8. *The Natural Remanent Magnetism of Sedimentary Rocks. (Preliminary Note).*

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§ 1. *Introduction.*

Since its discovery by G. Folgehraiter,[1] the natural remanent magnetism of igneous rocks has been studied by a number of investigators, the fruitful results of which have accumulated considerably. J. Königsberger[2] and Nagata[3] especially examined the physical mechanism of its development. Although the physical mechanism that is the cause of the remanent magnetization in micro-crystals of ferro-magnetic minerals in igneous rocks has not yet been thoroughly cleared, judging from experiments made, there is little doubt that it is developed during cooling of the rock-sample in a weak magnetic field from a temperature exceeding its Curie-point, whence it is called thermo-remanent magnetism.

On the other hand, it was found from Nagata's[4] experiment that the natural remanent magnetization of igneous rocks thus developed is fairly stable. In other words, it has been demagnetized but slightly during that long period from the end of the Tirtiary to the present time. Since, the bulk of the sedimentary rocks consist of fragments of igneous rocks, except in a few cases, such, for example, as limestone and siliceous rocks, the sedimentary rocks too ought to contain some permanently magnetized ferro-magnetic minerals. Were the direction of permanent magnetization of ferro-magnetic minerals contained in sedimentary rocks distributed at random, the resultant intensity of permanent magnetization of a sufficiently large mass of that sedimentary rock would be much small. If, however, the distribution in direction of magnetization along a special direction were particularly dense compared with those distributed in other directions as the result of the

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[1] G. FOLGHERAITER, *Rend. Acc. Lincci.*, **3** (II), (1894), 53.
[2] J. G. KÖNIGSBERGER, *Terr. Mag.*, **43** (1938), 119, 299.
[3] T. NAGATA, *Bull. Earthq. Res. Inst.*, **20** (1942), 192.
[4] T. NAGATA, *Bull. Earthq. Res. Inst.*, **21** (1943), 1.

geomagnetic force affecting the magnetized ferro-magnetic minerals during their deposition, the resultant intensity of residual magnetization of that sedimentary rock will be fairly intense, it being presumed to be correlated in some way with the direction of the geomagentic force affecting the deposit.

Assuming that the direction of residual permanent magnetization of the sediments exactly agrees with that of the geomagnetic force that affected the sediments in the course of their deposition, A. G. McNish and E. A. Johnson[5] estimated the general mode of secular variation in geomagnetic field from the direction of residual permanent magnetization of a number of rock samples collected from various depths of horizontal strata of verve and clay in the Pacific Ocean. Although a few rough determinations of residual magnetization of sedimentary rocks for special purpose have recently been published in connexion with[6] oil exploration, the work of McNish and Johnson stands out as the most interesting from the geophysical point of view, although all that they found was a mere trace of secular variation in geomagnetic field that remained on a sort of sediment in a certain district of U.S.A. for long geological periods.

For these reasons, it seems that we ought, first of all, to examine the nature of the natural remanent magnetism of sedimentary rocks, particularly, in connexion with the reliability of that important assumption that the direction of remanent magnetization of horizontally laid sedimentary rock agrees with that of the geomagnetic field that affected the sediments during their deposition. Even should this assumption be found sufficiently reliable, there still remains the further need, in order to gain a general aspect of secular variation in geomagnetic field, to collect data covering the direction of the natural remanent magnetization of horizontally laid sedimentary rocks of various ages found in as many regions as possible on the earth's surface.

It is with this idea in mind that we also took up the study of the nature of natural remanent magnetism of sedimentary rocks found in Japan.

§ 2. *The Direction of apparent residual magnetization of a mass consisting of fragments of igneous rocks deposited in the earth's magnetic field.*

A piece of volcanic rock (olivine-basalt ejected from Volcano Mi-

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[5] A. G. McNish and E. A. Johnson, *Terr. Mag.*, 43 (1938), 393, 401.

[6] E. D. Lynton, *Geophysics*, 3 (1938), 122; 4 (1940), 393.
D. C. Roberts and E. R. Webb, *Rep. Tech. Meeting Oil World Exposition, Houston, Texas*, (1939), 24.

hara),⁽⁷⁾ the normative amount of magnetite in it being about 4 percent, was crushed into small pieces, the diameter of which were less than 0·05 *mm*. After these were heated in air to 700°C, they were slowly cooled to room temperature in a magnetic field of 4·0 Oersteds, the rock fragments after this treatment acquiring the so-called thermoremanent magnetization, the specific intensity of which was about 0·065 e.m.u..

Into a glass tube, 26 *mm* diameter and 197 *cm* long, filled with water, and set in a vertical position, these rock fragments were dropped, a few pieces at a time, from the upper end of the tube, the particles then settling at the bottom. The velocity of descent, naturally, differed with the size of the particles, the largest particle descending with a velocity of 2 *cm/sec* and the smallest at that of 0·003 *cm/sec.* The mean velocity of descent was probably about 0·01 *cm/sec.*

To the lower end of the glass tube was connected a cylindrical glass bottle on which was marked the geomagnetic meridian. After all the fragments had been deposited in the glass tube, the water in it was slowly run out, the glass tube itself being also disconnected after the operation. The bottle containing the deposited fragments was left to stand in the shade for about a week. The deposited fragments of rock, then, almost coagulated, practically speaking. The direction of magnetization of this coagulated mass of fragments in the bottle was measured with an astatic magnetometer. An example of the results is given in Fig. 1, showing the declination of magnetization with respect to the geomagnetic meridian. As will be seen from this figure, the horizontal direction of apparent magnetization of the sediment exactly agrees with the geomagnetic meridian.⁽⁸⁾ It is worth while noting here that the specific intensity of apparent magnetization of the mass of sediment was about 0·023 e.m.u., that is, about one-third that of the initially magnetized mass of fragments. This experimental fact seems to show that each fragment of magnetized ferro-

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7) T. NAGATA, *Bull. Earthq. Res. Inst.*, **18** (1940), 102, 281.

8) The observed values given in Fig. 1 were subjected to Fourier analysis, the distribution of magnetization along the horizontal circle on a sphere containing the mass of sediment at its centre being approximately given by

$$M = 0{\cdot}745\cos(\theta - 0{\cdot}{}^\circ5) + 0{\cdot}025\cos(2\theta - 16^\circ) - 0{\cdot}005\cos(3\theta + 71^\circ)\,,$$

where the azimuth is measured from the geomagnetic meridian.

As shown in this result, compared with that of the first harmonic, the coefficients of higher harmonics are negligible, while the direction of dipole magnetization corresponding to the first harmonic agrees with that of the geomagnetic North with an error of only 0·5 degrees.

magnetic mineral as it fell in the water was subjected to the earth's magnetic field, with the result that, statistically speaking, the mean direction of magnetization of the total mass of deposited fragments agrees with that of the earth's magnetic field.

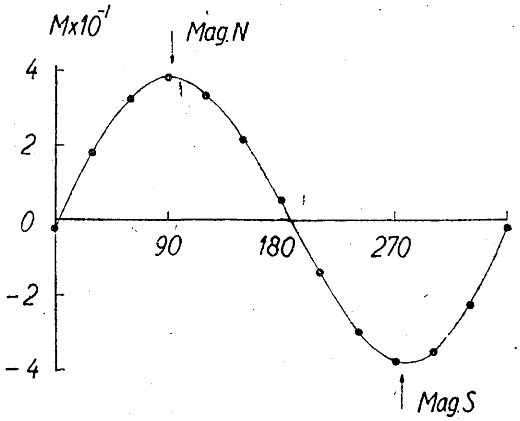

Fig. 1. Magnetization of a mass of deposit.

We shall next briefly deal with the general behaviour of a magnetized particle that is deposited through water in a uniform magnetic field. Denoting then the mass, moment of inertia, and the magnetic moment of the deposited particle by m, I, and μ respectively, and the coefficients of resistance due to viscosity of water for translation and rotation of the particle by ν and λ respectively, the equation of motion is given by

$$m\frac{d^2z}{dt^2}=-\nu\frac{dz}{dt}+mg\,, \tag{1}$$

$$I\frac{d^2\theta}{dt^2}=-\mu F\sin\theta-\lambda\frac{d\theta}{dt}\,, \tag{2}$$

where F is the intensity of applied magnetic field, θ being the angle of deviation of $\vec{\mu}$ from $\vec{F}$.

Assuming that $(z)_{t=0}=0$ and $\left(\frac{dz}{dt}\right)_{t=0}=0$, we get for the solution of eq. (1)

$$z=\frac{m}{\nu}gt+\frac{m^2}{\nu^2}g(e^{-\frac{\nu}{m}t}-1)\,. \tag{3}$$

Since, however, practically $\frac{\nu}{m}t\gg1$,

$$z\fallingdotseq\frac{m}{\nu}g\left(t-\frac{m}{\nu}\right), \tag{3'}$$

or more roughly,

$$z\fallingdotseq\frac{m}{\nu}gt\,, \tag{3''}$$

Similarly, since $\left|I\frac{d^2\theta}{dt^2}\right| \ll \left|\lambda\frac{d\theta}{dt}\right|$ in eq. (2) (the rotation of a particle in water being very slow, its motion being quasi-stationary), eq. (2) becomes approximately

$$\lambda\frac{d\theta}{dt} = -\mu F \sin\theta. \tag{2'}$$

Then, $\theta=\theta_0$ when $t=0$ being assumed, the solution of eq. (2′) is given by

$$\tan\frac{\theta}{2} = \tan\frac{\theta_0}{2}\exp\left(-\frac{F}{\lambda}\mu t\right). \tag{4}$$

From relation (4) it will be seen that θ is determined by the product of μ and t, provided θ_0, F, and λ are kept constant. This result will give the law of similitude between the behaviours of particles deposited in the sea and in water in a glass tube, seeing that the intensity of geomagnetic field F during geological ages and the quantity λ depending on the dimensions of the particle and the viscosity of water will not differ much from those given in the model experiment just described. On the other hand, we see from eq. (3″) that the time required for deposition of a particle from the surface of the water to the bottom is approximately proportional to the depth of water h in the two cases, the sea and the water in a glass tube. It may then be expected that the behaviour of a magnetized particle with its magnetic moment μ_e, deposited in a tube of water to a depth of 2 m, corresponds to that of magnetic moment, μ_s deposited in the sea, $h_s=h_e\frac{\mu_e}{\mu_s}$ deep. Since, in actual experiment, $h_e=2\,m$ and $\frac{\mu_e}{\mu_s}=10\sim50$,[9] it is concluded that the result of our model experiment corresponds to deposition of ordinary fragments of igneous rocks in a sea or lake that is about 20∼100 m deep.

Further, if we assume that θ_0 is distributed uniformly in all directions between 0 to 2π at the initial state of $t=0$, the number of

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[9] Since, as already mentioned, the intensity of magnetic field applied during the development of thermo-remanent magnetization of the test sample was 4·0 *Oe.*, i.e. about ten times the actual geomagnetic field, it is assumed that μ_e is about ten times μ_s, the intensity that ought to be developed in a geomagnetic field. However, since the thermo-remanent magnetization of ejecta of Mihara Volcano is very intense compared with that of other volcanic rocks, (see T. NAGATA, *Bull. Earthq. Res. Inst.* **20** (1942), 50), it may be in order to assume that μ_e/μ_s considerably exceeds 10, although the ratio would be less than 100.

fragments being considered sufficiently large, the intensity M of the resultant magnetization of unit volume of sediments is given by

$$\left.\begin{aligned} M=p\mu\overline{\cos\theta}&=\frac{p\mu}{\pi}\int_0^\pi \frac{1-\exp\left(-\frac{2F}{\lambda}\mu t\right)\tan^2\frac{\theta_0}{2}}{1+\exp\left(-\frac{2F}{\lambda}\mu t\right)\tan^2\frac{\theta_0}{2}}d\theta_0 \\ &=p\mu\tanh\left(\frac{F}{2\lambda}\mu t\right), \end{aligned}\right\} \tag{5}$$

where $t\simeq\frac{h\nu}{mg}$ and p is the number of magnetized particles in unit volume of sediment. Obviously, the resultant intensity of magnetization along the direction perpendicular to $\vec{F}$ here should be zero, as easily proved from the condition that all phenomena are in symmetry with respect to the direction of $\vec{F}$.

From the above-mentioned theory, it will be seen that the resultant magnetization of sediment containing a sufficiently large number of ferro-magnetic fragments is represented by a magnetic dipole whose direction agrees with that of the magnetic force affecting the fragments in the course of deposition, and that the intensity of the dipole increases hyperbolic-tangentially with increase in the time required for deposition of the fragments according to the depth of the water. Since $\frac{M}{M_0}=\tanh\left(\frac{F}{2\lambda}\mu t\right)\doteqdot\frac{1}{3}$ in our model experiment, which corresponds to the actual deposition in a sea, $20\sim100\,m$ deep, should the depth of the water be twice that, M/M_0 would be about 0·6, and even should the depth be one-half that, M/M_0 would still be 0·17.

It will thus be expected that the natural remanent magnetization of a horizontal stratum of sedimentary rock will not be very small, so long as it contains a fair amount of ferro-magnetic minerals, and also that its direction ought to agree with that of the geomagnetic field at the time it was deposited.

§ 3. *Measuring apparatus.*

In order to measure the natural remanent magnetization of the smallest possible test sample, the method of electro-magnetic induction, which was exactly the same in principle, as those used by McNish and Johnson⁽¹⁰⁾ and by Thellier,⁽¹¹⁾ was adopted. That is to say, the test sample was rotated at high speed in the centre of a multi-turned circular coil, the e.m.f. induced in this coil being amplified by means of a low frequency high-gain amplifier, the out-put current from which was eliminated through rotating commutator synchronized with the rotation of the test sample, the final D.C. current being measured with the aid of a galvanometer. A schematic view of the apparatus and its general electric circuit are shown in Fig. 2, the details being as follows.

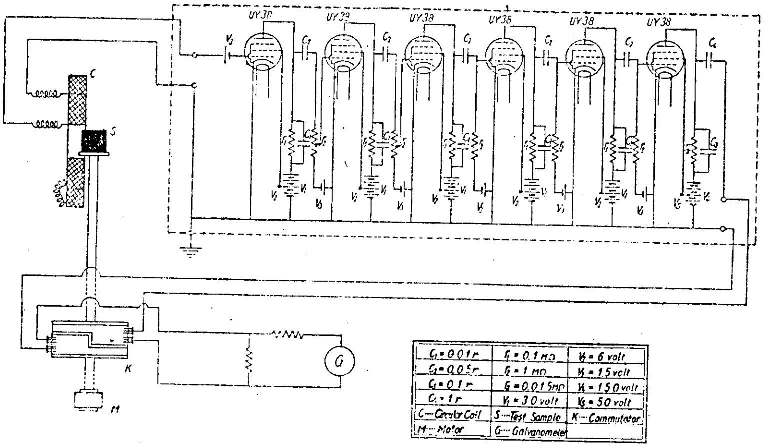

Fig. 2 General electric circuit in the apparatus for measuring the natural remanent magnetism of sedimentary rocks.

The photograph, Fig. 3. is an exterior view of the circular coil for electro-magnetic induction and its position relative to the test sample is shown in the photograph. This consists of two concentric circular coils, an inner coil, 60,000 turns, 6·0 *cm* inner and 11·4 *cm* outer diameter, and an outer coil, about 27790 turns, 11·4 *cm* and 13·9 *cm* inner and outer diameters, the two coils being so connected in series that the direction in turn of one coil is opposite to that of the other, so that by placing the circular double coil in a uniform magnetic field such that the axis of the coil is parallel with the direction of field, the magnetic flux passing through that area closed by all the turns in the coil is given by

$$\phi=\pi n^2 dH\left[\int_{r_1}^{r_2} r^2 dr-\int_{r_2}^{r_3} r^2 dr\right]=\pi n^2 dH(2r_2^3-r_1^3-r_3^3)\,, \tag{1}$$

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10) A. G. McNISH and E. A. JOHNSON, *loc. cit.*

11) E. THELLIER, *Ann. Phys. Globe*, 16 (1938), 156.

where n, d, r_1, r_2, r_3 denote respectively the number of turns of coil per *cm*, the thickness of coil, the inner radius of the inner coil, the outer radius of the inner coil (which is equal to the inner radius of the outer coil), and the outer radius of the outer coil. Then, if

$$2r_2^3 = r_1^3 + r_3^3 , \tag{2}$$

ϕ becomes zero.

That is, the uniform change in uniform magnetic field passing through the coil causes no electro-magnetic induction in the circular double coil. The radii r_1, r_2, and r_3 of the coil used in our experiment satisfies the condition given by the above mentioned relation. Actually, however, in order to satisfy eq. (2), it was adjusted experimentally with the aid of a large Helmholtz coil and a ballistic galvanometer by varying the number of turns in the outer coil. Thus, our double coil produces very little e.m.f. corresponding to the change (with respect to time) in the applied magnetic field, which is uniform or almost uniform with respect to its space distribution.

On the other hand, let us suppose a magnetic dipole μ, which is situated l *cm* from the centre of the double circular coil on its line of axis, and is rotating with vertical axis. Taking the (x, y, z) coordinate so that its origin coincides with the centre of the dipole, the z-axis being perpendicular to the surface of the circular coil, while the y-axis is parallel with the vertical, the magnetic potential due to the dipole is expressed by

$$\left.\begin{aligned} \mathrm{W} &= \frac{\mu_x x + \mu_y y + \mu_z z}{R^3} , \\ R^2 = x^2 + y^2 + z^2 , &\qquad \mu_x^2 + \mu_y^2 + \mu_z^2 = \mu^2 . \end{aligned}\right\} \tag{3}$$

The magnetic flux passing through that area that is closed by a turn of circular coil is then given by

$$\phi = \int_0^r \int_0^{2\pi} H_z r dr d\theta = 2\pi\mu_z \frac{r^2}{(r^3 + z^2)^{\frac{3}{2}}} , \tag{4}$$

where

$$H_z = \frac{\partial W}{\partial z} = \frac{\mu_z (r^2 - 2z^2) - 3\mu_x rz \cos(\theta - \alpha)}{(r^2 + z^2)^{\frac{5}{2}}} , \tag{5}$$

and

$$r^2 = y^2 + z^2 , \qquad \tan\theta = y/x , \qquad \tan\alpha = \mu_y/\mu_z , \tag{6}$$

whence the magnetic flux closed by all the turns in the double circular coil is

$$\Phi=\int_{l-\frac{d}{2}}^{l+\frac{d}{2}}\left\{\int_{r_1}^{r_2}\phi\frac{dr}{D}-\int_{r_2}^{r_3}\phi\frac{dr}{D}\right\}\frac{dz}{D}, \tag{7}$$

where d and D are the thickness of coil and effective diameter of wound wire respectively. Since, here the magnetic dipole is rotating with a vertical axis with a uniform velocity of f cycles/sec,

$$\left.\begin{aligned}&\mu_z=\sqrt{\mu_x^2+\mu_z^2}\cos 2\pi ft\equiv\mu_h\cos 2\pi ft,\\&\mu_x=\mu_h\sin 2\pi ft,\\&\mu_y=\mu_y \text{ (independent on time)},\end{aligned}\right\} \tag{8}$$

provided a suitable origin of time t is taken. Consequently, the e.m.f. induced in the double circular coil, owing to the flux-change due to uniform rotation of dipole, is given by

$$\left.\begin{aligned}E=&\frac{4\pi^2 f}{D}\mu_h\sin 2\pi ft\times 10^{-8}\\&\times\left[l\log\frac{r_1+\sqrt{r_1^2+(l-d/2)^2}}{r_1+\sqrt{r_1^2+(l+d/2)^2}}\cdot\left\{\frac{r_2+\sqrt{r_2^2+(l+d/2)^2}}{r_1+\sqrt{r_2^2+(l-d/2)^2}}\right\}^2\right.\\&\cdot\frac{r_3+\sqrt{r_3^2+(l-d/2)^2}}{r_3-\sqrt{r_3+(l-d/2)^2}}+\frac{d}{2}\log\cdot\frac{r_2+\sqrt{r_2^2+(l-d/2)^2}}{r_1+\sqrt{r_1+(l+d/2)^2}}\\&\cdot\frac{r_2+\sqrt{r_2^2+(l-d/2)^2}}{r_1+\sqrt{r_1^2+(l-d/2)^2}}\cdot\frac{r_2+\sqrt{r_2^2+(l-d/2)^2}}{r_3+\sqrt{r_3^2+(l-d/2)^2}}\\&\left.\cdot\frac{r_2+\sqrt{r_2^2+(l-d/2)^2}}{r_3+\sqrt{r_3^2+(l-d/2)^2}}\right].\end{aligned}\right\} \tag{9}$$

It is clear from eq. (9) that, in the present case, the e.m.f. induced in the inner coil fairly exceeds the e.m.f. of opposite sign induced in the outer coil, so that the resultant e.m.f. is the order of a few tens percent of that of the inner coil alone.12) Hence, it is found that the

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12) Since, in our apparatus, $l=2{\cdot}0$ cm, E becomes

$$E_{2\cdot 0}=1{\cdot}97\mu_h\sin 2\pi ft\times 10^{-2}\text{ volt},$$

whereas, if $l=0$,

$$E_0=3{\cdot}63\mu_h\sin 2\pi ft\times 10^{-2}\text{ volt}.$$

(The general formula for this case ($l=0$) was worked out by JOHNSON and McNISH, *Terr. Mag.*, 43 (1938), 393).

The e.m.f. induced in the former case is about one-half that in the latter case, where the coil constants and μ are assumed constant, whence for greater efficiency, it is desirable that l shall be as small as possible.

circular double coil produces an e.m.f. that corresponds to the rotation of a small test sample, which can be approximated with a magnetic dipole on the axial line of the coil, though it produces very little e.m.f. corresponding to almost uniform change in magnetic field due, for example, to electric motor (*M* in Fig. 2), magnetic disturbances from electric trolley cars, etc. Actually, in order to minimize the induced e.m.f. owing to the change in the component of geomagnetic force passing through the coil-surface as the result of its mechanical vibration, the circular double coil was set parallel with the plane of the geomagnetic meridian.

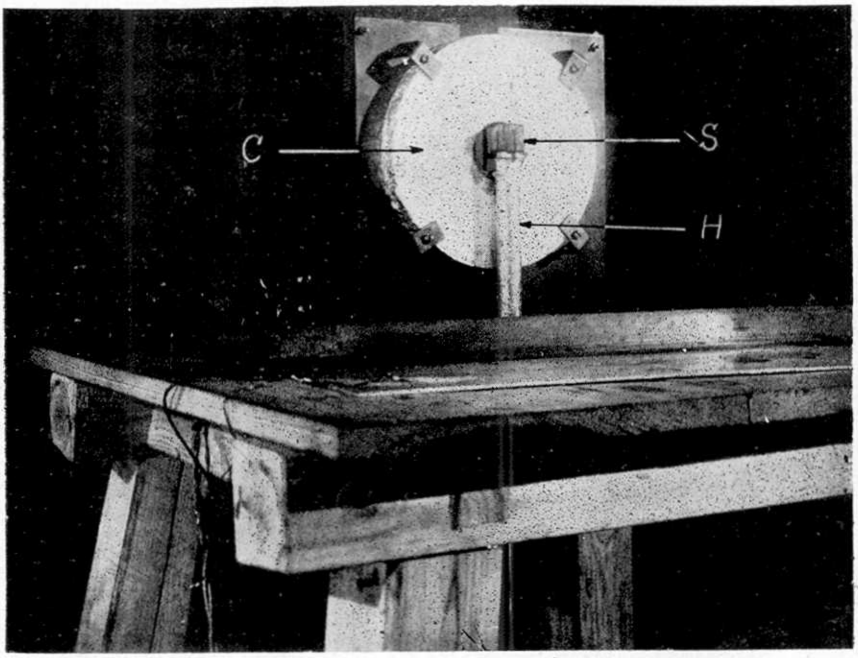

Fig. 3. The double circular coil and the sample-holder.

S. Specimen to be examined. (1·5 cm cube)
C. Induction coil.
H. Holder of specimen. (electrically shielded)

The test sample was always a 1·5 *cm* cube, cut off from a mass of sedimentary rock. As will be seen from Fig. 3, the cubic test sample was affixed with silk thread to a sample-holder made of ebonite, shielded by a tin-foil and earthed, in such a way that its centre coincided with the horizontal axis of the circular coil, a distance of 2·0 *cm* between the centres of the coil and the sample being always maintained.

In order to get the highest gain for a frequency of 20 cycles/sec, a low-frequency high-gain amplifier designed according to the theory proposed by E.A. Johnson[13] was used. The electric circuit and the numeral values of every part of the amplifier will be seen in Fig. 2, its characteristic curve for frequency, which was determined experimentally, being given in Fig. 4. As will be seen from this figure, the gain is maximum for a frequency of 18~22 cycles/sec, greatly diminishing (abruptly) for the higher frequency, exactly as expected from theory. The magnifying-ratio and the phase-lag of out-put current from in-put current of the amplifier for the case of 20 cycles/sec was about 95 *db* and 51° respectively under stable conditions. The gain (magnifying ratio) and phase-lag were checked by replacing the test sample with a small magnetic needle always before and after a set of observations, the result of actual calibration showing that the character of the amplifier was fairly stable during the whole period of experiment. Further, it will be worth while to note here that, in order to avoid the mechanical vibration due to various external disturbances, the amplifier was mounted on a wooden plate freely suspended from the ceiling, the period of free oscillation of this pendulum system being about 4 sec..

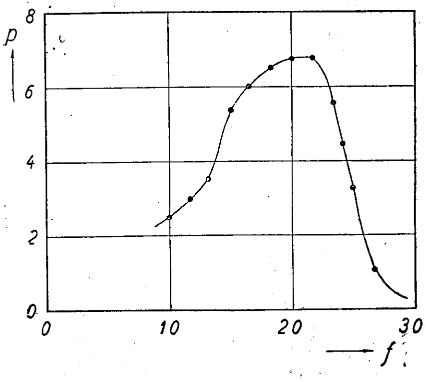

Fig. 4. The characteristic curve of amplifier for low frequency.
p. magnifying ratio in arbitrary scale.
f. frequency in cycles/sec.

The rotaing commutater consisted of an armature and brushes, both of copper. As already mentioned, this rotating commutater was connected to the holder of the test sample by means of a rod of alminium, whence the former rotated coaxially and synchronously with the test sample. The exterior of the commutater and its connection to sample will be seen from a general view of the apparatus given in Plate 1. Here, the phase difference between commutater and sample could be varied, its amount being read with the aid of a circular graduated disc attached to the commutater. In other words, the alternating e.m.f. generated in the circular coil and then magnified through the amplifier is commutated at any phase by means of the commutater, which is rotating synchronously with the foundamental tone of the alternating e.m.f..

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[13] E. A. JOHNSON and C. NEITZERT, *Rev. Sci. Inst.*, 5 (1934), 196.

Let $I=\sum_{n=1}^{\infty} I_n \sin(2\pi nft+\varphi_n)$ and ψ denote respectively the alternating current of in-put of commutater and the phase difference between I and the commutater. Then, the mean direct current of out-put of the commutater is expressed by

$$\left.\begin{aligned} I_D &= \frac{2}{T}\int_{\frac{\psi}{2\pi f}}^{\frac{\psi}{2\pi f}+\frac{T}{2}} \sum_{n=1}^{\infty} I_n \sin(2\pi nft+\varphi_n)\,dt \\ &= \frac{1}{\pi}\sum_{n=1}^{\infty}\frac{I_n}{n}(1-\cos n\pi)\cos(n\psi+\varphi_n) \\ &= \frac{2}{\pi}\Big[I_1\cos(\psi+\varphi_1)+\frac{I_3}{3}\cos(3\psi+\varphi_3) \\ &\qquad\qquad +\frac{I_5}{5}\cos(5\psi+\varphi_5)+\cdots\cdots\Big] \end{aligned}\right\}, \qquad (10)$$

where $T=\frac{1}{f}$. Thus, the higher harmonics of even order are nullified by the synchronized commutater, while the fundamental tone and higher harmonics of odd order remain as D.C. current in the out-put circuit, which is a function of I_n, φ_n, and ψ.

Since, actually, the rotating test sample was almost equivalent to a rotating magnetic dipole, and since the amplifier scarcely distorted the wave form of the alternating e.m.f., I_n $(n\geqq 2)$ was neglible compared with I_1. Consequently the phase difference ψ being varied from 0 to 2π, the intensity of the eliminated direct current changes in almost pure sine-form with ψ. Now, provided the rotation of the sample is uniform, the instantaneous e.m.f. induced in the circular coil is optimum when the direction of horizontal component of magnetization of the sample is parallel with the surface plane of the circular coil, as will be easily seen from eqs. (8), (9), (10). Therefore, correcting the phase lag (φ_1) owing to the amplifier, it is possible to determine the direction of horizontal component of magnetization of a test sample from the observed curve of $I_D \doteqdot \frac{2I_1}{\pi}\cos(\psi+\varphi_1)$. For detecting I_D, a galvanometer, about 10^{-10} current sensitivity and 4 sec. of free-oscillation, period was used in the state of its critical damping.

Since, obviously, every part of the apparatus, especially those movable in that space near the circular double coil, must be nonmagnetic, as many as possible of them were constructed of either wood, ebonite, or bakelite, while such parts as required to be of metal were made of either almost pure copper, aluminum, or tin-foil, excepting the electric motor, the source of motive power for rotating both sample and commutater. Since, however, the distance between the motor and the test sample was about 2·1 *m* (see Plate 1), the magnetic disturbances at the place occupied by the coil owing to rotation of the motor, was negligible compared with the change in magnetic field owing to rotation of the sample. On the other hand, every important part of the apparatus and the lead wires were closely shielded electrically, especially, the set of double circular coils and the sample holder, both of which, although sufficiently shielded with tin-foil independently,[14] were again shielded by means of a wooden box cover plated with tin-foil connected to earth. Finally, the velocity of rotation of both sample and holder was observed with the aid of a strobo-scope, the rotation being kept always at 20 or 25 cycles/sec. A general view of the apparatus is given in Plates 1, 2.

4. *Results of measurements.*

For the purpose of testing the characteristics of the apparatus, we first examined two samples[15] of tuff (andesitic and dacitic) collected from North Idu. As already mentioned, these test samples were cut into 1·5 *cm* cubes. Let the three orthogonal axes of the cubic sample and the intensities of the components along these three axes of natural remanent magnetization be denoted by x, y, z, and M_x, M_y, M_z respectively, where the magnetization of the sample is assumed to be sufficiently uniform. Taking first the z-axis as the axis of rotation, the magnetization of the sample was examined with the present apparatus, with the result that the components of M_x and M_y were obtained from the curve of $I_p=\frac{2I_1}{\pi}\cos(\psi+\varphi_0)$, where ψ was varied every 20 degrees from 0 to 2π. Taking next the x-axis and then the y-axis as the axis

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[14] When even a part of the shielder (tin-foil) of the circular coil or that of the sample-holder was lacking, rotation of the sample-holder was accompanied by generation of alternating e.m.f. in the coil, the frequency of the e.m.f. being equal to that of rotation of the sample-holder. This phenomenon is probably traceable to the elecrostatic induction between the circular coil and the electro-static charge on the surface of the sample-holder, which is of insulating material.

[15] According to H. TSUYA, these two samples are andesitic tuff from Koyama, Yuhune, lower Pleistocene, and dacitic tuff from Miyanosita, Hakone, lower Pleistocene.

of rotation, we obtained (M_y, M_z) and (M_z, M_x) respectively. The observed results are graphically shown in Figs. 5, 6, from which it will

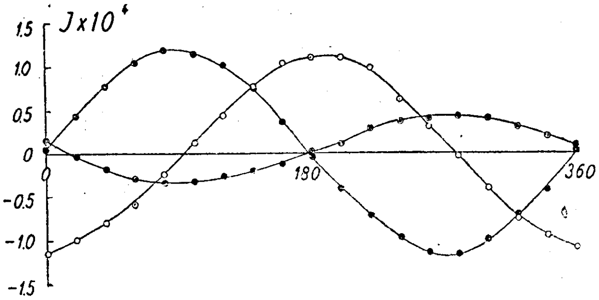

Fig. 5. Example of observed result. (andesitic tuff, Koyama, Yuhune)

be seen that the $I_D \sim \psi$ relations have almost a pure sine-form, showing that the magnetization of the cubic sample can be approximated sufficiently with a magnetic dipole (M_x, M_y, M_z), and that the amplifier scarcely distorts the sine-form of the in-put e.m.f..[16]

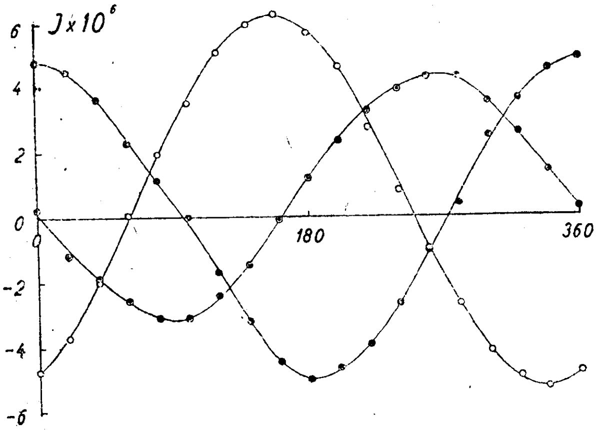

Fig. 6. Example of observed result. (Dacitic tuff, Hakone, Miyano-sita)

It will now be clear that the amplitude of the sine-curve of I_d, i.e. $\frac{2I_1}{\pi}$, is proportional to the intensity of the horizontal component of magnetization of the sample, namely, $\sqrt{M_x^2+M_y^2}$ for example, in the respective cases. On the other hand, as already mentioned, the de-

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[16] Since the magnetization of the andesitic tuff was fairly intense, it was possible to observe the wave-form of the out-put current of the amplifier with the aid of a cathode-ray oscillograph. The observed wave form was almost of pure sine form.

flection of the galvanometer was calibrated by replacing the sample with a small magnet, $8{\cdot}2\times10^{-5}$ magnetic moment, which was fixed horizontally to the sample-holder at a position coinciding exactly with the centre of the sample. From the above-mentioned three sets of observational results it was possible to determine two sets of intensities of the three components, M_x, M_y, M_z, theirs mean values being respectively

$$\left.\begin{aligned} M_x &= (+11{\cdot}40\pm0{\cdot}20)\times10^{-5} \\ M_y &= (+4{\cdot}02\pm0{\cdot}12)\times10^{-5} \\ M_z &= (+0{\cdot}02\pm0{\cdot}08)\times10^{-5} \end{aligned}\right\}\text{(andesitic tuff)},$$

$$\left.\begin{aligned} M_x &= (+4{\cdot}77\pm0{\cdot}15)\times10^{-6} \\ M_y &= (+3{\cdot}63\pm0{\cdot}08)\times10^{-6} \\ M_z &= (+1{\cdot}00\pm0{\cdot}09)\times10^{-6} \end{aligned}\right\}\text{(dacitic tuff)}.$$

That is to say, the direction of magnetization can be determined with an error of less than 3 degrees.

We next measured the direction of natural remanent magnetization of test samples of sand collected from various depth of a horizontal stratum. The samples examined was the upper 1·5 *m* of the Narita-bed (Upper Pleistocene), which is distributes horizontally over the districts of Tokyō and the northern parts of the Bôsô Peninsula (actually, from a cliff at Usui, near Inba-numa).

The horizontal plane and the geomagnetic meridian were determined with a clinometer where the examined rock was collected, and marked directly on the collected mass. These collected masses were cut every 2 *cm* along the vertical line, test samples of 1·5 *cm* cube being cut off from each plate, 2 *cm* thick, where a plane of the cubic surfaces was parallel with the horizontal plane, and the other parallel with the plane of the geomagnetic meridian. We then, assumed that each sample, 1·5 *cm* cube, represented the mean aspect of magnetization of a plate, 2 *cm* thick, of the examined stratum. An example of the results of measuring the magnetization of a cubic sample is shown in Fig. 7, from which it will be seen that the direction of magnetization can be determined with fair accuracy, notwithstanding that the specific intensity of remanent magnetization is markedly small, say, about 6×10^{-6} e.m.u..

Similarly the declination and inclination of natural remanent magnetization of 73 test samples were determined with an error, generally, of less than 2 degrees, and in a few cases, less than 3 degrees. The

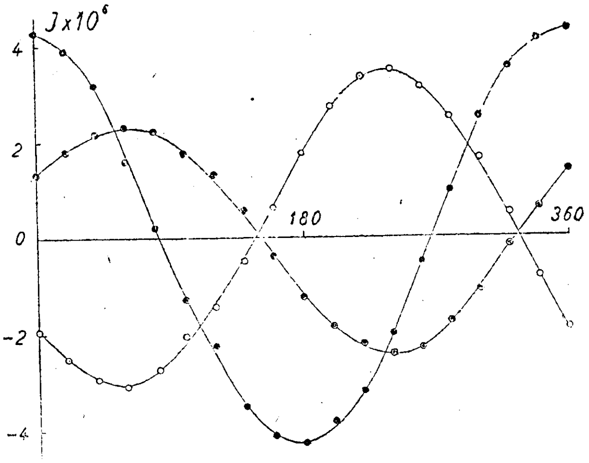

Fig. 7. Example of observed result. (Fine sand of Narita-bed)

observed final results are given in Table I, and graphically shown in Fig. 8, where the numerals under "depth" give the depth of centre of cubic sample from the upper boundery of the Narita-bed, (boundary between the Narita-bed and the Kantō-loam).

It will be clear from these results that the declination of remanent magnetization of every sample deviates fairly east from the present geomagnetic North, the mean value of δ of 69 samples being about 22° East. Further, it will be seen that the δ of the Narita-bed periodically changes with depth, at any rate, from the upper boundary to a depth of about one meter. There arises, however, the question whether or not this periodic change in δ is a character of the sedimentary rock at the very spot where the test samples were cut off or whether

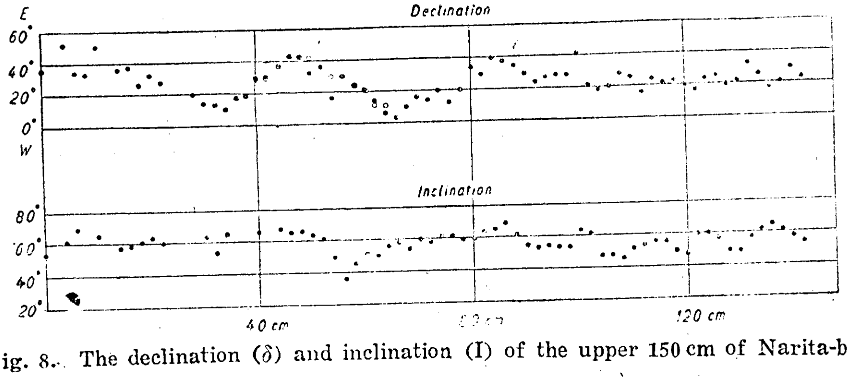

Fig. 8. The declination (δ) and inclination (I) of the upper 150 cm of Narita-bed.

Table I. Declination and Inclination of Natural Remanent Magnetization of Narita-bed.

No.	Depth of the Centre of Test Sample z	Declination δ	Inclination I	No.	Depth of the Centre of Test Sample z	Declination δ	Inclination I
1	1 cm	36°E	56°	27	53 cm	36°E	63°
2	3	—	—	(27′)	(53)	(37)	—
3	5	51	62	28	55	16	50
4	7	34	71	(28′)	(55)	(31)	—
5	9	33	—	29	57	31	37
6	11	49	66	(29′)	(57)	(30)	—
7	13	—	—	30	59	25	47
8	15	37	58	(30′)	(59)	(25)	—
9	17	39	59	31	61	22	53
10	19	27	61	(31′)	(61)	(20)	—
11	21	32	64	32	63	15	51
12	23	28	63	(32′)	(63)	(10)	—
13	25	—	—	33	65	7	57
14	27	—	—	(33′)	(65)	(10)	—
15	29	21	—	34	67	5	58
16	31	15	64	35	69	11	55
(16′)	(31)	(15)	—	36	71	16	61
(16″)	(31)	(15)	—	37	73	14	59
17	33	14	56	38	75	20	60
(17′)	(33)	(17)	—	39	77	11	62
18	35	9	66	40	79	19	59
(18′)	(35)	(8)	—	41	81	30	59
19	37	18	—	42	83	29	64
(19′)	(37)	(18)	—	43	85	40	67
20	39	19	—	44	87	37	70
(20′)	(39)	(20)	—	45	89	34	63
21	41	31	68	46	91	29	55
(21′)	(41)	(28)	—	47	93	24	53
22	43	32	—	48	95	27	55
(22′)	(43)	(30)	—	49	97	28	54
23	45	37	68	50	99	27	53
(23′)	(45)	(37)	—	51	101	41	64
24	47	44	66	52	103	21	63
(24′)	(47)	(43)	—	53	105	19	48
25	49	44	67	54	107	21	48
(25′)	(49)	(44)	—	55	109	28	46
26	51	33	66	56	111	25	52
(26′)	(51)	(42)	—	57	113	17	54

Table I. (*continued.*)

No.	Depth of the Centre of Test Sample z	Declination δ	Inclination I	No.	Depth of the Centre of Test Sample z	Declination δ	Inclination I
58	115cm	24° E	55°	66	131cm	22° E	49°
59	117	22	55	67	133	33	58
60	119	23	50	68	135	26	63
61	121	21	49	69	137	18	66
62	123	17	60	70	139	21	62
63	125	25	60	71	141	28	58
64	127	27	57	72	143	24	54
65	129	20	49				

it is a general character of the Narita-bed that is widely distributes in its neighbourhood. In order to answer this question further samples were collected from a place about 4 meters distant from that position where the test samples initially examined were obtained, of which only the declination of magnetization of samples corresponding to depths of from 30 *cm* to 65 *cm*, where the change in δ with depth was markedly large, was determined, with results as given in Table I (parenthesized numerals) and in Fig. 8 (with hollow circles).

From these results, it will be seen that the general tendency to change with depth is similar in the two cases, the δ of the two test samples collected from the same depth of the same stratum, but in different places, generally agreeing with an error of less than three degrees. There are, however, a few exceptional cases in which the δ of two samples from the same depth differ by more than 10 degrees (for example, Nos. 26, 26′ and Nos. 28, 28′.) a fact suggesting that, although the observational error in determining the direction of magnetization was less than 3 degrees, the amount of δ (and I) of a cubic sample is not always reliable when our aim is to determine the mean value of δ or I of a fairly widely distributed stratum of sedimentary rock of a certain given depth. It must further be noted that the collected samples corresponding to $0 \sim 14$ *cm* in depth contained the red-earth of Kantō-loam (which covers the Narita-bed), although not to a great extent. Since this fact shows that the upper parts of the Narita-bed were disturbed after deposition, most of the fluctuation of δ in the test samples collected from these parts may be the result of the above-mentioned disturbance. These circumstances render it safe to presume that the smoothed curve of the δ-depth relation alone represents the general tendency to change in δ with depth with regard to Fig. 8, we may say that the δ of the Narita-bed changes almost periodically with depth from its upper boundary to a depth of about 80 *cm*, the double amplitude and period with respect to depth being about 30° and 40 *cm* respectively, while from a depth of 90 *cm* to 145 *cm*, δ changes quasi-periodically with depth, the double amplitude and period being about 10° and 10 *cm* respectively. Taking various errors into consideration, however, the quasi-periodic change in δ with depth below 90 *cm* may not be trustworthy, although the marked periodicity in the stratum composing the upper 80 *cm* is sufficiently reliable. If then, the causation of natural remanent magnetism of a sediment is of such a mechanism as that discussed in §2 of this report, the δ corresponding to any depth ought to give the deviation in geomagnetic meridian at that time (from the present one), when the fragments composing the sediment were deposited, and consequently, that the δ-depth curve shows the general tendency of the secular variation in geomagnetic field during the period of deposition of the examined stratum. Unfortunately, however, since the velocity of accumulation of this bed cannot be determined at present, the time corresponding to the thickness of the stratum is unknown, whence it follows that only the mean value of δ and the amplitude of change in δ with depth can be adopted as measures of secular variation in geomagnetic field during Upper Pleistocene.

On the other hand, regarding the mode of change in inclination of magnetization with depth, the mean value of I of 63 samples[17] is 58°, and the amount of change in I with depth is clearly smaller than that in δ, the double amplitude of quasi-periodic change in I with depth being, generally, $10\sim15$ degrees, excepting the marked changes in samples drawn from 55 *cm* to 61 *cm* depths. If I also shows the geomagnetic dip at the time the examined sediments were deposited, the conclusion is that the mean geomagnetic dip during Upper Pleistocene was about 10 degrees larger than that at present (i.e. 48·°2[18] at the spot where the samples were collected), and that, generally speaking, the amount of secular variation in dip was fairly smaller than that in declination. The latter conclusion should not be unreasonable, because the amount of maximum change in declination and dip in the regular secular variation in geomagnetic field in London during the last four Centuries were, as is well known, about 34° and 8° respectively. In the I-depth curve, it will be further noticed that

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[17] Since five test samples (Nos. 5, 15, 19, 20, 22) were rendered useless after δ had been measured, determination of I was impossible.

[18] *Bull. Hydro. Dep. Japanese Navy*, 8 (1935).

the amount of I in most of the samples from 0 *cm* to 50 *cm* exceeds 60°, being from 60° to 70°, while in most of those below 100 *cm* it is less than 60°, being from 50° to 60° a result that may point to a tendency to secular variation during long periods.

§ 5. *Conclusion.*

In the foregoing paragraph, we assumed that the δ and I of the residual magnetization of the Narita-bed represented the declination and dip of geomagnetic force at the time that the fragments constituting the stratum were accumulated. Since, however, the bulk of the fragments composing the Narita-bed are fine sands, we naturally assume that this bed was formed not only through simple deposition of fragments through water, but through their flowing on the bottom of river outlets and landshelves after depostion[19] (their motion, dynamically speaking, being the "superposition of translation and rotation" of every particle). If so, then the question arises whether or not the direction of residual magnetization of a mass of fragments, the accumulation of which was the result of such mechanism as that just outlined, would still agree with that of the geomagnetic force affecting the fragments during their motion. (The experiments in progress in connexion with this problem are not yet concluded.) It seems possible, however, that the resultant magnetization of a mass of fine sands, containing a sufficiently large number of magnetized ferro-magnetic minerals, has the same direction as that of the magnetic force which affects the minerals throughout the whole period of their motion, provided we assume that the other various forces affect them haphazardly, although the intensity of resultant magnetization in this case would be less than that in the case dealt with in § 2.

On the other hand, the residual magnetization of a horizontal stratum, the accumulation of which seems to be the result almost solely of deposition through the sea, is now being studied in our laboratory. From the data of δ and I of various horizontal strata, which have been exhaustively studied from the geological point of view, are summarized, it is possible to get an idea of the general mode of secular variation in geomagnetic field in various districts through various geoloical ages, and by collecting a sufficiently large number of such data it ought also to be possible to trace the crustal motion of the earth during geological times from the data of direction of residual

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[19] See, for example, K. YABE, *Geol. Mag.*, 8 (1911); *Proc. Imp. Acad. Japan*, 5 (1930), 167.

magnetization of the folding stratum, provided the time of accumulation of the stratum is known.

It is the fervent hope of the writers to be able to contribute in future to our knowledge regarding the secular variation in geomagnetic field, and regarding the crustal motion of the earth, by studying the nature of residual magnetization of sedimentary strata.

In conclusion, the writers wish to express their hearty thanks to Prof. H. Tsuya and Prof. Y. Otuka for their useful advices from the geological point, and to Prof. T. Matuzawa, Prof. C. Tsuboi, and Dr. T. Hagiwara for much encouragement and valuable advices from the geophysical point side. The writers sincere thanks are also due to the Department of Education and the Hattori Hôkô Kai, with the aid of whose grant the present experiments were made possible.

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8. 水成岩の自然殘留磁氣 (序報)

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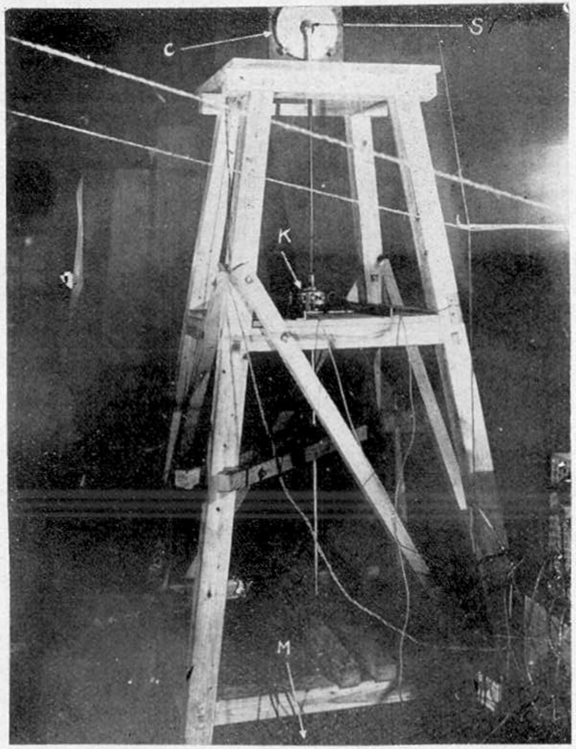
地球物理學教室 力武 常次

水平な堆積層の連續的に異れる深さの部分の試料の自然殘留磁氣の方向を測定する試みが最近 McNish 及び Johnson によつて爲された．筆者等は先づ沈澱物の自然殘留磁氣の表はす物理學的意味を模型實驗によつて確めた．即ち，地球磁場内冷却による熱殘留磁氣を持つ火成岩が細粒に破碎され，之等が水中を沈澱する際，地球磁場の作用によつて，結局水底の沈澱物の磁化方向は地球磁力のそれと一致する．猶ほ簡單な數理的考察の結果，一塊の沈澱物の磁化の見かけの强度とその沈澱物内の總ての磁化の算術和との比は $\tanh\frac{F}{2\lambda}\mu t$ で表はされる事が分る．但し F, μ, t はそれぞれ地球磁氣全磁力，强磁性細粒の磁氣能率及び水中沈降に要する時間を表はし，λ は細粒の廻轉に對する水の抵抗の係數である．

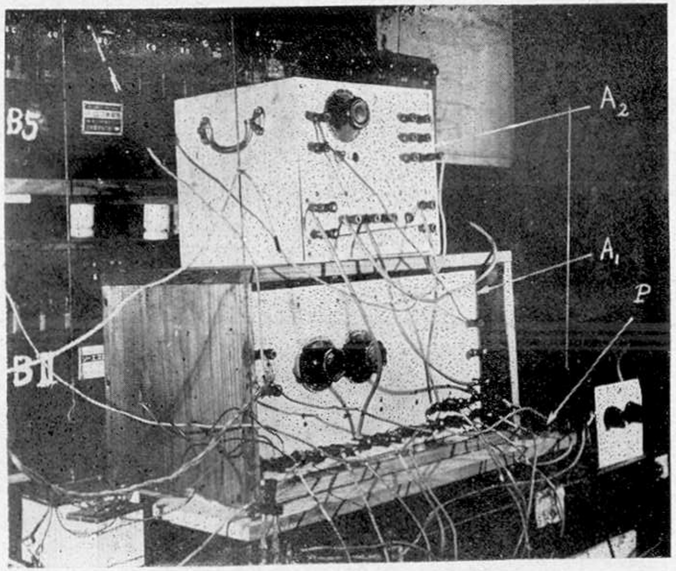
實際の水成岩の水平堆積層の殘留磁氣の測定に當つては，出來るだけ小さい試料に就いて高い精度で測定する爲に，本文第2圖に示す如き電磁誘導方式を採用した．即ち 1·5 cm 立方の測定試料を圓形線輪の中心線上に於いて廻轉し，線輪内の誘導電壓を試料の廻轉周波數に同調した高能率增幅器で擴大する．この出力側の電流を試料架臺に直結した廻轉整流器によつて整流し，之を檢流計によつて測定する．但し試料と廻轉整流器との位相差は任意の値に固定する事が出來る．上述の位相差を 0 から 2π 迄順次變へて最後の直流電流を測定した結果から，試料の磁化の强さ及び方向を決定し得る事は本文第3節に說明してある．此の實驗の主なる困難は測定試料の磁化の比强度が $10^{-6}\sim10^{-5}$ e.m.u. 程度の極めて微小なるが爲に，電磁的及び靜電的な外部擾亂を殆んど完全に除去すべき事にあつたが，多くの試みの結果，ほゞ滿足し得る狀態に達してゐる．

（震研彙報 第二十一號 圖版 永田・明石・力武）



The general view of apparatus for measuring the natural remanent magnetism of sedimentary rocks.

C, Double circular coil. *S*, Test-sample.
K, Rotating commutater. *M*, Motor.



The low-frequency high-gain amplifier.

A_1, Amplifier. A_2, Sub-amplifier.
P, Pendulum-system for escaping the external mechanical vibrations.

上述の如き測定裝置によつて，印旛沼畔に於いて採集した成田層細砂（自然狀態ではかなり良く凝つてゐる）の上部 1·5 m の部分の殘留磁氣を吟味した．試料は成田層をその關東ロームの境界面から 2 cm 毎の細層に分ち，各々の薄層の中央部から 1·5 cm 立方の試料を切りとつた．斯くの如き 72 個の立方形試料の殘留磁氣を順次測定した結果は，本文第 7 圖及び第 1 表に示す如く，偏角は平均に於いて現在の磁氣子午線から約 22° 東偏し，然も振幅に於いて約 30°，週期に於いて約 40 cm の著しい週期的變化を示し，之に對して伏角は平均に於いて約 58° であり（現在の地球磁場伏角の値より約 10° 大きい），且つ伏角の深さに從ふ變化は偏角のそれの如くには著しくない．若し之等の結果が，模型實驗の示す如き，又理論の期待するが如き，物理的意味を持つとするならば，成田層の偏角及び伏角は即ちその堆積の行はれた中上部洪積紀に於ける東關東地方の地球磁場の偏角及び伏角の永年變化の模樣を表はす事になる．殘念な事には堆積に要した時間が明瞭には分らない故に，地層の深さを時間の經過に換算する事は今の處困難である．

更に他の一つの問題は，測定に用ひた成田層は細砂であり，その堆積に於いては單なる水中の沈降といふよりも，寧ろ河口近くの陸棚に於ける渦流動によると見る方が自然である．然らば，細砂が水底に於いて，廻轉，平行移動等の不規則な運動を爲しつゝ堆積した場合も猶ほ地球磁力の影響が著しく作用するか否かゞ問題となる．この問題の解決は目下進行中であり，一方に於いて純粹に水中沈澱によると思はれる水平堆積層に就いて測定を續行し，地質時代に於ける地球磁場永年變化を追跡すると共に，他方に於いては，逆に之等の結果を物指として，變動せる地層に於ける殘留磁氣の分布から過去の地殼變動を推定し，從來の地質學的，地形學的方法による諸結果と照合するに到らしめたい希望である．

この研究は筆者の一人永田へ與へられたる服部報公會の研究援助費及び文部省科學研究費によつて遂行せられたものである．記して關係當局に厚く感謝の意を表する．