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Relations between the short period changes in geomagnetism and in telluric currents

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Summary

The relations between the changes in geomagnetism and in telluric currents of which the periods are a few scores of *minutes*, are discussed on the basis of data obtained by observation at the Centre de Physique du Globe, Dourbes, Belgium. The particular stress is laid upon the anisotropic behaviour of the changes in telluric currents with relation to the changes in the vertical component of the geomagnetic field. First, with acceptance of Maxwell's equations, a theoretical relation between the above components is deduced on the assumption that telluric currents flow in parallel straight lines at the observation point. According to this result, the directions of the principal axes of earth conductivity and the gradient per unit conductivity can be approximately determined if ΔZ and the components of ΔE be observed for the duration of one geomagnetic variation. Second, the data of the changes in telluric currents and in geomagnetism observed at Dourbes are examined and some examples of their relations are illustrated for each quadrant. And also the schematic types of the variations are deduced from these examples. It is very remarkable that the variations in earth-potential take a strongly predominant direction in marked contrast to the geomagnetic variations. Furthermore, anomalous behaviour of the variation ΔZ of short periods is discussed with relation to the anisotropic behaviour of the changes in telluric currents. The directionalities of the ΔZ variations observed at Dourbes and two Japanese observatories are shown in the diagrams and expressed by the empirical formulae. The anomalous behaviour of the variation ΔZ is concluded to be closely related with the anisotropy of earth-conductivity. In this connection, the present studies are confined to phenomenological ones. Last, a brief comment is given on the observations of the changes in telluric currents and the direct measurements of anisotropic distribution of surface resistivity on the Miyake Island, Japan, where an anomalous behaviour of the changes in geomagnetic vertical component has been reported.

1. Introduction

Hitherto the relations between the changes in geomagnetism and in telluric currents have been studied by many geophysicists. From the theories and analysis developed by them, distributions of electric conductivity of the earth-interior have been inferred; the same methods with regard to shorter period variations are applicable to surface exploration[1]. On the other hand, anomalous behaviour of the geomagnetic vertical component in comparison with the other components during the short period variations such as the bay-type ones, has been found and discussed in Japan[2] and Germany[3]; their causes are attributed to the anomalous subterranean structures of the two regions respectively from the viewpoint of electric conductivity. Furthermore, the local characteristics or anisotropic behaviour of telluric currents variations have been studied independently of geomagnetism[4].

Some theoretical discussions in the above-mentioned studies treated very simplified models of the earth such as the stratified strata or spherical shells neglecting horizontal anisotropy; other studies solved Maxwell's equations under special conditions only for mathematical brevity except the study by H. ERTEL[5] who discussed the currents in the anisotropic earth-crust induced by the changing magnetic field but disregarded changes in the vertical geomagnetic component. Here, the author inserts a comment concerning Maxwell's equations in relation to the actual observations. If displacement current is neglected, electric and magnetic quantities in the earth are connected by the following equations:

$$rot\,\boldsymbol{H} = \boldsymbol{i} \;, \tag{1}$$

$$rot\,\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \;, \tag{2}$$

and

$$div\,\boldsymbol{B} = 0 \;, \tag{3}$$

where $\boldsymbol{H}$, $\boldsymbol{E}$, $\boldsymbol{B}$ and $\boldsymbol{i}$ denote magnetic field, electric field, magnetic induction and electric current-density respectively; between these quantities there are the following relations:

$$\boldsymbol{i} = (\sigma)\,\boldsymbol{E} = \frac{1}{(\rho)}\,\boldsymbol{E} \;, \tag{4}$$

and

$$\boldsymbol{B} = (\mu)\,\boldsymbol{H} \;, \tag{5}$$

where σ, ρ and μ denote respectively electric conductivity, resistivity and magnetic permeability which are all tensor quantities in general.

Assuming that the equations $div\, \boldsymbol{i} = div\, \boldsymbol{B} = 0$ hold good, one gets

$$rot\, \boldsymbol{H} = \frac{1}{(\rho)} \boldsymbol{E} \,, \tag{6}$$

and

$$rot\, \boldsymbol{E} = -(\mu) \frac{\partial \boldsymbol{H}}{\partial t} \,. \tag{7}$$

Since the variations in geomagnetism and earth-potential on the earth-surface are to be treated, the above equations are rewritten as follows :

$$rot\, \Delta \boldsymbol{H} = \frac{1}{(\rho)} \Delta \boldsymbol{E} \,, \tag{6a}$$

and

$$rot\, \Delta \boldsymbol{E} = -\frac{\partial \Delta \boldsymbol{H}}{\partial t} \,. \tag{7a}$$

Of six components of the above equations, a direct proof can be practically carried out of only one component :

$$\frac{\partial (\Delta E_y)}{\partial x} - \frac{\partial (\Delta E_x)}{\partial y} = -\frac{\partial (\Delta Z)}{\partial t} \,, \tag{8}$$

where ΔZ is the vertical component of the geomagnetic variations.

In fact, A.P. BONDARENKO[6] carried out experiments by means of two couples of parallel lines to measure the $rot\, \Delta \boldsymbol{E}$ and one horizontal coil to measure the variations of the vertical geomagnetic component ; he justified, at any rate, the above equation.

In the following discussions, it is assumed that Maxwell's equations hold good or that the changing parts of the telluric currents are induced by the external magnetic variations.

2. Deduced relations between the changes in telluric currents and in geomagnetic vertical component

Starting from equation (8), each term of the left side is converted as follows :

$$\left.\begin{aligned} \frac{\partial (\Delta E_y)}{\partial x} &= \frac{\partial}{\partial x}\left(\frac{\Delta E_y}{\Delta E_x}\right) \cdot \Delta E_x + \frac{\partial (\Delta E_x)}{\partial x} \cdot \frac{\Delta E_y}{\Delta E_x} \\ \frac{\partial (\Delta E_x)}{\partial y} &= \frac{\partial}{\partial y}\left(\frac{\Delta E_x}{\Delta E_y}\right) \cdot \Delta E_y + \frac{\partial (\Delta E_y)}{\partial y} \cdot \frac{\Delta E_x}{\Delta E_y} \end{aligned}\right\} , \tag{9}$$

where the z-component of the rotation is separated into two parts, variations of direction and variations of magnitude. Therefore one gets

$$-\frac{\partial(\Delta Z)}{\partial t}=\frac{\Delta E_y}{\Delta E_x}\cdot\frac{\partial(\Delta E_x)}{\partial x}-\frac{\Delta E_x}{\Delta E_y}\cdot\frac{\partial(\Delta E_y)}{\partial y}$$

$$+\Delta E_x\frac{\partial}{\partial x}\left(\frac{\Delta E_y}{\Delta E_x}\right)-\Delta E_y\frac{\partial}{\partial y}\left(\frac{\Delta E_x}{\Delta E_y}\right). \tag{10}$$

If it be assumed that telluric currents flow in parallel straight lines in the vicinity of the observation point, and that one of the directions of the principal axes of earth-conductivity coincides with the vertical line to the surface and if the directions of the above axes be denoted as x, y and z, one gets

$$\frac{\partial}{\partial x}\left(\frac{\Delta E_y}{\Delta E_x}\right)=\frac{\partial}{\partial y}\left(\frac{\Delta E_x}{\Delta E_y}\right)=0\ , \tag{11}$$

and

$$\frac{\partial(\Delta E_x)}{\partial x}=\frac{\partial(\rho_{xx}\cdot\Delta i_x)}{\partial x}=\left|\frac{\partial\rho_{xx}}{\partial x}\right|\cdot\Delta i_x+\rho_{xx}\frac{\partial(\Delta i_x)}{\partial x}$$

$$=\left|\frac{\partial\rho_{xx}}{\partial x}\right|\cdot\frac{\Delta E_x}{\rho_{xx}}\ , \tag{12a}$$

where the condition $div\,\Delta\,\boldsymbol{i}=0$ is taken into consideration. And similarly

$$\frac{\partial(\Delta E_y)}{\partial y}=\left|\frac{\partial\rho_{yy}}{\partial y}\right|\cdot\frac{\Delta E_y}{\rho_{yy}}\ . \tag{12b}$$

Substituting these conditions into equation (10), one obtains

$$-\frac{\partial(\Delta Z)}{\partial t}=\Delta E_y\frac{\left|\frac{\partial\rho_{xx}}{\partial x}\right|}{\rho_{xx}}-\Delta E_x\frac{\left|\frac{\partial\rho_{yy}}{\partial y}\right|}{\rho_{yy}}$$

$$=\Delta E_y\cdot X-\Delta E_x\cdot Y\ , \tag{13}$$

where X and Y are defined as follows :

$$X=\frac{\left|\frac{\partial\rho_{xx}}{\partial x}\right|}{\rho_{xx}}\quad\text{and}\quad Y=\frac{\left|\frac{\partial\rho_{yy}}{\partial y}\right|}{\rho_{yy}}\ . \tag{14}$$

These are the gradients per unit resistivity respectively in x- and y-direction and are constant at respective observation points in general. Accordingly, no variations should be observed in the vertical geomagnetic component at a point where both X and Y are equal to zero if the above-mentioned assumptions are accepted.

As the first approximation, let the anisotropy of conductivity in only one horizontal direction be assumed and let the direction of the aniso-tropy be taken as the x-axis (Fig. 1). According to the above approximation, Y equals zero and thus one gets

$$-\frac{\partial(\varDelta Z)}{\partial t} = \varDelta E_y \cdot X \ . \tag{15}$$

In this case, namely when Y equals zero, the x-axis, one of the principal axes, can be determined as the direction for which $\varDelta Z$ reaches either a maximum or a minimum.

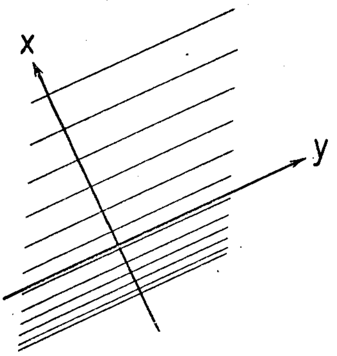


Fig. 1. Vertical plane-structure for conductivity as the fisrt approximation.

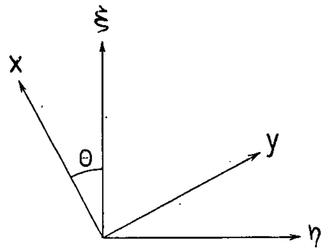


Fig. 2. Directions of principal axes of resistivity x and y.

In general, when the components of telluric currents in any direction for instance, ξ- and η-component shown in Fig. 2, are known, equation (15) will be expressed in the following form :

$$-\frac{\partial(\varDelta Z)}{\partial t} = \varDelta E_\xi \cdot \sin\theta \cdot X + \varDelta E_\eta \cdot \cos\theta \cdot X \ . \tag{16}$$

Hence, if $\varDelta Z$ and the components of $\varDelta E$ be observed during one cycle of geomagnetic variation, the directions of the principal axes of resistivity and the value of X, namely, the gradient per unit resistivity can be determined.

For Dourbes the mean values of θ and X are obtained from several observations shown in the next paragraph as follows :

$$\theta \doteqdot 34° \quad \text{and} \quad X \doteqdot 0.015/km$$

Thus one of the principal axes at Dourbes lies in the direction of about 6 *degrees* from north over east.

3. Observed relations between the changes in the telluric currents and in geomagnetism at Dourbes, Belgium

The writer analyzed the data of telluric currents and geomagnetism obtained by observations at the Centre de Physique du Globe at Dourbes, Belgium. Its geographical position is 50°05'8 N latitude and 4°35'7E longitude. The span between the E and W electrodes for measuring telluric currents is 2240 *meters* and its direction is N 64°E, while the distance between the N and S electrodes is 1460 *meters* and their direction is N 28°W. Earth-potential is recorded by an electronic potentiometer of the Honeywell-Brown type of which the sensitivity is usually 1 *millivolt* per *millimeter* on the records; the paper speed is 30 *centimeters* per *hour*. The details of the observation at Dourbes were already reported by E. LAHAYE and A. DE VUYST[7]. The present data of telluric currents and geomagnetism are those for the epoch from July to December, 1959 which were placed at the writer's disposal by the Centre de Physique du-Globe. It was a pity that the records of telluric currents at that epoch were a little disturbed by artificial electric currents.

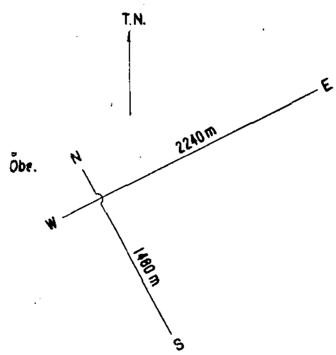


Fig. 3. Observation of telluric currents at Dourbes, Belgium.

From the records for the above period, about 30 bay-type disturbances of geomagnetism were selected; the vector-diagrams of geomagnetic and geoelectric field in the horizontal plane were obtained together with the variations of the vertical geomagnetic component. The whole duration of a disturbance is divided into six equal intervals; the time of its beginning being denoted by t_0 and that of its end by t_6, while the midpoint of the duration by t_3. The variational part of each component is defined approximately as the deviation from the straight line connecting the values at t_0 and t_6 on magnetograms and records of earth-potential. Some of them in each quadrant are shown in Fig. 4; their time of occurrence, duration and the amplitude ratio of the corresponding components of earth-potential and geomagnetism, are listed in Table I.

For the isotropic medium T. TERADA[8] obtained the following relations between the amplitude ratio of earth-potential and geomagnetism:

Table I. Variations in earth-potential and in geomagnetism illustrated in Fig. 4.

Fig. Nos.	Time of Occurrence 1959 (G.M.T.)	Duration (*min.*)	Amplitude Ratio $\left(\frac{mV/km}{\gamma}\right)$ $\frac{\Delta E_x}{\Delta D}$	$\frac{\Delta E_y}{\Delta H}$
4-1	25 July 23^h00^m	35	−6.1	0.68
2	15 Aug. 17 26	64	−4.9	0.93
3	17 Aug. 02 10	40	−2.5	0.42
4	20 Aug. 04 13.2	4.9 (Sc)	−1.8	0.18
5	5 Sept. 01 10	25	−1.7	0.58
6	4 Sept. 00 07	30	−0.95	−2.2
7	2 Nov. 01 53	67	−0.75	−0.48
8	16 Sept. 19 52	43	−2.1	1.8
9	21 Aug. 00 10	35	−3.9	0.75
10	18 Aug. 18 00	40	−2.4	0.44
11	26 Sept. 12 10	35	−5.4	1.0
12	22 Sept. 02 02	37	−1.6	0.70
13	21 Sept. 20 43	22	−0.84	0.47
14	5 Sept. 21 59	56	−1.3	0.95
15	21 Sept. 16 49	24	−0.58	∞
16	21 Aug. 17 40	60	−2.2	1.8

$$\frac{\Delta E_x}{\Delta D} \propto \frac{1}{\sqrt{T}} \quad \text{and} \quad \frac{\Delta E_y}{\Delta H} \propto \frac{1}{\sqrt{T}}, \tag{17}$$

where T is the period of the variations. At Dourbes the above relations do not fairly hold for the bay-type variations as shown in Table I, perhaps because the distribution of conductivity there, may be anisotropic for such durations. Furthermore, no distinct phase-differences between the two changes are observed. Concerning the above points, A. DE VUYST and L. BOSSY[9] have already studied minutely the variations of shorter periods at Dourbes.

Figs. 4–2, 4–11 and 4–15 show examples of the variations in which the vertical components almost do not change whilst Fig. 4–4 represents the sudden commencement of a geomagnetic storm. The changes of earth-potential shown in Figs. 4–8 and 4–16 are rather qusetionable, because such changes are transitional and seldom occur. Summarizing the tendency of variations in Fig. 4, one may obtain the schematic types of variations in each quadrant at Dourbes as shown in Fig. 5. It is very remarkable that $\boldsymbol{E}$-field is not always perpendicular to $\boldsymbol{H}$-field contrary to Maxwell's law and in fact, this was first pointed out by K. BIRKELAND[10] in 1913. In Figs. 4 or 5 their relations are suggestive : variations in geomagnetic field take almost all directions uniformly though there may be a statistically predominant direction according to the types of disturbacnes and to the geomagnetic latitude of the observation point[11], while variations in earth-potential take a strongly predominant direc-

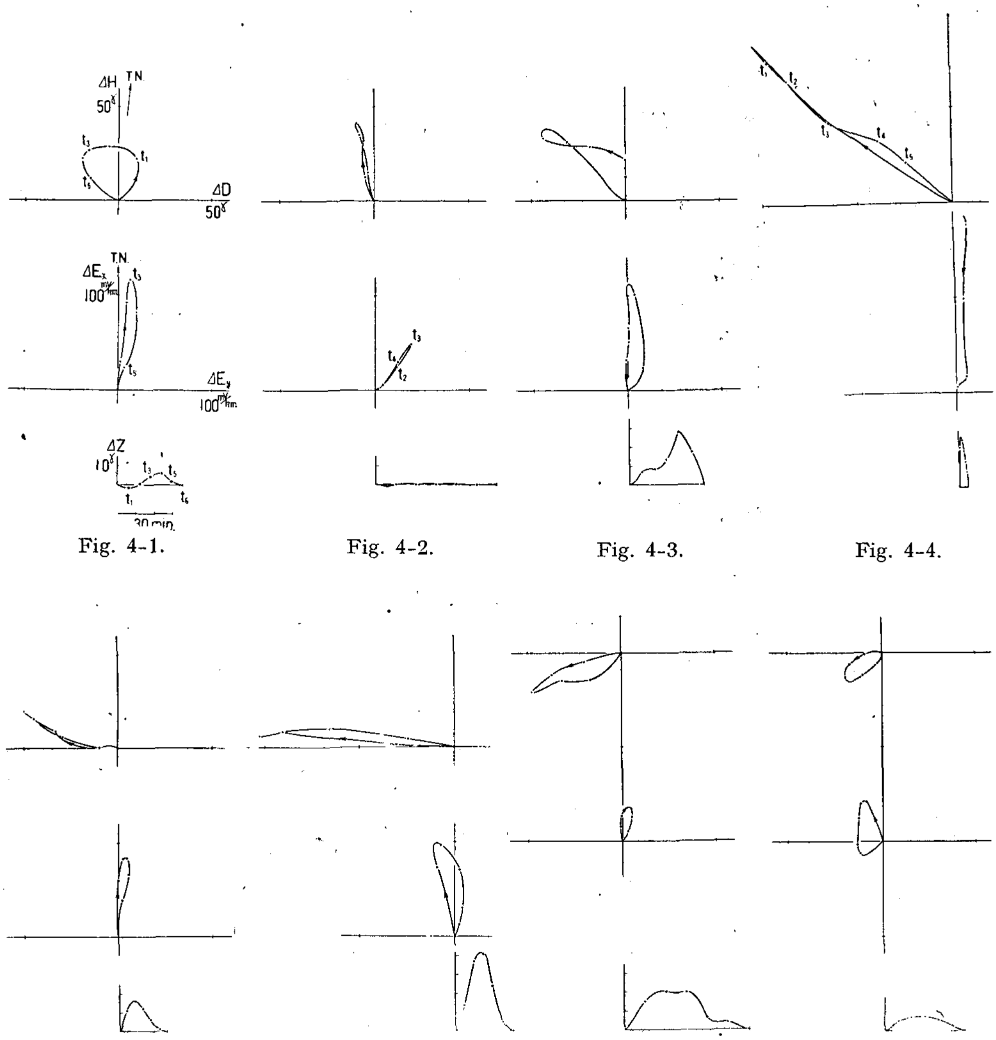


Fig. 4-1. Fig. 4-2. Fig. 4-3. Fig. 4-4.

Fig. 4-5. Fig. 4-6. Fig. 4-7. Fig. 4-8.

Fig. 4. Examples of the horizontal vector-diagrams of geomagnetic and geoelectric variations and the simultaneous variation in the vertical geomagnetic component. The figures are arranged successively according to the horizontal quadrant in which the geomagnetic vector changes.

tion, here about 6 *degrees* from north over east excepting the transitional cases. It is very reasonable that this predominant direction coincides with that of the maximum resistivity of the earth at the point.

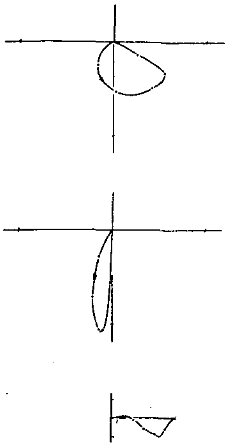


Fig. 4-9.

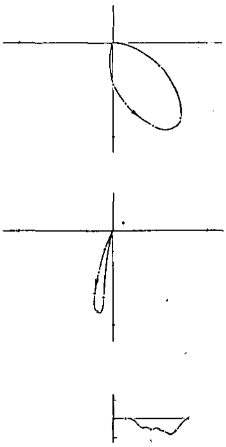


Fig. 4-10.

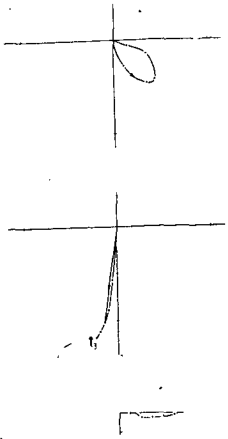


Fig. 4-11.

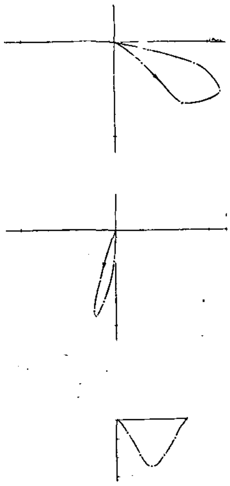


Fig. 4-12.

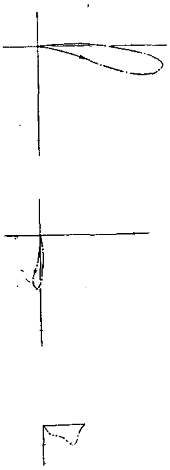


Fig. 4-13.

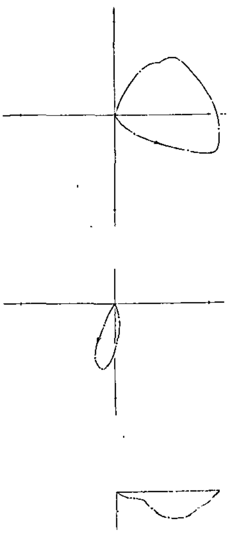


Fig. 4-14.

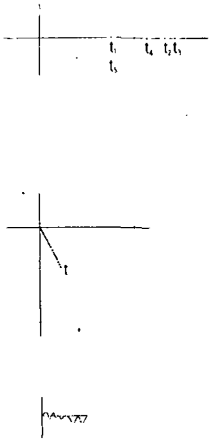


Fig. 4-15.

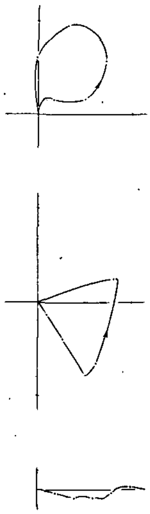


Fig. 4-16.

The travelling direction along the vector-diagrams of earth-potential has relations with the simultaneous variations of the vertical component in such a manner as regulated by equation (13).

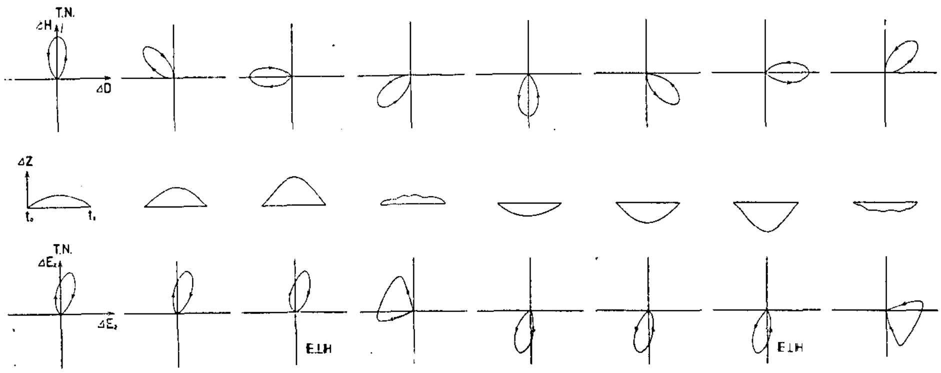


Fig. 5. Schematic types of variations of geomagnetic and geoelectric fields in each quadrant at Dourbes.

In Figs. 4–2 and 4–15, the ratio $\Delta Ey/\Delta Ex$ is constant during the variation, because the vector-diagrams are straight lines, and not loops. The ΔZ-variations which are deviations from the base-line as defined above, are approximately zero and, in such cases, the gradients of the base-lines should satisfy equation (13). As shown in the figures there is no conspicuous tendency in the direction of such variations of earth-potential though examples are few. Thus it may be concluded that the anisotropy of earth-conductivity apparently has no effect on the earth-potential variations which are represented as straight-lined vector-diagrams and that the angle between such variations of earth-potential and geomagnetism is not conspicuously different from a right angle.

4. Anisotropic behaviour of the changes in telluric currents and in geomagnetic vertical component

Anomalous behaviour of the short period variation of ΔZ has been found at some regions in the world. The causes of their origin have been fathomed by several investigators including the present author[2),3)]. Here, the writer wishes to discuss the phenomenon in relation to the above-mentioned anisotropic behaviour of the changes in telluric currents.

At Dourbes the variation ΔZ shows close parallelism to the variation $(-\Delta D)$, namely westward declination, on the magnetograms. An example of the schematic relations between the variations in the geomagnetic horizontal and vertical components and in telluric currents, is shown in Fig. 6: all the variations $1\sim4$ in the geomagnetic horizontal vector-diagram correspond to only one type of the northward variation in telluric currents and also to

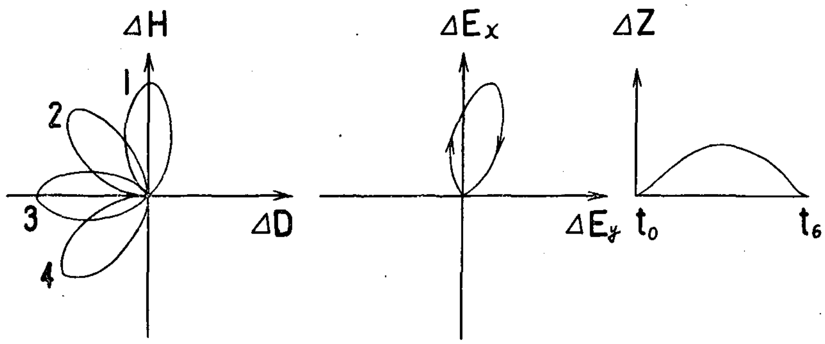


Fig. 6. An example of the schematic relations between the variations in the geomagnetic horizontal and vertical components and in telluric currents.

only one type of positive variation in the vertical component, of which the relative amplitude differs according to the azimuth of magnetic vector. From these relations, it is proved that the positive variation ΔZ occurs statistically most frequently with westward geomagnetic variations. Such apparent anisotropy of geomagnetic variations has been found in Japan by the present author in collaboration with T. RIKITAKE[12]. Two stations in the central part of Japan, Aburatsubo (35°09′ N, 139°37′ E) and Maze (37°44′N, 138°48′ E) with a distance of about 300 *km* apart, show the typically different characteristics: at the former station, ΔZ is anomalously large for the north-south changes of the geomagnetic vector or shows strong parallelism to ΔH on the magnetograms, though quite small ΔZ is observed when the vector changes in the east-west direction ; at the latter station, ΔZ is fairly large whenever the magnetic vector is directed towards the east or west, though ΔZ is quite small for usual variations whose magnetic vectors lie nearly in the north-south direction. To examine the anisotropic behaviour of ΔZ at the Belgian and Japanese observatories, the ratios of ΔZ to the changes of the horizontal geomagnetic resultant vectors ΔR at the time of maximum amplitude during each variation, are obtained for the three observatories and plotted by azimuth in Fig. 7. In regard to the observational data from Dourbes, mainly the bay-type variations for the second half of 1959 are examined. The difference of the epochs in which the data from each observatory were obtained, does not matter in such statistical analyses. In the above directional diagrams the radial distance gives the values of $\Delta Z/\Delta R$ and the azimuth expresses the direction of the geomagnetic vector, while the small crosses and circles denote respectively the positive and negative values of ΔZ. Comparing these figures

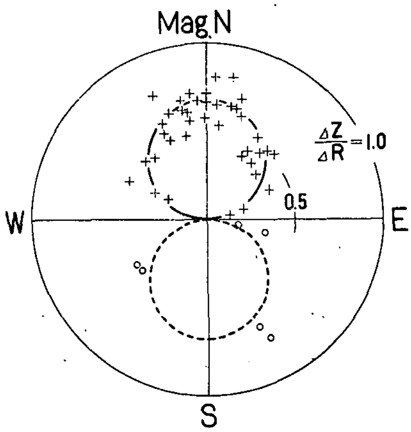


Fig. 7. (a) Aburatsubo

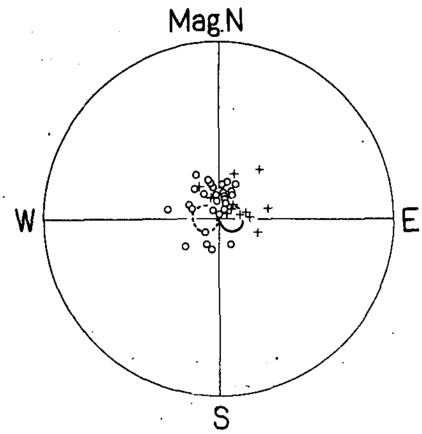


Fig. 7. (b) Maze

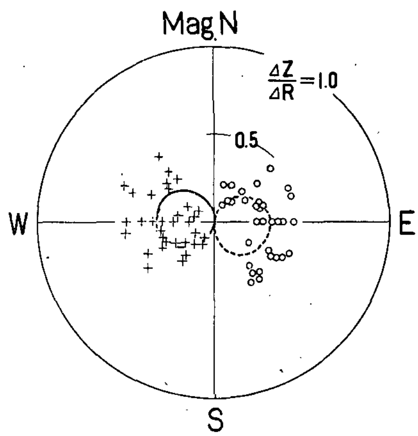


Fig. 7. (c) Dourbes

Fig. 7. Anisotropic behaviour of ΔZ at the Japanese and Belgian observatories.

with each other, one will see explicitly that the characteristics observed at Dourbes are of similar type but more typical than those observed at Maze and that they make a complete contrast to those observed at Aburatsubo. On the other hand, the ratio $\Delta Z/\Delta R$ can be expressed by the following empirical formulae obtained by means of least square method using the above data :

$$\frac{\Delta Z}{\Delta R} = 0.68\frac{\Delta H}{\Delta R} + 0.01\frac{\Delta D}{\Delta R} \quad \text{for Aburatsubo,}$$

$$\frac{\Delta Z}{\Delta R} = -0.01\frac{\Delta H}{\Delta R} + 0.15\frac{\Delta D}{\Delta R} \quad \text{for Maze,}$$

and

$$\frac{\Delta Z}{\Delta R}=0.04\frac{\Delta H}{\Delta R}-0.33\frac{\Delta D}{\Delta R}\quad \text{for Dourbes.}$$

These formulae are shown with full and broken lines respectively for positive and negative values of ΔZ in Fig. 7. To repeat the statement, at Dourbes the amplitude of ΔZ depends mostly on $(-\Delta D)$ while at Aburatsubo it depends on ΔH and is anomalously large.

Hence, it may be concluded that the theory basic to an interpretation of the anomalous behaviour of geomagnetic variations observed in the central part of Japan including Aburatsubo and Kakioka (36°14′ N, 140°13′E), should be compatible with the anisotropic behaviour of geomagnetic variations observed at Dourbes. From this standpoint, the anomalous behaviour of the geomagnetic vertical component of short-period variations, the writer believes, may be due to the apparent anisotropy of subterranean conductivity which can be caused by some features of the surface distribution of conductivity affected by sea and land areas and also by the discordancies in the deep subterranean parts. Here, the writer has confined himself to phenomenological discussion and postpones further quantitative studies until the future.

5. Observations of the changes in telluric currents on the Miyake Island, Japan

Here, the writer refers to the observations carried out on the Miyake Island being 170 *km* distant southward from Tokyo, in order to examine, as a special case, the relations between anomalous behaviours of the changes in the vertical component of geomagnetic field and anisotropy of subterranean conductivity. On the Miyake Island, B. KAWAMURA et al.[13] of the Japanese Hydrographic Office made a magnetic observation by a portable geomagnetic variograph simultaneously with absolute measurements in 1957. They found that the ratios $\Delta Z/\Delta H$ of short-period variations observed at the two stations being situated at the north and south coasts of the island, are remarkably different in such a manner as 0.2 and 1.0 respectively in spite of their near positions, about 7.8 *km* distant each other.

In 1960 the writer observed the changes in telluric currents for a few days and also directly determined the anisotropic distribution of surface resistivity at the above two stations accepting the KAWAMURA's observations of the geomagnetic variations there. Earth-potential between electrodes 200 *m* apart was observed by the usual method connecting the resistance of $20K\Omega$ to galvanometers. During the period of observations 9 and 6 bay-type variations in

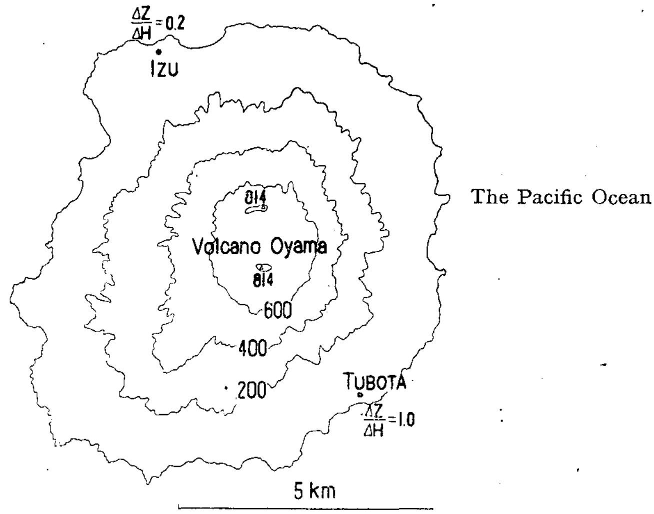
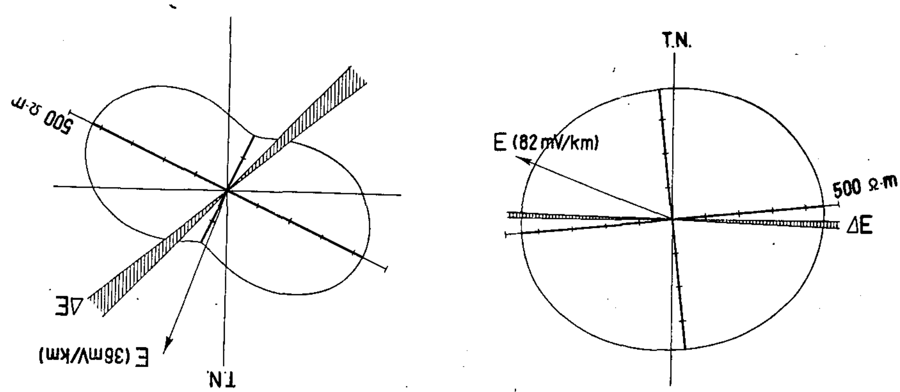


Fig. 8. The raito $\Delta Z/\Delta H$ of short period variations observed on the Miyake Island (after the Japanese Hydrographic Office).



(a) The north station (Izu) (b) The south station (Tubota)

Fig. 9. Results of the observations of telluric currents and surface resistivity on the Miyake Island.

Thick lines : Principal axes of surface resistivity
E : Average direction of stationary telluric currents
ΔE : Range of direction of changing telluric currents

telluric currents of which periods were 10~60 *minutes*, were registered respectively at the north and south stations, though the observations were not simultaneous. The directions of the observed changes are shown in Fig. 9, where also the average directions of the stationary telluric filed are given. On the other hand surface resistivity was measured by the apparatus of Gish and Rooney in three directions where four electrodes were uniformly spaced at successive distances (200/3) m and larger distances were not realizable due to the topographical difficulties. Subsequently two-dimensional expressions of resistivity-tensors at the earth surface were obtained as shown in Fig. 9 by the following relations:

$$\left.\begin{aligned} \rho_1 &= l_1\,\rho_{xx} + m_1\,\rho_{yy} + l_1 m_1\,\rho_{xy}\ , \\ \rho_2 &= l_2\,\rho_{xx} + m_2\,\rho_{yy} + l_2 m_2\,\rho_{xy}\ , \\ \rho_3 &= l_3\,\rho_{xx} + m_3\,\rho_{yy} + l_3 m_3\,\rho_{xy} \end{aligned}\right\} \qquad (18)$$

where ρ_i denotes the observed resistivity along the direction (l_i, m_i) and ρ_{xx}, ρ_{yy} and ρ_{xy} are the components of resistivity.

At the north station (Izu) surface resistivity is rather anisotropic and the minor principal axis of resistivity coincides approximately with the average direction of the stationary telluric currents which were measured along the spans of 200 m. At the south station (Tubota) surface resistivity is almost isotropic and hence the stationary telluric currents would be much affected by the surrounding topographies, geological formations and configuration of coast lines.

As for the predominant direction of changing telluric currents or those induced by changing magnetic filed, it is the north-east direction at the north station, while almost the east-west direction at the south station; the former may correspond to the small value of $\Delta Z/\Delta H$ and the latter to the large one according to the discussions in the previous sections. In conclusion, anomalous behaviours of the changes in the vertical geomagnetic component observed on the Miyáke Island are attributable to the anisotropic distribution of resistivity in the deeper parts and not at the earth surface and also to configuration of sea water or most probably to superposition of both the effects. In this respect, further quantitative studies shall be desirable in future.

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