesite.	1·09	0·50	22	—	—

Table VIII. Chemical Compositions of the Specimens.

	No. 1[12]	No. 2[15]	No. 3[14]	No. 9[12]	No. 14[13]
SiO_2	51·23	50·78	53·01	52·45	51·67
Al_2O_3	15·24	17·05	14·83	13·43	19·88
Fe_2O_3	4·18	3·65	5·35	4·60	3·25
FeO	8·99	8·76	9·98	10·02	6·97
MgO	4·85	4·55	3·82	4·78	3·30
CaO	11·14	11·08	9·97	10·23	9·46
Na_2O	2·19	2·20	1·76	1·99	2·18
K_2O	0·54	0·25	0·46	0·52	0·40
H_2O+	n.d.	0·95	0·01	n.d.	1·26
H_2O-		0·01	0·01		1·00
TiO_2	0·83	0·77	0·61	1·39	0·92
P_2O_5	0·03	0·11	0·32	0·33	0·10
MnO	0·33	0·21	tr.	0·31	0·16
BaO	0·03	—	—	0·03	—
S	0·10	—	—	0·18	—
Total	99·68	100·39	100·13	100·32	100·55
Norms. Q	5·35	4·68	12·67	9·61	9·31
Or	3·34	1·67	2·78	3·34	2·23
Ab	18·35	13·35	14·68	16·78	18·35
An	30·04	35·88	31·15	26·15	43·39
Wo	10·57	7·67	6·85	9·41	1·16
En	12·01	11·34	9·54	11·95	8·23
Fs	12·01	12·13	12·79	12·80	8·83
Mt	6·02	5·32	7·87	6·71	4·63
Il	1·52	1·52	1·21	2·58	1·82
Ap	tr.	0·33	0·66	0·65	0·33

teristics of various igneous rocks. This will be the subject of the writer's further studies on thermo-remanent magnetism.

It must be mentioned here that J. G. Königsberger[16] and others have already reported the results of their studies in the relation between the magnitude of Q_t and grain-size and the chemical composition of the ferromagnetic minerals contained in the rocks, namely, FeO, Fe_2O_3, and

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12) I. IWASAKI, *Analyst.* (I. IWASAKI, *Journ. Chem. Soc. Japan.*, **56** (1935), 1511.)

13) S. TANAKA, *Analyst.* (H. TSUYA, *Bull. Earthq. Res. Inst.*, **15** (1937), 215.)

14) S. NAKAZIMA, *Analyst.* (H. TSUYA, *Zisin.*, **12** (1940), 475.)

15) This rock specimen was analyzed by Mr. S. NAKAZIMA in Dr. TSUYA'S laboratory in the E.R.I. at the writer's request. The writer wishes to express his sincere thanks to these two gentlemen.

16) J. G. KÖNIGSBERGER, *loc. cit.*

TiO_2, according to whom, a solid solution of magnetite and Fe_2O_3 in excess seems to give a large value of Q_t, although the microscopic mechanism of this phenomenon is not clear at present. They also assumed that the transcendental temperature in the process of causation of the thermo-remanence is the Curie-point, chiefly because the former almost agrees with the latter of pure magnetite. On the other hand, R. Chevallier[17] measured the temperature-change of magnetization of seven rocks in a rather strong magnetic field (larger than 100 Gauss) by means of the magnetometric method. According to him, the Curie-point in absolute temperature scale of the solid solution of FeO and Fe_2O_3, or more strictly speaking, of FeO and Fe_3O_4, decreases nearly proportionally to the percentage of the amount of FeO in excess, that is, the Curie-point seems to be proportional to the ratio $Fe_2O_3/(FeO+Fe_2O_3)$, so long as the ratio is smaller than 0·69, where FeO and Fe_2O_3 compose Fe_3O_4 without excess of FeO or Fe_2O_3. On this ground he proposed a phenomenological theory of the relation.

In the present study, however, the mode of causation of the thermo-remanent magnetism was more minutely observed, where the permanently magnetized component and the component reversible for applied external magnetic field, namely, the induced magnetism, are separated in the sense of a first approximation. Hence, the two temperatures t_0 and t_c in $P(t)$ as well as its functional form, should be examined in their relation to the composition of the material, while the temperature change of the induced magnetization, reversible at any rate for a weak magnetic field, should be measured independently, for example, by the ballistic method.

Aside from the foregoing problem, the results of our studies thus far may furnish interesting suggestions on the physical conditions in the earth's crust, seeing that the two processes of causation and disappearence of thermo-remanent magnetism occur in the earth's crust, if its temperature either increases or decreases in a geomagnetic field. However, the temperature in the earth's crust at depths exceeding 20 km from the earth's surface is believed to be higher than 600°C, while the largest part of the causation and disapperence of thermo-remanence is accomplished during the change in temperature from 300°C to 600°C. Consequently, the change in magnetization of the earth's crust due to variation in its temperature, if any, can be expected only in its outer part, where the thickness of the crust is less than 20 km, so long as we assume that the critical temperature of the thermo-remanence is not greatly affected by increase of the hydrostatic pressure in the earth's crust.

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[17] R. Chevallier et J. Pierre, *Ann. Phys. Paris*, **18** (1932), 383.

On the other hand, according to J. Bartels,[18] secular variation in geomagnetism seems to be due rather to an inhomogeneous variation in the magnetic condition of the earth's crust, in view of the fact that expansion of the secular variation by means of spherical harmonic analysis failed to give such good convergency as that of the general permanent field, and because the first term $P_1(\cos\theta)$ in the expansion series was not so prominent as in the latter. The isoporic charts by H. W. Fisk[19] and by A. G. McNish[20] lead to the same conclusion. It may therefore be presumed that the change in intensity of thermo-remanent magnetism in the subterranean layer due to rise and fall of the isotherm near t_o would be a contributory cause of the secular variation. Explanation of the secular change by changes in the induced magnetism caused by the rise and fall of the Curie-point isotherm in the earth's crust is regarded as beset with the difficulty that the magnetic susceptibility of the rocks composing the upper part of the crust is too small compared with the amount required for explaining the intense focus of distribution of the secular variation. However, adding the effect of magnetism during cooling to changes in induced magnetism, we may expect the presence of a larger amount of magnetic change in the earth's crust; the total intensity amounting to about ten times that of induced magnetism in the intermediate rocks, while in the case of basic rock, such as basalt, given in Table VII, whose chemical composition is nearly the same as the average composition of plateau basalt given by R. A. Daly,[21] the intensity amounts sometimes to more than one hundred times. In these circumstances, we may expect that the contribution of the temperature change within the earth's crust to secular variation in geomagnetism would be much larger than that estimated so far.[22]

The disturbance in the geomagnetic field as the effect of magnetism during cooling would be particularly marked in volcanic regions, where the temperature and its space gradient in the earth's crust near the surface may be much higher and larger respectively than those in other districts. A severe volcanic activity, especially, would be followed by local anomalous geomagnetic changes, at any rate, in the neighbourhood of the volcano. For example, as mentioned in the introduction to this paper, the severe volcanic eruption of Miyake-island, in July 1940, was

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[18] J. BARTELS, *Veröff. Preuss. Meteor. Inst. Abhandl.* 8 Nr. 2 (1935).

[19] F. W. FISK, *Third Rep. Comm. Solar and Terr. Relationship.* (1931).

[20] A. G. MCNISH, "*Terrestrial Magnetism and Electriary,*" 1939, New York, pp. 329~330.

[21] R. A. DALY, "*Igneous Rocks and the Depth of the Earth,*" (1933) New York.

[22] J. G. KÖNIGSBERGER has also proposed almost the same theory on the origin of the secular variation in geomagnetism, (*Z. S. Geophys.* 8 (1932), 322.)

accompanied with a fairly large geomagnetic change in the island. All the results of geomagnetic observations accomplished by four parties independently, namely, by R. Takahasi and K. Hirano,[23] with a vertical intensity variometer; by T. Minakami,[24] with a dip-circle, by the writer[25] with a dip-magnetograph: and by Y. Katô[26] of the Tôhoku Imperial University, with an earth inductor, gave without exception a large secular variation, more than twenty minutes in dip or a few hundred gamma in vertical intensity. The details of these results will be given in the reports by the respective observers. We shall merely say here that we have not the slightest doubt that a local anomalous variation of considerable magnitude occurred simultaneously with the volcanic activity.

Although so far, we have not obtained so precise a knowledge of the distribution of the anomalous variation as to enable us to determine the mechanism of the origin of the variation uniquely, there will be no doubt that much of the variation was due to the change in the thermo-remanent magnetization of the basaltic rocks of the island.

It is scarcely necessary to stress the fact that the effusive rocks ejected from volcanoes always retain natural remanent magnetism of fairly large magnitude, nor that permanent magnetism is the thermo-remanent magnetism produced during its cooling in the geomagnetic field, as a number of investigators have reported. Consequently, that the geomagnetic field near a large mass of newly ejected rock slowly varied owing to the change in the magnetic intensity of the mass as the result of magnetization caused during cooling, can also be readily considered, the phenomenon having been recognized by a number of investigators.[27]

6. Conclusion and Summary.

The equations of condition for causing magnetism during cooling, established in the present study, may be accepted as a first approximation to the unravelling of the phenomenon. The experiments always seem to be subject to errors of a few per cent, namely, the error in measuring the temperature of the specimen owing to its lack of homogeneity, and

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23) R. Takahasi and K. Hirano, *Zisin.*, **12** (1940), 510.

24) T. Minakami, *ibid.* 507.

25) T. Nagata, *ibid.* 496.

26) Y. Kato, *Proc. Imp. Acad. Japan.*, **16** (1940), 352.

27) Y. Kato, *loc. cit.*

T. Minakami, Read before the 165th meeting (1940) of the E. R. I. Not yet published.

to that in measuring the magnetic intensities. The other serious cause of errors is that the exact standard condition of a rock was not attainable, not even in the initial state of the experiment at 0°C, for there is no means at present of knowing what is the normal state of a rock both from the standpoint of petrology and that of the magnetism of such a complex aggregate of matter as a rock. These obstacles are inevitable in the quest for a full understanding of the apparent magnetic properties of a rock. In order to circumvent this difficulty, it is necessary to examine the property of magnetism during cooling of each mineral composing a rock, the mutual reaction between them, and lastly the law that functions them, such as the apparent magnetic property of a rock.

In the present phenomenological description of the mode of causation of magnetism during cooling, this magnetism at whatever temperature, is regarded as a permanent component separated from the component that is reversible with respect to the applied magnetic field. Although this is done for convenience, it does not seriously differ from the truth, not at any rate within the limits of the apparent intensity of magnetization. The reliability of this separation was directly proved by the fact that the intensity of magnetization of a sample diminished slightly in magnitude of the order of the magnetization induced, the permanent component defined as $J_c(t,H)$, however, remaining unchanged when the external magnetic field was removed at any temperature during the cooling process. This fact may allow us to presume that a part or whole of the induced magnetism at t remains as permanent residual magnetism when the temperature becomes $t-dt$, when induced magnetization corresponding to $t-dt$ also appears.

Although, whether this phenomenon is due to a character of the ferromagnetic minerals in the rock alone or whether it is the result of their reaction with other minerals, is not clear at present, there is no doubt that the phenomenon is a result of the ferromagnetic property of the semi-conducting material. Moreover, the relation between $P(t)$ and $\chi(t)$, if obtained, will give a clearer aspect of the mode of causation of the magnetism during cooling. According to measurements of the temperature change in magnetic susceptibility $\chi(t)$ of a few basic rocks in a magnetic field of 2·2 Gauss, $\chi(t)$ seems to increase about 20~50% at temperatures of from 100°C to 200°C below the Curie-point, although the increase was not so marked as that in iron in a weak magnetic field, as reported by J. Hopkinson[28] and others. After measuring $\chi(t)$ in a weaker magnetic field, a comparison of the characteristics of $\chi(t)$

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28) J. HOPKINSON, *Proc. Roy. Soc. London*, A. **45** (1889), 318.

and $P(t)$ will be made. For the present, however the writer presumes that a part of $\chi(t)$ may concern $P(t)$.

Summarizing the conclusions reached in the present study, we may say that

(1). Thermo-remanent magnetism is defined as the magnetism that persists (remains) after the specimen has been cooled to 0°C or to ordinary room temperature.

(2). The magnetism $J^{(t')}_{t\cdot H}$, caused during cooling from t to t' in magnetic field H is given by

$$\vec{J}^{(t')}_{t\cdot H}=\vec{H}\cdot\int_{t}^{t'}P(t)\,dt,$$

where $P(t)$ has the functional form given in Fig. 3.

(3). The causation of magnetism during cooling is independent of the velocity of cooling.

(4). The permanent component of magnetization of a fresh specimen in the initial heating process is nearly zero, regardless of the intensity of H.

(5). Although $J^{(t')}_{t\cdot H}$ seems to be reversible with change in temperature, disappearence of magnetization due to increase in temperature does not depend on H.

(6). Although $P(t)$ seems to be in the same order as or rather smaller than $\chi(t)$, the magnitude of $\int_{t_c}^{0}P(t)\,dt$ is usually much larger than the susceptibility.

(7). The causation and disappearence of magnetism during cooling are expected to occur in the earth's crust. This phenomenon is related to secular variation in geomagnetism as well as to regional and local magnetic changes.

In conclusion, the writer wishes to express his sincere thanks to Dr. H. Tsuya, Dr. C. Tsuboi, and Dr. R. Takahasi, for their encouragement and advice in the course of the present study, and to Prof. S. Kaya for his interest in this study. His hearty thanks are also due to the Hattori Hôkô Kai, with the aid of whose grant the present experiment was carried out, and to Mr. H. Isiwara for assistance rendered.

6. 火成岩に於ける熱殘留磁氣生成の機構に就いて（序報）

地震研究所 永田武

火成岩の自然殘留磁氣及び熱殘留磁氣に關しては J. Königsberger, G. Folgheraiter, P. Mercanton, R. Chevallier 其の他の甚だ多くの研究があり，本邦に於いても中村清二博士，松山博士，及び筆者等の研究がある．この報告に於いては，火成岩の熱殘留磁氣生成過程に於ける諸狀態及び生成の條件等を觀測し，その生成機構の究明への準備とするものである．この研究で得られた結果を要約すれば次の如くである．

（1） 弱磁場 (H) に於いて，任意の溫度 t から常溫 (20°C) 乃至 0°C まで冷却した後の火成岩は，旣に良く知られてゐる樣に熱殘留磁氣 $J_{t\cdot H}$ を持つ．

（2） $J_{t\cdot H}$ は少くとも弱磁場の範圍では，磁場の強さに比例する．(第2圖．第3圖)．

$$\vec{J}_{t\cdot H}=\vec{H}\cdot J_t. \tag{3}$$

（3） J_t (又は $J_{t\cdot H}$) は第1圖に示す如き傾向を有し，t_o に於いて $\frac{\partial}{\partial t}J_t$ が極大，更に高溫の t_c に於いて J_t が最大値に達し，それ以上の t に對しては一定である．即ち t_c 以上の高溫から弱磁場冷却をした後の J_t は，その岩石の一特性常數である．これを J_{t_c} で表はし，飽和熱殘留磁氣と呼ぶ．

（4） 火山岩を高溫から 0°C まで冷却する場合に，ある溫度 $t_i+\Delta t$ から t_i までの Δt の間のみ磁場 H を與へ，他の溫度區間では常に $H=0$ に保つ時，やはり殘留磁氣が表はれる．之を部分磁場冷却磁氣と呼び，$\Delta J_{t_i\cdot H}$ を以て表はす．Δt の幅を一定に保つて，異れる t_i に於ける $\Delta J_{t_i\cdot H}$ を測定した結果は第4圖に示す如く，t_o' に於いて極大値をとり，t_c' 以上では 0 である．又實驗誤差の範圍で t_o', t_c' はそれぞれ t_o, t_c に一致する．

（5） $J_{t\cdot H}$ と $\Delta J_{t\cdot H}$ の間には

$$\sum_{t_i=0}^{t-\Delta t}\Delta J_{t_i\cdot H}=J_{t\cdot H}. \tag{6}$$

$$\frac{\partial}{\partial t}J_{t_i\cdot H}\cdot\Delta t=\Delta J_{t_i\cdot H}. \tag{7}$$

が成立する．(第5圖．第6圖)．

（6） Δt を更にいくつかの溫度區間に分けて，それぞれに對應する部分磁場冷却磁氣を求めると，結局

$$\lim_{\Delta t\to 0}\frac{\Delta J_{t_i\cdot H}}{\Delta t}=\frac{\partial}{\partial t}J_{t_i\cdot H}'=H\cdot P(t). \tag{13}$$

が成立すると考へられる．

（7） 以上の結果を綜合すると結局

$$\vec{J}_{t\cdot H}=\vec{H}\cdot\int_t^o P(t)dt. \tag{14}$$

なる關係が得られる．更に (14) 式を擴張して，t から t' まで磁場冷却した場合に表はれる磁場冷却磁氣を $J_{t\cdot H}^{(t')}$ で表はせば

$$\vec{J}^{(t')}_{t\cdot H}=\vec{H}\cdot\int_{t}^{t'}P(t)\,dt. \tag{15}$$

が得られる．

（８） 冷却速度か 1°C/sec 以上の範圍では，第一近似として $\varDelta J_{t\cdot H}$ は冷却速度に無關係といふ結果を得た．從つて (14) (15) 兩式は冷却速度に無關係に成立する．

（９） (14) (15) 兩式の表はす性質を直接に觀測する爲に，不定位磁力計によつて，弱磁場内の任意の溫度に於ける帶磁の强さを測定した．その結果，初期狀態に於いて剛磁性を持たない試料の最初の加熱過程では，誘導磁氣 $H\cdot\chi(t)$ のみが表はれるのに對して，t_c 以上の高溫からの磁場冷却の過程に於いては，帶磁の强さが $H\cdot\chi(t)+J_c(t\cdot H)$ である．$J_c(t\cdot H)$ は剛磁性成分であつて，磁場 H を取除いてもそのまゝ殘留する．$H\cdot\chi(t)\ll J_c(t\cdot H)$ なる試料について $J_c(t\cdot H)$ の溫度變化を求めた結果，(第 13 圖)

$$J_c(0\cdot H)=J_{t_c\cdot H},\quad J_c(t_c\cdot H)=0. \tag{21}$$

$$J_c(t\cdot H)=J_{t_c\cdot H}-J_{t\cdot H}. \tag{22}$$

を得，更に $\varDelta J_{t\cdot H}$ との間には (6) (7) 兩式と同様の關係が成立する事を認めた．結局

$$\vec{J}_c(t\cdot H)=\vec{H}\cdot\int_{t_c}^{t}P(t)\,dt=J^{(t)}_{t_c\cdot H}. \tag{25}$$

であつて，(15) 式を直接證明した事になる．

(10) 熱殘留磁氣 J_o を旣に剛磁性として保存してゐる試料を加熱すれば，その J_o を生成する過程を表はす $J_c(t\cdot H)\sim t$ 曲線に殆んど等しい經路を逆行して，J_o は減少する．即ち

$$\frac{\partial}{\partial t}J_o=-H\cdot P(t). \tag{27}$$

但し，(27) 式の H は J_o を生成する時に與へた H であつて，加熱の場合には無磁場の場合にも，上述の事は成立する．

(11) 以上の實驗結果は，任意の溫度に於ける微小溫度區間 $\varDelta t$ の間の溫度變化に對して，溫度降下に對して剛磁性を生成し，上昇に對して消失する性能を有する，溫度變化に對して可逆的なある物理的狀態 $P(t)\varDelta t$ が存在し，冷却の際にはこの狀態に外部磁場 $\vec{H}$ が作用して $\vec{H}\cdot P(t)\varDelta t$ の剛磁性が表はれるのに對し，加熱の場合には，その狀態の消失の故に，H の有無には無關係に $\vec{H}\cdot P(t)\,dt$ だけ剛磁性が消失するといふ事を暗示する．この現象の微視的機構は今後の問題である．

(12) 十數個の試料に就いて，χ，J_{t_c}，t_o，t_c，$Q_t\equiv J_{t_c}/\chi$ 等の實際値を例示したが (第 VII 表)，Q_t が一般に１より大きく，100 近くに達する場合も存在する事を考慮すれば，地磁氣の永年變化，特に火山活動に伴ふ局部的異常變化に對して，地殼内の岩石に於ける磁場冷却磁氣の生成及び消失が，主要なる原因と考へられる事を論じた．一般に $P(t)\leqq\chi(t)$ ではあるが，ある有限範圍の溫度變化に對しては $\int P(t)\,dt$ が問題になり，この値が χ に比して大きいといふ事實が，地球物理學上の問題では注意されればならないと思ふ．

この研究は服部報公會の御援助によつて遂行されたものであり，此處に同會に對して厚く感謝の意を表する．