The Local Characteristics of Earth-Currents

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GENERAL INTRODUCTION

—PRESENT STATUS OF OBSERVATIONS AND INVESTIGATIONS OF EARTH-CURRENTS—

So-called absolute values of earth-current potentials, which are meant by the potential differences themselves measured by any suitable method and apparatus between two points on the earth's surface, generally consist of various kinds of potentials due to different causes and circumstances in different localities, but generally speaking, they can be divided into two parts; the one is caused by some agencies prevailing in the outer space of the earth, while the other by ones seated in the earth including a number of exteraneous effects near the electrodes.

The first part is mainly responcible for the so-called universal earth-currents, such as the daily variations, micro-pulsations, various kinds of irregular disturbances and so on. In recent years their general features have been fairly well understood and successfully explained by the increased observational data and the maxwellian fundamental theory of electromagnetic induction in the heterogeneous earth's crust [1]. However, our poor knowledges of the heterogeneous and generally anisotropic properties of the subterranean mass prevent us obstinately from our endeavour for the further precise understanding for the subject. Indeed, it can scarcely be doubt that the amplitude and phase of the universal earth-current potentials do not obey any simple law of distribution, but differ markedly from place to place. At the foot of a small hill apart about three hundred metres from the Kakioka Magnetic Observatory, we observed the mean amplitude in the eastward component more than two times as great as that observed simultaneously in the observatory's compound, while in the northward component the former was less than one half times the latter. As it is well known, the direction of potential gradient is generally restricted to a more or less fixed direction in spite of the corresponding changes of geomagnetic vectors in wide range [2] At some places, for example, the daily variation in the northward component does not apparently agree with that in theeas tward component of the horizontal magnetic field, but does follow much more closely the time-variations in the latter, while at other stations that in the eastward component is rather like that in the north component of geomagnetism itself reversed [3]

On the other hand, when the data are reported or discussed, it has been customarily assumed that the physical and chemical states of the subterranian mass considered, or at least its electric conductivity govering the current flow, may be independent of time, and time rate of its change, if any, may be negligible small compared with the period of earth-current variations considered. Unfortunately, moreover, we have had no long continued observations of earth-resistivity, and then it is too much to say that at present we have nothing about the mode of time variation, if any, of the conductivity, and further whether it may be connected to the other geophysical phenomena, or not.

Therefore, at first one of the most fundamental and burning questions for the present status in the study of the universal earth-currents is to establish a better and more skilful equipment for the observations of earth-current potentials and conductivities, and clear up their local characteristics so as to promote the validity of the prevailing theory to make better understanding of the world-wide features as well as of the possible connection to the other branches in science.

The second part of earth-currents has been supposed to be of relatively local character itself, even though we may have a possibility of a certain weak but rather constant general circulation of earth-currents [4]. Consequently, only a little analyses of these fields have been done in rather specified localities probably on account of some observational troubles; for example, electrode performances, faulty insulation, variable contact potentials and so on. It has been frequenty emphasized that absolute values of earth-currents are entirely of geophysically meaningless, because of their unavoidable introduction of a number of extraneous effects at electrodes. But at the present time it is certainly said that at least their geophysical significances for the time variations should be patiently and seriously discussed from various standpoints of views by using more recent data distributed in different localities and continued in longer periods, because we have had a few materials available for these specified problems. In fact, for example, accompanying with the occurrences of some earthquakes and volcanic erruptions, abnormal changes of earth-currents have been frequently reported, though not so systematically [5]. On these occasions it seems to be plausible to expect some abnormal changes of existing current flow, or creation of some new electric fields in the earth due to the heterogeneous distribution of the subterranian masses of which physical and chemical properties may vary gradually or suddenly with time.

On the other hand, Marc Deschevrens and others [6] reported a electric tide which might be produced by the tidal motion of the seawater in the permanent earth's magnetic field, though his currents were criticized by S. J. Mauchly as a mere of electrochemical potentials at electrodes [7]. However, we can not theoretically deny the possibility of above-mentioned like local currents due to the motion of seawater in the geomagnetic field. Recently the Admirality of Great Britains reported a natural and tidal earth-currents in the Clyde estuary and along the length of the English channel [8].

We have, moreover, a number of similar unsolved problems in this field of earth-currents, such as those of anomalous mountain effects [9], some characteristic features of electro-motive forces appeared across the boundaries of different geological formations and faults, irregular surface currents due to unbalanced atmospheric electric charges [11], and so on.

Thus, for all things considered, we are faced to many questions awaiting for further extended investigations, or to start anew to make fundamental researches parallel with more elaborate routine observations improving the measuring method and apparatus.

Meanwhile, the present auther has devoted himself in some years to the observations and studies of earth-currents to intend to clear up some of these burning questions of the subject and treat as many unsolved problems as he can. Some of results obtained were reported at several places, a few of them being published. The present paper contains some of his recent works which are divided in two parts; the first deals with mainly the universal potentials in respect to their local characteristics as well as their world-wide features, discussing some observational methods and techniques. Some results concerning the electrical conductivity may afford a new information to the studies of earth-currents as well as some allied branches of geophysics. In the second part are described some aspects of local earth-currents, one of which may suggest a possibility of some large scale changes of physical properties in the earth's interior.

References.

〔1〕 a. J. A. Fleming, "Terrestrial Magnetism and Electricity" (Physics of the Earth-VIII), 270—306 (1939).

b. S. Chapman and J. Bartels, "Geomagnetism" I, 417—445 (1951).

c. Wien und Harms, Handbuch der Experimental Physik, Bd. **25**, "Geophysik" I, 645—647 (1928).

d. 畠山久尚, 地電流 (岩波物理学講座)

e. J. E. Burbank, Terr. Mag., **10** (1905).

f. W. J. Rooney, Researches of Dep. Terr. Mag., Carnegie Inst., Washington, Vol. IX (1949) and XV (1949).

g. W. J. Rooney and O. H. Gish, Researches of Terr. Mag., Carnegie Inst., Washington, Vol. XVI (1949).

h. Kakioka Magnetic Observatory, Annual reports for 1934, 1935 and five years report of "Geoelectricity", 1934—1940.

i. H. Hatakeyama and M. Hirayama, Jour. Meteorol. Soc. Japan, **12** (1934), 449.

j. S. Chapman and T. T. Whitehead, Trans. Phil. Soc., **22** (1922); Terr. Mag., **28** (1923).

k. H. Ertel, Naturw., **20** (1932); Berlin, Veröff. Met. Inst. No. 387 (1932) and No. 391 (1932).

l. T. Nagata, Bull. Earthq. Res. Inst. **22** (1944), 1.

m. T. Rikitake, Bull. Earthq. Res. Inst., **24** (1946), 9; **29** (1951), 2.

〔2〕 Especially compare their vector diagrams of diurnal variations of earth-currents at Watheroo, Huancayo, Ebro and Nemuro with those of geomagnetism. ([1] a and Chapter II).

〔3〕 〔1〕 a and Chapter II.

〔4〕 a. K. Terada, Geophy. Mag., C.M.O. Tokyo, **9** (1935).

b. T. Hoshi, Memo. Kakioka Mag. Obs., **2**, No. 2—3 (1939).

〔5〕 a. J. Milne, Trans. Seism. Soc. Japan, **15** (1890).

b. K. Shiratori, Japan. Jour. Astro. Geophys., **2** (1924).

c. N. Noto, Japan. Jour. Astro. Geophys., **10** (1933), 2.

d. J. Suzuki and Inada, Proc. Imp. Acad., Tokyo, **6** (1933).

c. H. R. Scultetus, Zeit. f. Geophy., Heft 8 (1932).

f. T. Yoshimatsu, Memo. Kakioka Mag. Obs., **6** (1951), 1 and references given there.

〔6〕 a. M. Deschevrens, Terr. Mag. **24** (1918), 1; Terr. Mag., **24** (1919), 4.

b. F. B. Young, H. Gerrard, and W. Jevons, Phil. Mag., **40** (1920).

〔7〕 S. J. Mauchly, Ter. Mag., **24** (1919), 4.

〔8〕 Trans. Oslo Meeting, IATME Bull., No. 13 (1950), 132.

〔9〕 a. V. Oberguggenberger, Wien, Sitz-Ber., Ak, Wiss., Math.-natur. Kl., Abt. IIa, **135** (1926).

b. O. H. Gish, Trans. Amer. Geophys. Union, 14th Annual Meeting (1933).

c. J. Koenigsberger u. O. Hecker, Zeit. f. Geophy., **1** (1925).

〔10〕 a. H. Hunkel, Zeit. f. Pract. Geologie, **36** Jahrg. Heft 9, 1928.

b. H. Haalk, Ger. Beit. z. Geophysik, Bd. **23** (1929), 106.

c. S. Sakuma, Bull. Earthq. Res. Inst., **30** (1952), 25.

〔11〕 R. Ambronn, "Methoden der angewandten geophysk", 116 and references quoted there.

CHAPTER I

THE MEASUREMENT OF EARTH-CURRENT POTENTIALS AND ITS RELAIABILITY

§ 1. Introduction

Superficially the method of the earth-current measurement is simplicity itself and does not differ in principle from an ordinary physical measurement of potential difference in first kind or second kind of conductor. We must, however, take seriously into considerations following some characteristic points in these field of science.

In the first place, the earth may be probably considered to be a complex semiconductor; especially the electric state of its upper layer, in which some of the main parts of the measuring equipments are installed, is mainly governed by its constituents and quantities of electrolytic substances contained. And generally it is apt to vary over rather wide limits beyond our control, so that it tends to rise various extraneous effects at the electrodes. Much efforts, therefore, have been done by many investigators to get electrodes free from any such contact potentials, but, unfortunately no satisfactory success has been done, at least in the permanent installation, though the non-polarizing liquid electrode is surely superior for the temporary observation in respect to its small contact potentials. We must, therefore, allow for some of these contact potentials and try to minimize them as possible as we can, and more practically as constant as possible compared with other portions of potentials considered [12]. Although these statements seem to be rather negative for us, in practice even this last requirement is not so easily realized as it is the case. These anomalous variations, however, are used to be distinguished from other portions of potentials by comparing two or more independent bases in the same direction. One of the most fundamental and urgent necessity for earth-current measurement is to improve the method of electrode installation to be suited for the permanent routine observation at the very place.

As to other requirements for the satisfactory measurement, similar careful practices must be done for the installation of the underground wires protected from any fault insulation and natural corrosions, and sometimes for the construction of some suitable shaped electrodes of small contact resistances compared with that of the remainder of the circuit. These two requirements seem to be more or less easier to artificially controll than contact potentials, but various initial testing and practice of the former should be most carefully carried out as well as that of electrodes themselves, because of the difficulty of testing their correct order of function at any time when once burried in the ground.

Besides of these points, various kinds of minute techniques may be required in practice for the method of recording and installation, corresponding to the apparatus used and the different geological, tophographical and hydraulic states at the very station. From these points of views, in this chapter are given some observational simple experiments and notes on the essential points, on which the accuracy of the measurement depends mainly but so systematically have not been treated, and general description of the method and equipment made at the Kakioka Magnetic Observatory through which important data used in this paper are supplied.

§ 2. Some experiments and notes on the measurement of earth-current potentials

1. *Base length*

Generally speaking, it is difficult to say in a word how long and in what directions the base lines should be installed. The matter differs for different subjects of investigation and localities of the subterranian structure in the neighbourhood of the station. For instance, at the ordinary observatory recording of such sorts of earth-currents as the world-wide and rather short period variations, one to ten Km lines running in northward and eastward directions are usually installed [13]. On long lines, running scores or hundred kilometres long, we have some advantages in such points as the negligible small electrode potentials compared with the universal earth-current potentials, low sensibility of instrtuments used, more representative features of the current flow in the vicinity of the station and so on. For the permanent routine work, however, it may be more desirable to construct cheaply and to keep permanently the lines in satisfactory conditions, even it is required to use somewhat higher sensitive instruments or recording apparatus. Hence, from only this point of view, and further from the need of uniformity of the structure in the area included in the measurement, it may be apparently said that the more the line is short, the better it goes. Of course, we may frequently encounter with troublesome and difficult events to overcome for the satisfactory measurements of small quantities considered [14], if unduly short lines were operated without any sensible precaution against various extraneous effects. In order to harmonize those merits and failures, at ordinary observatory it may be safe to choose the base length as long as a few kilometres at most, provided carefull precaution and patient endeavour for maintenance of all parts of the equipment.

On the other hand, at a place where the subterranian structure is so complex that the distribution of its electrical conductivity becomes heterogeneous or even anisotropic, we may have a few base systems with different base length and directions of the lines. The need of these auxiliary equipments can be justified by the precise knowledge about the distribution of the current flow in respect to that of conductivity in both horizontal and vertical directions. A more important point in some sense is that these duplicate or multiple systems can manifest themselves as a powerful tool for the investigation of local, or sometimes regional characters of earth-currents.

2. *Geomagnetic and atmospheric electric induction on the overhead line.*

It is unquestionably desirable to use the highly insulated cable lines for connection between the recording instruments and electrodes, because when the aerial lines are used the following points should be cared of; electromagnetic induction on them due to the time changes of the geomagnetic field or mechanical motion of the lines in the permanent geomagnetic field, electrostatic induction effects of atmospheric electricity, and some mechanical damages of leading wires and their supporters. But frequently are used the overhead lines instead of cables, because of the expense entailed and serious injury upon the crops.

〔A〕 *Geomagnetic induction on the line*

(i) Induction due to the transient geomagnetic field changes.

Two test base lines were set in the compound of the Kakioka Magnetic Observatory, one of which formed a vertical rectangular loop of the area 100 m^2 with its overhead line and the ground, while an insulated wire for another base was laid down on the surface of the ground in a straight line, running in the same direction as the former base. Earth-current potentials for each base were photographically recorded by means of two sensitive galvanometers with the same instrumental constants as shown in Table 1.

Table 1.

Galvanometer	Period	C. D. Res.	Coil Res.	Current sens.	Scale value
	7.5^s	110Ω	104Ω	$1.1.10^{-9}$amp/mm	$2.8.10^{-5}$volt/100m/mm
Speed of Recording	6.0 mm/minute				

Considering the fact that the more the magnetic field changes quickly, the more induced current in a loop becomes large, the amplitudes of the same short period variations with their time duration ranging from ten seconds to one minutes were read out from two records. The amplitudes of the selected variations are given in three groups in Table 2.

Table 2. Comparison of amplitude of potentials, A, of the universal short period variations observed with two sets of lines; the one makes a vertical loop with the ground and another with no loop.

A: expressed in mm unit.

Range	A_γ	A_0	Range	A_γ	A_0	Range	A_γ	A_0	Mean	A_γ	A_0
0—5.0	4.0	4.0	5.1—10.0	5.2	5.3	>10.1	12.1	12.3	0—5.0	3.81	3.79
	2.0	2.1		7.0	7.0		13.9	14.0	5.1—10.0	7.14	7.16
	5.0	5.0		6.0	6.0		10.1	10.3	>10.1	14.56	14.54
	2.8	2.8		7.0	7.0		10.2	10.2			
	3.0	2.8		8.0	8.0		22.8	22.5			
	5.0	5.0		6.0	6.0		16.9	16.7			
	4.0	4.0		7.0	7.0		15.8	16.0			
	4.0	4.0		8.1	8.0		14.0	13.9			
	5.0	5.0		10.0	10.1		11.0	11.0			
	3.3	3.2					22.2	22.0	Total Mean	8.75	8.74
							11.2	11.0			

A_γ: Line with a loop. A_0: Line with no loop.

As it had been expected before the experiment, we could not detect any appreciable difference in amplitude between two sets of base lines as far as the accuracy of the measurement was concerned. We could also find no phase differences between two records in the limit of error, four seconds. From the theoretical standpoint of view, however, the magnitude of induced electromotive force, V, in a coil due to the varying magnetic force, H, which passes perpendicularly through the coil can be expressed as follows,

$$V=S.N.\frac{dH}{dt}.10^{-8}\text{ volts},$$

where S and N are the area and number of turns of the coil. Then, in the case of the above experiment, V can be calculated as $V=10^{-7}$ volts for $S=100\,m^2$, and $4.5.10^{-6}$ volts for $S=4500\,m^2$, respectively, when $N=1$, $\frac{dH}{dt}=10^{-5}$.

The maximum area of the loop in the sense said above is approximately $4500\,m^2$ for the regular east base line of one and half kilometers long at Kakioka. At any rate, therefore, it is clear that induction effect due to the varying geomagnetic field with period as low as ten seconds is not so important.

(ii) Induction due to the motion of the line in the permanent geomagnetic field.

On the other hand, we have an another equivalent induced electro-motive force due to the relative motion of the overhead line to the permanent geomagnetic field when the wind and other mechanical forces act to oscillate the line in favourable conditions. The line is more or less flexible and not always bound on the insulators in the same manner at each point and, moreover, the external mechanical forces, of which most effective one is wind, usually change their direction and magnitude with respect to time and space. Consequenly, the roop formed between the line and the ground changes its area with time, and then the induced E.M.F. will become so irregular and indefinite that it would not be so easy to grasp the exact mode of the matter. Neverthless, the order of magnitude of the induced E.M.F. may be estimated as follows. For example, at the Kakioka Magnetic Observatory we have an eastward line of one and half kilometer long as above-mentioned of which wire is fixed at fifty one points on the insulators. The mean area of each segment of the line formed between it and the horizontal line connecting two consecutive points amounts to about $3.10^4\,cm^2$. For simplicity's sake, if we assume that each segment has the same area said above and as a rigid body oscillates about the horizontal axis in the plane perpendicular to the geomagnetic meridian with the same phase, then the induced E.M.F. in the whole line can amount to the order of millivolt. The magnitude estimated in this idealized case is not so small enough to be neglected compared with other kinds of universal earth-currents. In practice, however, such an idealized uniform condition can not be realized, and moreover, owing to the rapidness of the motion of the segment, only a few percent of this amount will be actually recorded by an ordinary galvanometer or such like apparatus with its proper period of a few seconds. Actually, during the long period of observation at Kakioka we could not detect any remarkable trace on the electrogram even when rather strong wind blew, It is necessary. however, to take these effects into account when the small and rapid variations such as micropullsations comparable with those of the earth ground are to bê recorded.

〔B〕 *Atmospheric electric effects upon the line*

Accompanying with the disturbances in atmospheric electricity in such bad weathers as thunderstorms, heavy rains, snowfalling, solid precipitation and etc, we have frequently recorded some irregular and rather larger variations in both components at Kakioka. The amplitude of these variations differ markedly at different localities, and depend upon the prevailing meteorological conditions, topography, height of the overhead line and etc. On the meteorologically calm days, however, no such remarkable abnormal changes can be observed. Therefore, such kinds of local effects due to the changes of atmospheric electricity, of which major part may due to the antenna-earth current, are only occurred in very specified time intervals, and then give no serious handicap for the discussion of the general aspects of earth-currents.

Generally speaking, however, we have some possibilities to suppose more extended spatial correlation, or rather world-wide relation between earth-currents and atmospheric electricity through the transfer of electricity between the air and the earth, but the discussion for these problems are out of the scope to be treated in the present chapter.

An example at the Kakioka Magnetic Observatory is shown in Fig. 1, which was accompanied with the precipitation of hailstone of moderate intensity. The maximum ranges of this variation recorded by some lines are given in Table 3. It shows how much differ these variations at different localities. In reference to this, the topographical and geological features near the observatory are shown in Fig. 2 together with the site of the observatory. For convenience's sake for the further statement, some of the regular and temporary base lines drawn in the figure are numbered and their base lengths are also given in Table 4.

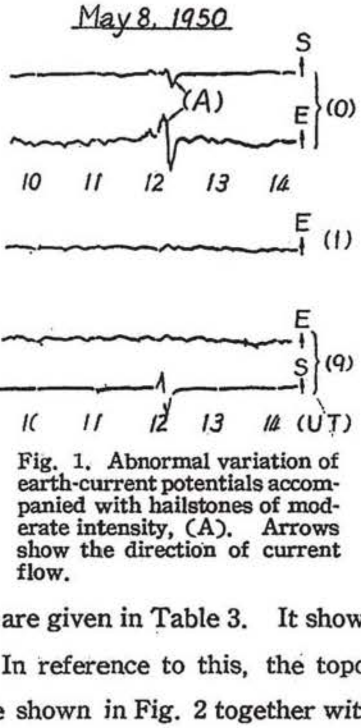

Fig. 1. Abnormal variation of earth-current potentials accompanied with hailstones of moderate intensity, (A). Arrows show the direction of current flow.

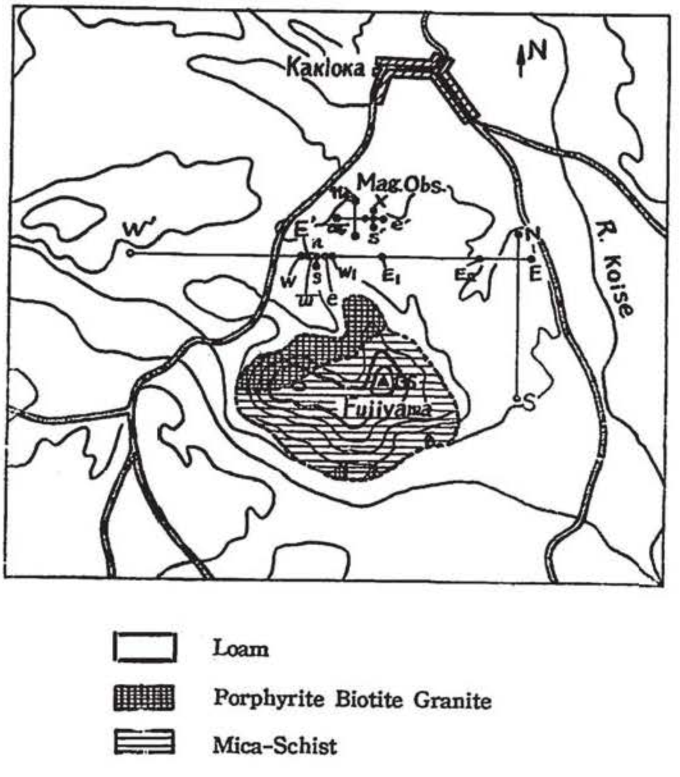

Fig. 2. Arrangement of regular and temporary earth-current lines, and geological and tophographical sketch near the Kakioka Magnetic Observatory.

Table 3. Local abnormal variations of earth-current potentials accompnied with hailstones at Kakioka

Base line*	Base length		Max. range, mV/km		Amplitude ratio of universal currents	
	EW	NS	EW	NS	EW	NS
(0)	1.50km	1.10km	79.8	36.8	1	1
(1)	100m	100m	0.6	—	0.70	0.92
(9)	100m	100m	0.6	160.5	1.24	0.64

* Refer to Table 4.

Table 4.

Base line		Designated number of base lines
Component	length	
EW NS	1.50km 1.10km	(0)
ew ns	100m 100m	(9)
e'w' n's'	100m 100m	(1)
E_1W_1	350m	(3)
E'W'	1.35km	(2)
E_2W_1	1.05km	(4)
e_1w_1 n_1s_1	210m 210m	(5)

In connection with this phenomena, it should be remembered that some abnormal variations in bad weather are often mistaken as those due to atmospheric electricity, but they are really caused by fault insulation of the line and insulators.

3. *Insulation*.

It is one of the most important requirement for the satisfactory measurement of earth-currents to keep the total circuit in adequate insulation throughout the measuring period notwithstanding any unexpected changes in the natural and artificial circumstances under which the measurements are regularly carried on. The difficulties in obtaining adequate insulation are mainly encountered in the field equipments, that is, overhead and underground lines, together with insulators and leads joining the electrodes to the lines. Sometimes the faulty insulation of the overhead lines may be introduced unconsciously by touching and injuring their coating with something like branches of trees, except the gradual decrease of insulation resistances of the lines and insulators due to the changes of their materials over a period of years. As to the underground lead joining the electrodes proper to the lines, the matter is very troublesome, for its insidious effects are influenced by various kinds of changes of physical and chemical states of the surface layer of the earth. The following experimental results may give an idea of the order of error to be introduced in the measurements due to faulty insulation,

〔A〕 *Error due to faulty insulation of the line and insulator.*

(i) Simple circuit.

The simplest case of measuring arrangements will be considered; more complicated ones can be treated in the similar manner. In Fig. 3, the overhead line is supposed to be earthed between Px and Qx through the total-resistance X, then the current i_g flowing in the line can be expressed as follows;

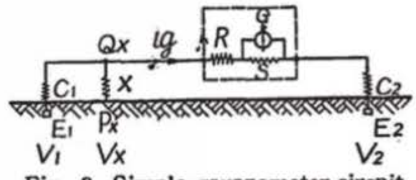

Fig. 3. Simple gavanometer circnit.
R: High manganin séries resistance.
G: Coil resistance of galvanometer.
C_1, C_2: Contactresistance at the electrode E_1 or E_2.
S: Universal shunt resistance.

$$i_g = \frac{v}{R_0}\left\{\frac{X+C_1\frac{v_x}{v}}{X+C_1(1-\frac{C_1}{R_0})}\right\} \equiv \beta\frac{v}{R_0},$$

$$v=v_1-v_2, \qquad v_x=v_X-v_2$$

$$R_0=R+\frac{GS}{G+S}+C_1+C_2$$

where v_1, v_2 and v_x are earth-current potentials at the points of electrodes E_1, E_2 and earthed point Px; C_1 and C_2 the contact resistances at the respective electrodes. Since the condition $\beta \leqq 1$ is usually fullfied for $C_1/R_0 \ll 1$ in practice, though the case of $v_x > v_1$ when $v_1 > v_2$ can be possible along some path of the overhead line, i_g will become generally small compared with the case when the line is kept in perfect insulation, i.e.,

$$i_g < (i_g)_\infty = \frac{v}{R_0}$$

It is to be noted that the reduction coefficient β is almost determined by the ratio of the contact resistance at the electrode to the insulation resistance at the pole or some point on the line.

(ii) Model experiment.

These considerations were illustrated in the following simple model experiment of which arrangement is shown schematically in Fig. 4. Two similar rectangular copper electrode P_1 and P_2 (2.0 cm × 2.0 cm) was immersed at a horizontal distance l apart in the concentric $CuSO_4$ solution in which an approximately uniform electric field was set up between copper electrodes E_1 and E_2. All splices joining P_1 and P_2 to heavy rubber doubly coated wires m_1 and m_2 was thickly coated by high quality pitch to be impervious to the

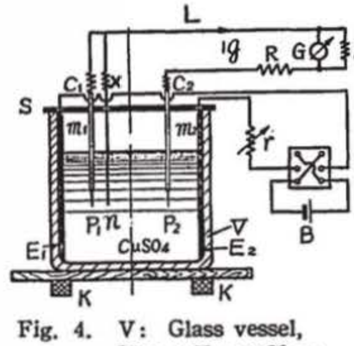

Fig. 4. V: Glass vessel, 18cm × 21cm × 21cm.
S: Wooden plate cover.
E's: Copper plate electrodes.
m: Heavy rubber wire.
p's: Copper plates.
n: Copper wire.
K: Porcelain insulater.
$1=P_1P_2$, $x=P_1n$.

solution. A copper wire n, 1 mm in diameter, was then dipped into the solution at the distance x from P_2 on the line joining P_1 and P_2. The current i_g passing through a galvanometer G, its sensibility being $1.50 . 10^{-8}$ Amp. per mm and period 2 seconds, was measured for two cases when n was connected to the base line L and disconnected from it, corresponding to the actual cases of faulty and perfect good insulation. Some examples of the results thus obtained and calculated values by the expression of i_g in (i) are given in Table 5's. The example A shows the linear functional relation between i_g and x. The examples B_1 and B_2 were carried out to check the asymptotic variation of i_g by increasing X/C_1, all tabular values of currents being expressed by divisions of the deflection.

Table 5A. Relation between i_g and x

$(i_g)_\infty$	x(cm)	i_g	
		obs.	cal.
18.5	6.1	16.4	16.6
18.4	5.3	15.5	15.6
18.4	4.4	14.9	14.7
18.4	2.9	13.1	13.1

$X=17\Omega$

$C_1=C_2=14\Omega$

$R+\frac{GS}{G+S}=11000\Omega$

$l=8.0$cm

one div$=0.6.10^{-3}$ volts.

Table $5B_1$. Relation between i_g and X/C_1

$X_0(\Omega)$		5.10^2	$1.5.10^3$	$3.5.10^3$	7.10^3	2.10^4
i_g	obs.	16.1	17.0	17.8	18.2	18.4
	cal.	15.9	17.2	17.8	18.3	18.4
$(i_g)_\infty$		18.8	18.8	18.6	18.7	18.6
X/C_1		0.75	2.20	5.10	10.15	29.0

$C_1=690\Omega$, $R=14000\Omega$, $l=8.0$cm, $x=5.5$cm

$X=X_0+Cn$, $Cn=17\Omega$; contact resistance at n.

Table $5B_2$.

$X_0(\Omega)$		10^2	5.10^2	10^3	5.10^3	10^4	5.10^4	3.10^5	10^6
i_g	obs.	13.3	14.0	14.8	17.0	17.8	18.5	18.9	19.0
	cal.	13.2	14.0	14.7	17.0	17.8	18.7	19.0	19.0
$(i_g)_\infty$		18.9	18.9	18.9	18.9	18.9	19.0	19.0	19.0
X/C_1		0.04	0.17	0.34	1.67	3.32	16.7	99.5	332

$C_1=3014\Omega$, $R=14000\Omega$, $l=8.0$cm, $x=4.5$cm.

In the above experiments contact resistances at P_1 and P_2 were assumed to be equal and one half of the effective resistance between P_1 and P_2. The contact resistance at n was calculated in the same way by subtracting the contact resistance at P_1 from the effective resistance between P_1 and n. The good coincidence between the experiment and calculation proved that the uniform electric field was fairly well established in the solution, and it was not disturbed by the arrangements of the experiment and the current flowing in the circuit, showing no appreciable polarization effect at electrodes. Indeed, as it is seen in Fig. 5 the potential drop between the electrode P_1 and n (V_1-V_x) was increased linearly with the increasing distance between them.

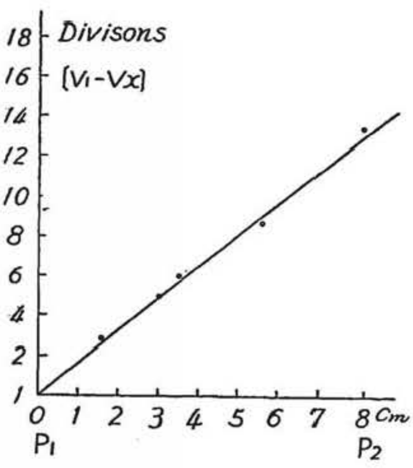

Fig. 5. Potential drop between P_1n, (V_1-V_x), and distance between P_1 and n.

(iii) Field experiment.

A similar field experiment was carried out for the east component of the universal earth-currents at Kakioka. Some experimental details are given in Table 6 where all resistances were measured by the Kohlrausch's bridge, notations being to be referred to Fig. 3 or the expression of i_g.

Table 6.

C_1	X	Distance E_1 E_2	Distance E_2 P_X	R_0
$1.2.10^3\Omega$	$1.2.10^3\Omega$	100^m	57_m	$301.1.10^3\Omega$

The decreament of the amplitude of the short period variations when X was connected to the line is clearly seen in Fig. 6, where the amplitude is plotted referred to the same variations recorded by an another independent adjacent eastward line of equal length as a reference base. From these two linear relations we obtained the coefficient $\beta=0.80$, while the calculated value is $\beta=0.79$.

When the measurement is under fear of low accuracy by large contact resistances or low insulation resistances, the scale value, or voltsensibility of the electrogram is frequently calibrated by impressing the known electromotive force in the total circuit including the earth instead of substituting it only across the galvanometer unit in place of lines (Fig. 7). In the former method of scaling, scale value is apt to be disturbed

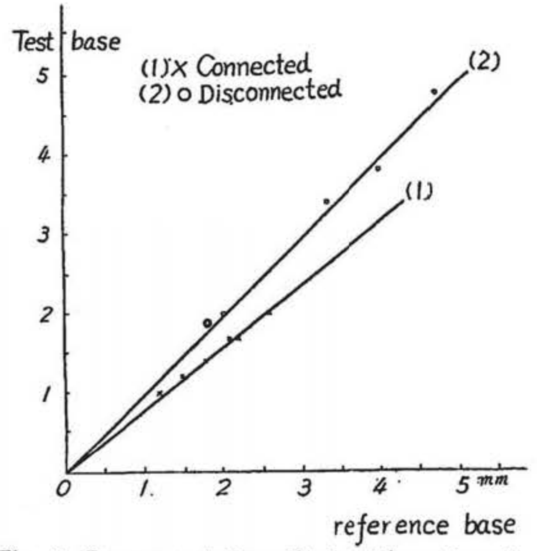

Fig. 6. Decreament of amplitude of the universal earth-current potentials when the line is artificially earthed through the insulating resistance X.

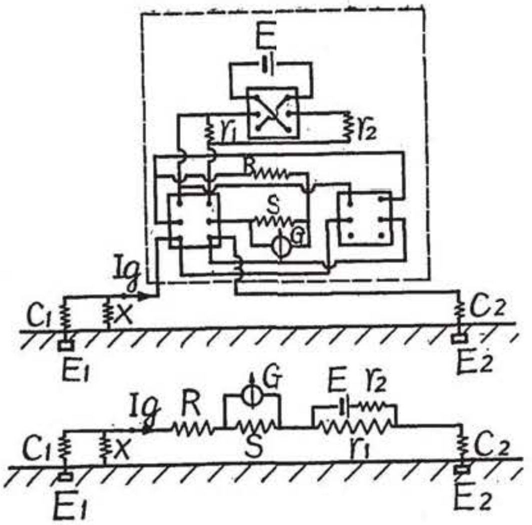

Fig. 7. Galvanometer method with the calibrating circuit for the total resistance including the earth.

during the time of operation by the short periodic fluctuation of the universal currents themselves, and sometimes polarization currents. If we keep the resistance of the circuit in such a way that, $R+\frac{GS}{G+S}+\frac{r_1 r_2}{r_1+r_2} \gg C_1+C_2$,

the scale value determined by the latter method becomes approximately independent of contact resistances C's and X.

At any rate, from these considerations it can be concluded that the contact resistances at electrodes should be minimized as possible as we can in order to avoid both unstable potentials due to the variations of contact resistances and insidious errors caused by the faulty insulation of the lines and insulators, provided no unstable contact potentials are consequently introduced in the circuit.

[B] *Errors due to faulty insulation of measuring apparatus.*

Although it seems apparently to be much easier to keep the measuring apparatus in the room than to keep the outdoor equipments in adequate insulation, we must take care of the occurrence of faulty insulation effects during the long period of observations, especially when potentials are to be recorded photographically by means of sensitive galvanometers in a dark room. Most of events happened at Kakioka and other places were due to the unsatisfactory conditions of the galvanometer set, that is, damage of insulation between two terminals of a galvanometer, leakage through the tripods and leading wires connected from the shunt resistance to the galvanometer, and so on. These unsatisfactory conditions were all caused by the accumulation of very small dust particles on the surfaces of insulators in the course of long time recording in a dark room, of course, the events beeing promoted by the moisture content in the air. The rest minor parts were due to the faulty insulation at terminals of various connections and natural decreament of insulation resistance of insulators used.

These insidious errors due to faulty insulation, however, can be detected and preventable by the effort of constant and careful cleaning the main portions of galvanometer sets and all terminals in the circuit and checking for the constancy of daily scale values, jointly using the suitable devices for protecting the all apparatus from the dust accumulation, variations of air humidity and temprature. For example, coating bared portions of the leading wire near the terminals and tripods with high quality liquid insulator, sealing the wax on the surface of concrete block on which the galvanometers were set, and sometimes setting the galvanometers in a suitable thermostat, or in a semi-underground house in which temperature and humidity were kept approximately constant, and etc., were all experienced to be simple and useful for the present problem.

At last, it is not to be forgotten that in some case all dry cells or batteries, usually 1~6 volts, used in the calibrating circuit or potentiometer circuit should be carefully insulated.

4. *Contact resistances and their time variations*

Some examples of the effective contact resistances between two electrodes and their time variations measured at Kakioka are given in Table 7, which were all measured by the Kohlrausch's bridge with the alternating current source of ten thousand cycles. As is seen in the table, their mean values extend from the minimum two hundred ohms of NS component to the maximum seven hundred ohms of ns, while for each base the maximum deviation from its mean in the course of the year approximately amounts to 20%. Thus, in this case the effective contact resistance of EW, or ns component above-mentioned only amounts to less than one percent of the high series resistance inserted in the circuit, and at least the seasonal variations of all components can be neglected in the measurement of potentials. As it is well known, the contact resistance is principaly controled by the surface area of the electrode, closeness of contact between the surface of the electrode and its adjacent part of the soil, amount of moisture content, kinds of salts contained in it, and so on. Then, at different places and by different process of installation, we may have sometimes so large contact resistances, or their remarkable time variations that the accuracy and stableness of the measurement are principally decided by the unavoidable changes of chemical and physical states of the ground. In practice, however, it may be more important to keep the constant contact resistance in long period than to make it as small as possible, if we can not realize simultaneously these two conditions. Any extraneous effect at the electrode, which may be accidentally introduced by making mechanically the contact resistance as small as possible, should be avoided, because any unstable contact potential is usually much troublesome to treat than to avoid the effect due to a rather large contact resistance.

Table 7. Effective contact resistances (R) in some indepndent base lines at the Kakioka Magnetic Observatory. ($\times 10^3 \Omega$)

Date		1948 19/IV	29/V	28/VI	31/VII	28/VIII	(1) 31/VIII	(2) 16/IX	(3) 17/IX	19/IX	30/X	24/XI	8/XII	1949 22/I	22/II	23/III
Base* line	EW	0.64	0.62	0.56	0.60	0.63	0.60	0.55	0.45	0.48	0.54	0.51	0.54	0.55	0.60	0.63
	ew	0.57	0.55	0.50	0.49	0.44	0.45	0.42	0.44	0.44	0.49	0.50	0.53	0.58	0.59	0.60
	ns	0.82	0.78	0.67	0.64	0.59	0.59	0.54	0.56	0.57	0.60	0.65	0.68	0.75	0.75	0.76
Remarks		(1) affer rain; (2) heavy rain; (3) affer heavy rain														

* Refer to Table 4.

Referring to the further continued data [15], the contact resistance generally undergoes a rather simple seasonal variation with a maximum in the interval from the later spring to the early summer, and a minimum in the autumn months, though some irregularities are found in the period from the later summer to the early autumn (Table 7). And the mean amplititude of the seasonal variation seems to make no remarkable change from year to year as far as these electrodes are concerned. On the occasions of heavy rains, however, the contact resistance of the regular eastward base, (O)-line, decreased rapidly and recovered gradually, of which mechanism may be connected to the irregularities appeared in the period from the latter summer to the early autumn above-mentioned.

Although we have no need in this chapter to touch the further details of the contact resistance, it may be worthy to see a similar seasonal variation of the earth's

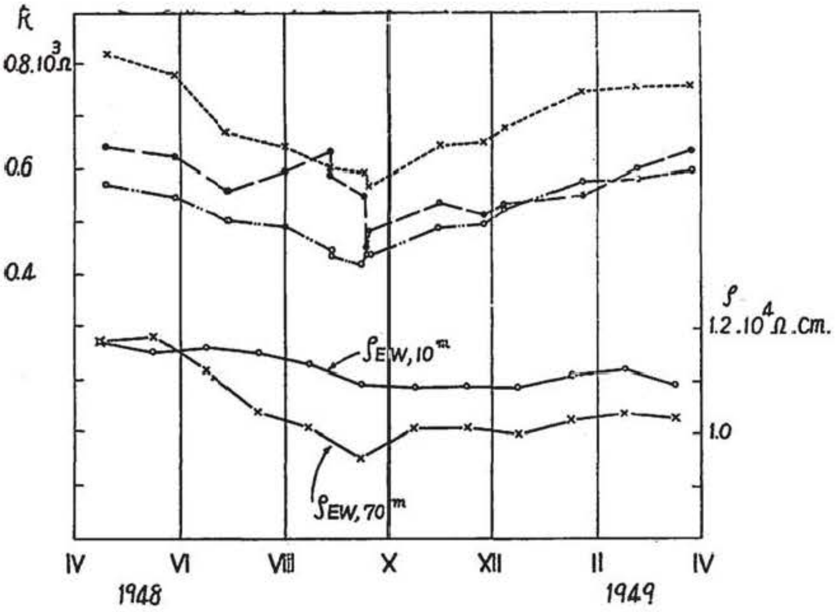

Fig. 8. Seasonal variation of effective contact resistances and earth-resistivities at Kakioka.

resistivity of the upper layer of the earth. In Fig. 8 are shown the seasonal variations of both effective contact resistances (R) and resistivities (ρ) which were measured by the method of Wenner-Gish-Looney with a megger type ratiometer (L-10 type resistivity meter by the Yokogawa Electric Works). In the vicinity of the observatory the uppermost layer up to the depth about one hundred meters below the surface has a rather uniform resistivity of about $10^4\Omega.\mathrm{cm}$. It may be expected from this figure that the seasonal variation of the contact resistance can be principally controled by that of resistivity, but depends locally upon the physical and chemical states in the adjacent part of the ground to the electrodes.

5. *Variations of contact potentials*

From the electrochemical point of views, there should be no potential difference existing between two electrodes which are identically equal in their phycical and chemical states and made to contact with a homogeneous and isotropic medium. However, this is not practically realized in earth-current measurements, even if we use two identically equal electrodes. Therefore, it is a common sense among the earth-currentists that one of the most important points in the earth-current measurement is how to minimize the contact potentials and how long to keep it in a constant state, because it is practically impossible to burry the electrodes in the ground without some contact potentials between any two electrodes. In order to get a pair of electrodes to meet these troublesome demands, skilful methods have been proposed by some authers [16]

In our routine works it was frequently effective in practice to burry both electrodes in some artificially prepared substances in place of the natural soils. At Kakioka two electrodes were burried in large volume of charcoal fine gravels, of which some details of performance will be described in the next paragraph. For an another example, at Owashi ($\lambda=136°$ 12'E, $\varphi=34°04'$N), a branch station of the Magnetic Observatory, by replacing the very sandy ground of about three cubic meters with the fine clayey soil, in which double-carbon electrodes were installed, large contact potential variations were almost disappeared in the eastward line (Fig. 9a). Before this reconstruction of electrodes the record of this base showed the very typical and large contact potential variations due to the rainfall as shown in Fig. 9a. For the northward base, however, there was seen no remarkable improvement, because we made no replacement of soil for the south elec-

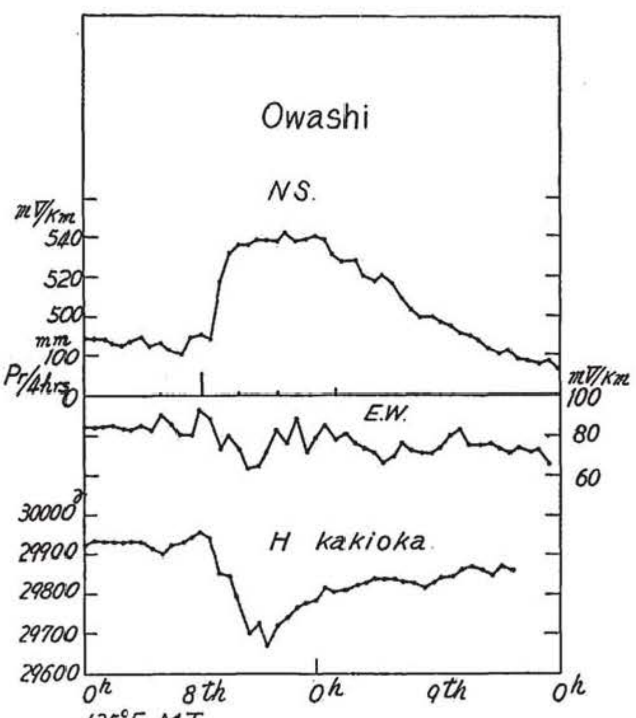

Fig. 9a. An example showing improvement of electrode performance by replacing the natural ground with other substances at Owashi.

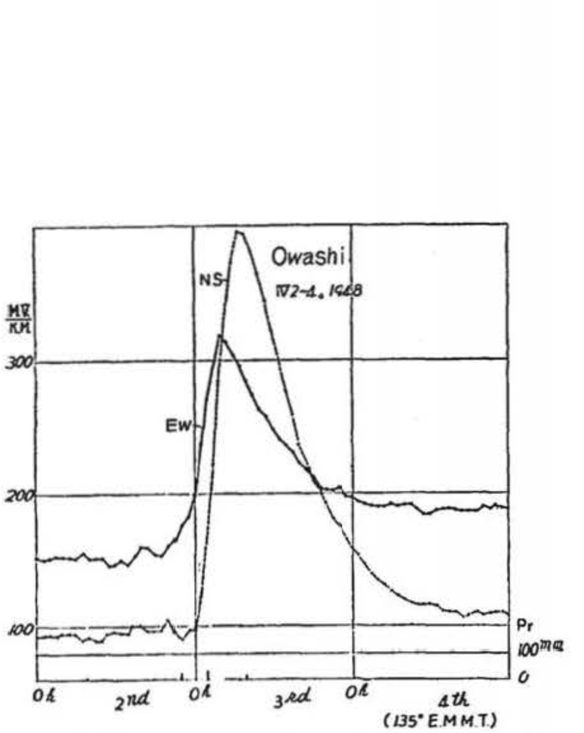

Fig. 9b. Large and rapid abnormal changes of earth-current potentials due to rainfall at Owashi.

trode only. This improvement for the eastward base may be explained by the very small change of moisture content in the carefully compacted clayey volume said above due to its smaller coefficient of permeability compared with that of the very sandy part surrounding it.

An another example of similar, but more elaborate electrode performance was carried out at Kakioka for the equipment of the sub-regular eastward line, (2)-line, of which recording was started in April, 1950. This base was situated on the line extended westwards of the regular eastward line, (0)-line, and its east-pole was set down about ten meters eastwards to the west-pole of the latter. The electrode used is schematically shown in Fig. 10. Two carbon rods were burried in charcoal gravels, which were carefully packed in a hollow concrete cylinder enclosed by sand layer, and connected parallel with the overhead line. All outer surface of the concrete cylinder and its cover were coated with pitch to protect the vessel from the percoration of moisture from the surrounding soil, except the bottom side. For the underground leading wire was used the lead cable wire. As it is

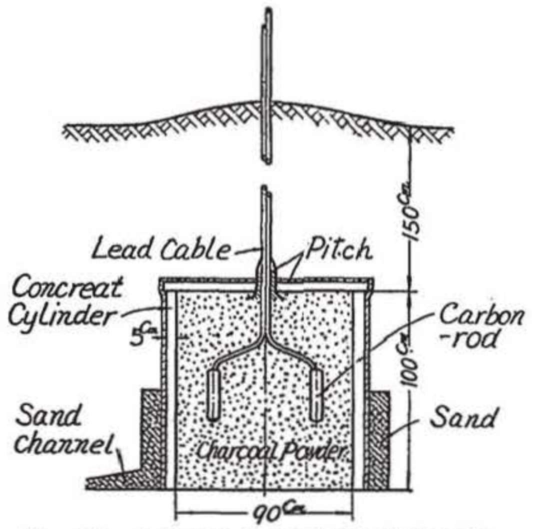

Fig. 10. A "pot" electrode burried upside down.

seen in Fig. 11, variations of daily mean values of potential gradients observed by this line and the regular EW line, (0)-line, are fairly in good accordance each other in spite of the latter base being set down about sixteen years ago. As a whole,

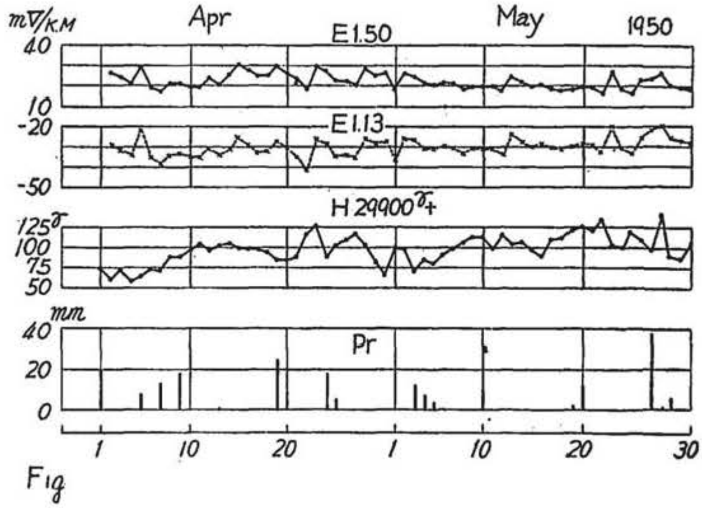

Fig. 11. Comparison of daily mean values of two independent base lines with different electrodes, "pot" electrode and copper-charcoal electrode.

they made also no appreciable long period variations due to some extraneous effects near the electrodes, showing hardly connection with neither the corresponding daily means of the horizontal intensity of geomagnetism, nor amount of rainfall.

These examples, therefore, tell us that if we can pay our careful and proper considerations to both construction and installation of electrodes, and together with to the circumstance of the place, we can expect a possibility to get a fairly good condition of electrodes, and consequently stable contact potentials.

Concerning to the electrode performance, it must be also noted that though it is frequently less emphasized to protect splices joinning the underground wire to the electrode proper from permeation of soil moisture, remarkable contact potentials can be appeared especially when the soldered joints are imperfectly exposed to the ground. Referring to this point, the following simple experiment was carried out. By the same arrangement shown in Fig. 4, contact potential between P_1 and P_2 was measured when soldered jointed points between m's and p's were exposed to the solution by tearing off the pitch layers coated on their surfaces. Some of the results are given in the following Table 8.

Table 8. Variations of contact potential due to imperfect insulation at splices.

Pitch layer	Contact potential between P_1 and P_2	
(1) exist on both side of P_1 and P_2	0.06mv	P_1 negative
(2) no layer on one side of P_1 only and P_2 unchanged	19.60	P_1 negative
(3) no layers on one side of both P_1 and P_2	0.35	P_1 positive
(4) no layers on both sides of P_1 and one side of P_2	15.33	P_1 negative
(5) no layers on both sides of P_1 and P_2	0.18	P_1 positive

Therefore, when we have some different materials with different physical and chemical states at some parts of electrodes, or its underground wires, serious precaution must be paied for the electrode performance, for instance, when the lead electrodes are used.

As it is easily understood by the above experiment, similar precaution should be paied for the perfect protection of underground wires from the abrasion and corrosion, even no different materials being contained in them. If a part of the copper wire directly, or through low insulation is exposed to the soil, at which depth it might has different physical and chemical states from those at the electrode proper, the very part of the wire would take a role of an another electrode. The contact potentials thus produced may be apt to vary especially near the earth's surface, accompanying with the variations of various kinds of meteorological elements, i.e., temperature, amount of rainfall, content of soil moisture and so on. An actual example will be shown in Fig. 12 in which all curves are drawn by the original millimeter readings. In the compound of the Kakioka Magnetic Observatory, a temporary eastward line, 100 meters long, was installed in October, 1944, adjacent to the sub-regular base, (1)-line. In this case as the underground wire was used a simple lead cable, thickness of the outer lead cover and inner single layer gum were 0.6 mm and 1.0 mm, respectively. At first, registrations were found normal, but seemed gradually to become out of order before not so long time passed after installation. In the figure D's curves will be responsible for the samples showing these different processes. The curves, D's, are calculated from the hourly values of both sub-regular base and temporary one by the following expression,

$$D_1 \equiv e_1-\alpha e_2=s_1\,(l_1-l_2/\beta), \quad \beta=\frac{\Delta l_2}{\Delta l_1}, \quad \alpha=\frac{\Delta l_1 . s_1}{\Delta l_2 . s_2}=\frac{1}{\beta}\,\frac{s_1}{s_2},$$

where

e_1 : hourly absolute values of the sub-regular base line.

e_2 : hourly absolute values of the temporary base.

l_1 : length of ordinate in mm on the recording paper for e_1

l_2 : length of ordinate in mm on the recording paper for e_2

Δl_1 : mean length of ordinate in mm corresponding to the amount of changes of short-period variations of the universal earth-currents for the sub-regular base line.

Δl_2 : corresponding value to Δl_1 for the temporary base line.

s_1 : scale value (mv/km) for the sub-regular base line.

s_2 : scale value (mv/km) for the temporary base line.

Since it is reasonable to suppose that the electric conductivity of the earth is constant during the time interval, now two days, as far as the present bases are concerned, D_1 can be responsible for a kind of residual potential which depends upon the local potentials, mainly contact potentials. Then, if the curve D_1 shows a straight line, both bases relatively have no variable contact potentials, while when it does not so, both or either of them contain some variable potentials in the interval of time concerned. In the figure the upper D_1 curve (Dec. 19-20, 1944), which corresponds to the normal state at the biginning of the installation, shows almost a straight line in the limit of error, while on the contrary, the lower D_1 (Dec. 9-10, 1950) changes with a large diurnal variation. On the other hand, we have no such a diurnal variation in the D_2 curve which is calculated in a similar way as done for D_1 by combing the sub-regular base, (1)-line, and regular EW base, (0)-line. Then this large diurnal variation of D_1 must be originated in the temporary base only. Indeed, it is very reasonable to see an intimate correlation between D_1 (Dec. 9-10, 1950) and the simultaneous variation of soil temperature as shown in the lowest curves, because the reexamination of the underground lead wires showed clearly faulty insulation at two parts of the west pole wire. It is to be especially noted here that the " residual potentials ", or "D-curve" method proposed here will be useful for the detection of various kinds of local changes supperposed on other parts of potentials, which may otherwise be over-looked even by a keen observer due to their small amplitude or indefinite occurrence.[17]

6. *Comparison of universal earth-current potentials observed with differentt kinds of electrodes and apparatus,*

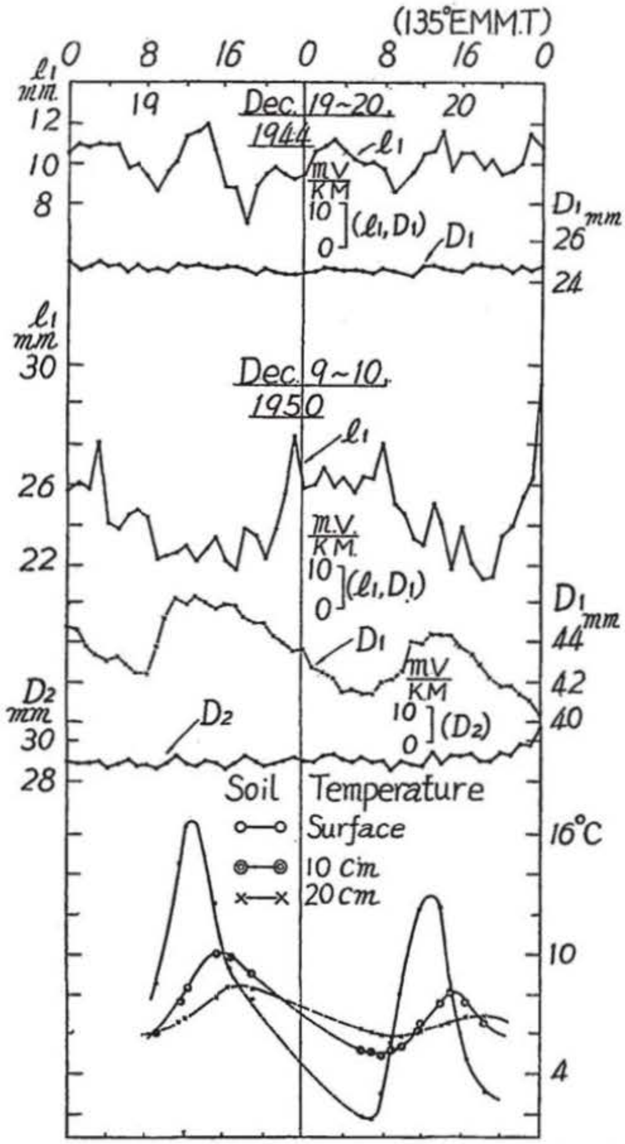

Fig. 12. An example showing abnormal variations of earth-potentials due to faulty insulation of a underground leading wire.

〔A〕 *Galvanometer method with different kinds of electrodes.*

In order to check whether some independent records obtained by the usual simple galvanometer method with different kinds of electrodes and different order of magnitude of current flowing in the circuit do accord with each others, or not, three temporary continuous observations were carried out in the compound at the Kakioka Magnetic Observatory. Each of the lines is equally of 100 meters long and laid almost in the same east-west vertical plane. In order to get accurate readings avoiding any error due to gradual change of absolute values, only short period variations continued less than thirty minutes were selected on the records. The calibration of potentials was made for the total circuit including the ground. The electrodes used were of following three kinds, saturated $CuSO_4$ non-polarizing single electrode, [18] carbon rod double electrodes, [19] and copper plates burried in charcoal powder; their structures are schematically shown in Fig. 13. Some details of the measurement and mean relative ampli-

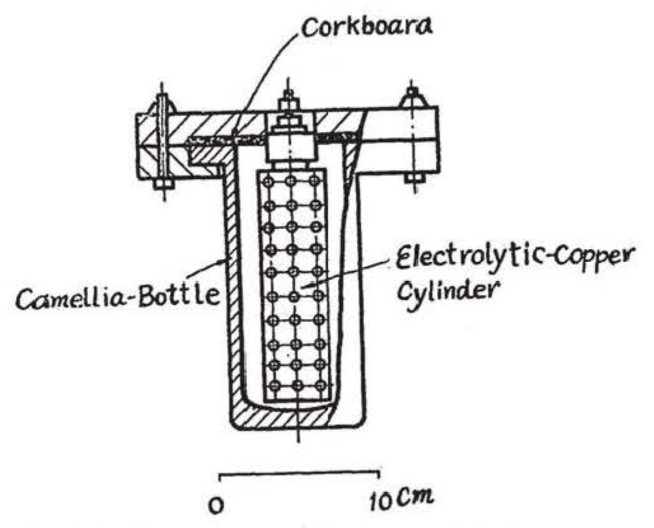

Fig. 13a. $CuSO_4$ non-polarizing camellia-bottle electrode.

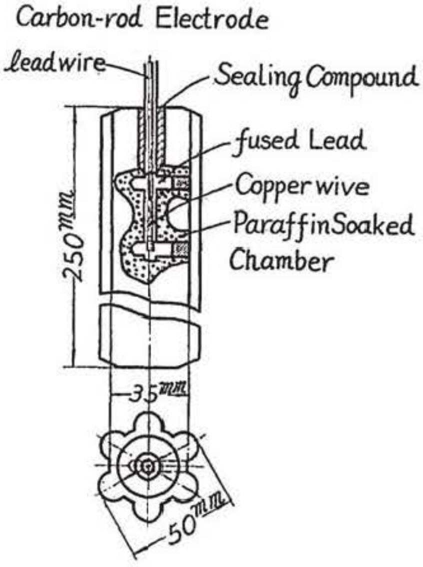

Fig. 13b. Carbon rod electrode.

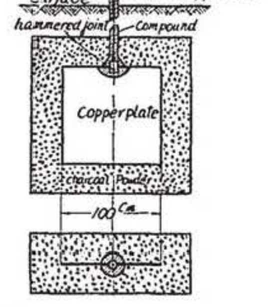

Fig. 13c. Copper-charcoal electrode.

tude ratio which are derived from the mean values of potentials for each specified interval of amplitude range are given in the following Table 9. As it may be expected only from the table, we can find no statistical significant difference between any two mean values of potentials among the three observations. It addition to the above experiment, further test observations were carried out for shorter lines down to ten meters long, and the former result was satisfactorily justified. As it is reasonably expected, therefore, it may be

Table 9. Mean relative amplitude ratio for short period variations of universal earth-curents.

		Amplitude range: mv/km				Sc	Ea	h
		0-1.99	2.00-3.99	4.00-5.99	>6.00	(Amp/mm)	(Amp.)	(cm)
Number of obs.		12	8	3	2			
Electrode	$CuSO_4$	1	1	1	1	$1.0.10^{-9}$	$2.5.10^{-8}$	20
	Carbon	0.97	0.98	0.95	0.98	$12.0.10^{-8}$	$4.0.10^{-8}$	57
	Copper	0.99	0.99	0.97	0.98	$1.3.10^{-7}$	$1.2.10^{-6}$	350

Sc: Current sensibility of galvanometer.
Ea: Mean absolute value of potentials expressed by current.
h : depth of electrode at their middle points.

sufely said that the method of continuous galvanometric recording of earth-current potentials can afford the same result within the limit of error when the field equipment is in favourable conditions, notwithstanding that the nature of material, dimension and arrangement of electrodes themselves and, in a certain case, the magnitude of the current flowing up the circuit, are all different in wide range.

〔B〕 *Micromax self-recording potentiometer method*

At Kakioka we compared the amplitudes of the universal earth-currents measured by two independent methods, the one was the simple galvanometric method above-men tioned and the other that of the self-recording potentiometer of micromax type.[20] The current sensibility of the galvanometer attached to the potentiometer is about 10^{-7} amp/mm, which corresponds to 0.6 mv/mm on the recording paper, and the balancing operation can be repeated every two seconds. The potential differences to be measured are intermittently marked on the sheet every fourty five seconds by synchronous devices. The bases used for comparison are two eastward lines of which one is the regular line, (0)-line, and the other running 1.05 km *long* easterly from the point 150 meters east to the east pole of the former base. An example of comparison for the diurnal

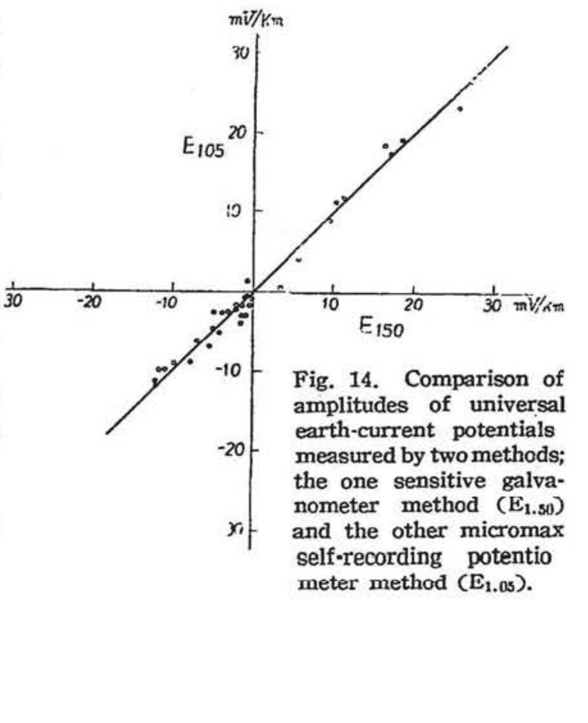

Fig. 14. Comparison of amplitudes of universal earth-current potentials measured by two methods; the one sensitive galvanometer method ($E_{1.50}$) and the other micromax self-recording potentio meter method ($E_{1.05}$).

variation is showh in Fig. 14 in which for the galvanometer method all available hourly departures from the mean in the whole period are given at just times, while for the potentiometer method each corresponding value is interporated by two consecutive points before and after the just time. As it is seen in the figure two method afford a good coincidence as a whole; their mean values of the absolute magnitude of departures are $E_{1.05}=6.79$ mv/km and $E_{1.05}=6.85$ mv/km, respectively. Moreover, more direct comparison by using the same instantaneous values for short period universal variations showed better coincidence even for each individual observation. On the other hand, similar comparisons between two observations made by the galvanometric method only give no differences nearly within the limit of error. [21]

〔C〕 *Polarization.*

At last but not least a word should be added to the above-mentioned statement that we could hardly find any appreciable amount of so-called polarization effect as far as the above experiment was concerned. In order to avoid or minimize polarization it is desirable on principle to measure statically; or to keep the amount and duration of current flowing in the circuit as small as possible, in practice the latter, that is, potentiometric method will be better for the measurement. Nowadays, some types of self-recording potentiometers with skillful mechanical or electronic devices may be applied to it. For the observation of rather long period phenomena, an intermittent recording may be better for the aim of minimizing polarization, but at the ordinary observatory continuous recordings of such short period variations as their duration time less than some minutes are needed as well as those of diurnal variations. From this point and other technical reasons, the sensitive galvanometric method is conveniently used, and can be also effective, as already written, for minimizing polarization, provided satisfactory performance of electrodes, small contact potentials and perfect insulation. Some experiments[22] and field works suggest that a part of polarization can be controlled by the physical and chemical natures of different soils or artificially introduced materials around the electrodes. At any rate it is possible to make polarization as small as to be practically neglected by using suitable method, proper apparatus and electrodes.

§ 3. Measurements of earth-current potentials at the Magnetic Observatory (Kakioka) and its branch observatories

1. Mesurements of earth currents at Kakioka.

As it is sometimes given in the preceeding paragraph, there are some independent bases at Kakioka of which (0)-lines (Table 4 and Fig. 2) are now operating as a regular routine bases. For convenience's sake for the further statement, some essential points of the equipment at Kakioka will be reviewed together with topography and geology near the observatory. (23)

(i) Topography and geology.

The observing place, Lat. 36°13.9′N and Long. 140°11.5′E, is located in the north-eastern part of the Kwanto-Plane into which a chain of mountains of Tsukuba block juts out to north-south, their average height being about four hundred meters. As showh in Fig. 15 the observatory is situated in the middle part of a small basin

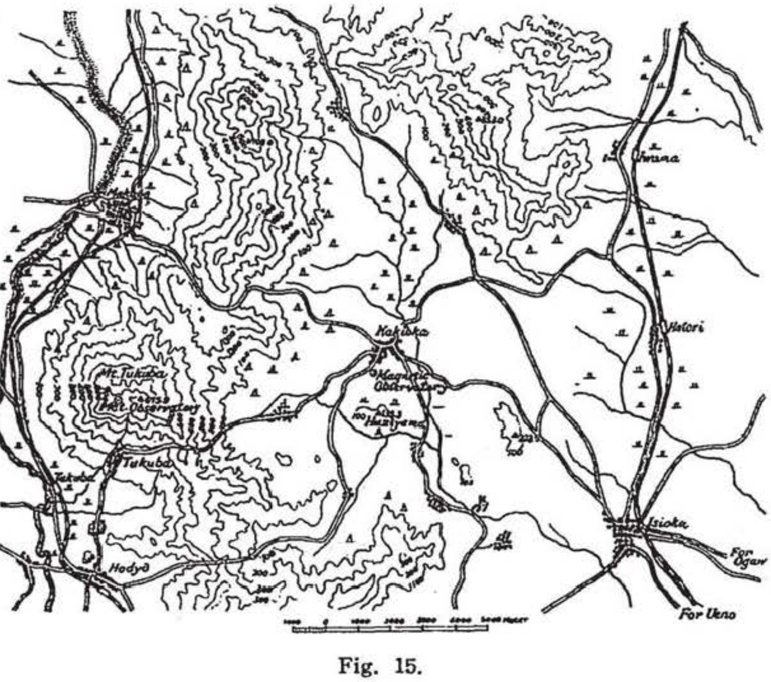

Fig. 15.

elongated in the north-south direction to the east side of this chain of mountains. A small river, the Koise, runs through the basin from north-south to south-east and empties into the Lake Kasumigaura at the distance about 20km from the observatory. A small hill 136 metres high above the sea-level, stands about one kilometre apart in due south from the observatory, along its foot being laied down the regular eastward line.

According to the geological survey carried out in the neighbourhood of the Tsukuba mountain blocks by the Geological Survey Bureau[23] and to our preliminary measurement of earth-resistivity made in the visinity of the observatory, it was shown that the geological structure in the hilly parts are more or less complex due to abundance of granite and micaschist. The land near the observatory is, however, covered with the superficial uniform layer of loam, except in the upper part of the hill, where rocks lay bare at several points of the surface. It can be presumed that the magnitude of universal earth-current variations or their direction of current flow may be locally modified by such geological structures of subterranin masses with high resistivity.

(ii) Layout and equipment.

Some essential points of the equipment for the regular base only will be described; here we have no touch about the sub-regular short base, (1)-lines, installed as early as in 1932. The system of installation of the base is of a cross type, but not a right angle common electrode one[35]; the east and north lines intersect perpendicularly at a point 70 meters west of the east electrode and 90 meters south of the north one. The base length of the north component line is 1.10 km, its direction being north five degrees west. The east line is 1.50 km long and runs to north eighty five degrees east. This orientation of the lines was adopted to be suited to the topography and low expense, but has no inevitable need for the observation. The area in the immediate vicinity along the lines is more or less flat, the maximum range of its ruggedness being less than ten metres at most, and quite negligible compared with the base length. The overhead lines, doubly coated rubber insulated copper wires, are supported by porcelain double cup insulators fixed on wooden pilars at a height about four metres above the surface. The maintenance of all field equipments in good conditions has been carried on by laborious tour of inspection along the long course of lines and careful testing for their damages and faulty insulation.

The electrode in use is of double-electrode type, that is, consists of two copper plates of one metre square connected parallel to the main line. Each plate is burried vertically in fine oak charcoal gravels of three or four hundred kilograms at the depth of about three meters or more below the surface, the horizontal distance being five meters apart. The part of lead-covered cable from each plate was tested for its insulation and coated with asphalt of superior quality to protect the part from corrosion and leakage. The soils in the immediate vicinity of the east and north electrodes are rather brown colour loam to the depth about two meters from which it becomes sandy, while the uppermost layer at the south and west electrodes are more clayish brown loam up to the depth three metres. During the installation the charcoal fine gravels were packed firmly and uniformly around the electrodes with careful and patient endeavour to make a pair of electrode as equall as possible. The digged soils were returned back in the hole in their natural order of deposit and harden by falling a heavy weight uniformly upon the whole area of the hole.

As the method of recording is used a galvanometric one. The sensibility of the galvanometer is enough for the ordinary recording at the order of $10^{-8}\sim10^{-9}$ amp./mm, because amplitude of earth-current potentials is relatively large; especially for the east component mean maximum range of the diurnal variation amounts to 19.1mv/km in the sunspot minimum year 1943. In each circuit is inserted a series resistance of manganin wires of some ten thousand ohms. It is so large compared with the effective contact resistances of the electrodes that the total reistance of the circuit becomes almost equal to the series resistance itself. The earth-potentials are photographically recorded and calculated by the deflections of the galvanometer and the scale values, which are frequently calibrated by a standard electromotive force impressed across the galvanometer unit in place of the line. The hourly zero positions of the galvanometer, from which hourly values are read, are automatically marked on the recording paper by opening the circuit for two minutes from just time with the clock-controlled murcury relay. The recording is made on the floor in a semi-underground house at the depth two metres below the surface. A model of the simple circuit is shown in Fig. 16.

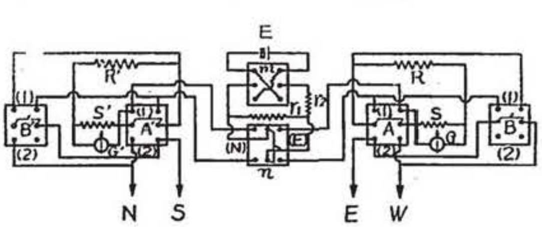

Fig. 16. A model circuit for the galvanometric method making possible to have two kinds of calibration; the one for total circuit including the earth and lines, while the other excluding them.

Regarding the measuremennt of earth-resistivity some details will be given in the latter chapter.

2. Routine observations of earth-currents at observatories attached to the Magnetic Observatory (Kakioka).

At present routine observations of earth-currents are going on at following three places, Memambetsu in Hokkaido District, Kanoya in Kyushyu District and Haranomachi in the middle part of Japan Island. Their geographical coordinates and base length are given in the following Table 10. The equipments at these places are rather similar with those at Kakioka, but electrodes themselves used are of double carbon rods (Fig. 13b) except copper cylinders at Memambetsu.

Table 10.

Observatory	Lat. (N)	Long. (E)	Base length	
			EW*	NS*
Memambetsu	43° 55′	144° 12′	160m	195m
Kanoya	31 25	130 53	1.65km	2.80km
Haranomachi	37 37	140 56	1.33km	0.85km

* Geographical east-west and north-south

Due to the violent meteorological disturbances, in the specified period of a year the maintenance of the regular recording is so difficult and frequently spoiled at Memambetsu and Kanoya. At these places underground cables and special devices of the construction and performance of electrode are strongly demanded.

Concluding Remarks for the chapter. I

In this first chapter are discussed the fundamental problems of earth-current measurements, that is, the method and apparatus used, performance and maintenace of field equipment and various kinds of errors which may be introduced in the measurement. In some sense, though they seem to be simple, they have not hitherto been treated so systematically that even at present there remain some obscurities to prevent the active improvement in this field of geophysics. The experimental and actual field informations will make better survice to the observations of various kinds of earth-current potentials, and further precise understanding of this branch of science.

References.

(12) a. (1) e.

b. O. H. Gish, Terr. Mag., **28** (1923), Sept.

c. O. H. O. Gish and W. J. Rooney, Terr. Mag., **35** (1930), Dec.

d. S. K. Bnerji, Memo. India Met. Dep., **26** (1933), 1.

e. K. Burkhart, Geofisica, **19** (1951).

(13) (1) a.

(14) a. (1) e.

b. G. Arnold, Beit. z. Geophys, Bd. **49**, Heft 1/2 (1937).

M. Kitamura, Memo. Kakioka Mag. Obs., **6**, (1951), 1.

(16) (12) c; (12) d.

(17) T. Yoshimatsu, Jour. Met. Soc. Jap., **15** (1937), 4.

(18) By the courtesy of Dr. Iwase it was used in experiment.

(19) Z. Kishimoto, "Musen to Zikken", Tokyo, **30** (1943) 1. (in Japanese)

(20) Leeds and Northlap type manufactured by the Y. E. W., Tokyo.

(21) K. Yanagihara, Memo. Kakioka Mag. Obs., **6** (1951), 1.

(22) H. Hatakeyama and T. Yoshimatsu, Jour. Met. Soc. Jap., **11** (1933), 5.

(23) (1) g.

(24) Geological Map, "Tukuba", Zone 22 Col. 4, Sheet 99 (1927), (Geological Survey by H. Sato in 1924).

(25) a. (1) a, p. 284.

b. O. H. Gish and W. J. Rooney, Teir. Mag., **35** (1930), Dec.