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Study on Geomagnetic Variation of Telluric Origin

Part I. On Geomagnetic Variation Caused by Oceanic Tidal Current

By

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(Communicated by Prof. E. Nishimura)

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Abstract

Observations ranging over several months with two variometers of geomagnetic declination, were made at three places on a strait to study geomagnetic effects caused by ocean tides. Obtaining good effects clearly observed and they were then all found to be reasonably explainable as caused by dynamo effect of the oceanic tidal current of the strait.

1. General Introduction

Geomagnetic elements anywhere suffer various changes, such as diurnal variation, magnetic storm, micro-pulsation and large secular variation. Except for the secular variation, all changes are considered to be caused by the motion and activity of the sun through the ionosphere and that as an intermediary. Secular variation is interpreted at present as originating from the regional and turbulent motion of matter in the earth's core. Secular variation never appear as a phenomenon common to all parts of the world, but it often does show similar tendencies in regions as wide spread as Europe and North America. The geomagnetic variation treated in the present article does not belong to any of those described above. It is not for a world-wide or large regional variation, but one having an extremely local character as observed, for example, only in the area of several scores of kilometers at most in length.

It is important and attractive to ascertain whether or not there exists any local change with time of geomagnetic elements in the area near the epicenter of a destructive earthquake, or near the crater of an active volcano, or in any area greatly disturbed by the movement and deformation of the earth's crust. Concerning the problem of connection of the local magnetic change with destructive earthquakes, Y. KATO published in series (1938, 1940, 1949, 1953) some papers on the local change of geomagnetic inclination as measured at places near the epicenters of destructive earthquakes before and after their occurrence. He reports that the amount of change of geomagnetic inclination considered to be related to an earthquake reaches to more than 10′ at the epicentral region. His surveys were mainly by dip circles or earth-inductors at proper yearly intervals, and a continuous observation by self-recording methods near the epicenter was not discussed. The geomagnetic variation related to the volcanic eruption has been studied by many researchers in our country, especially for Volcano Asama, Volcano Mihara and others. Detailed reports have been made on the geomagnetic survey and continuous observation of declination at Asama by T. MINAKAMI (1938, 1940, 1944) and recently T. RIKITAKE and I. YOKOYAMA discussing fully the relation between the volcanic activity and geomagnetic change for Volcano Mihara (1955).

In addition to the above, continuous recording observations with the geomagnetic variometer have also been made by Geophysical Institute and Disaster Prevention Research Institute, both attached to Kyoto University, for studying local geomagnetic variations related to destructive earthquakes, volcanic eruptions and other local disturbances. Namely, long period geomagnetic observations with a self-recording apparatus have been made by our Institute at Volcano Aso since 1932 as cooperative work of the Second International Polar Year, and continuous observations with a self-recording variometer for declination have been put in operation at fifteen stations in our country since 1942 to detect any relation between geomagnetic variation and earthquake-occurrences.

Besides these observations some efforts had been made for definitely detecting any local and minute geomagnetic variations by eliminating instrumentally the extensive and large variations of a diurnal or stormy character. In one method for this purpose various types of magnetic torsion balance were designed and examined.

Concerning the problem of geomagnetic variation of telluric origin, the phenomena of magnetostriction of the earth and the crust might possibly be considered apart from the problem of geomagnetic variation connected with earthquake-occurrence, volcanic eruption and the like. As the cause of magnetostrictive change of geomagnetic elements, the earth and crustal deformation caused by earth tidal force, the deformation of land by tidal load of sea water, and the like deserve an investigation and discussion. The study on this problem will in near future be reported in continuation of the present paper.

Summarizing the present plan of study, the following items will be investigated and discussed in each part of the present paper on geomagnetic variation of telluric origin :

Part I. On geomagnetic variation caused by oceanic tidal current

Part II. On geomagnetic variation associated with earthquakes

Part III. On geomagnetic anomaly observed at some areas of hot spring

In continuation of the above three articles, the followings are programmed.

Part IV. On geomagnetostrictive phenomena

Part V. On observation with geomagnetic torsion balance

Part VI. On local character of geomagnetic anomaly.

In the present article of Part I, observational results with a variometer of geomagnetic declination at three places near the strait are described. Those observation places are referred to Kitan Strait near Wakayama City, Akashi Strait near Akashi City, and Kanmon Strait near Shimonoseki City respectively, and all these straits are famous for their rapid tidal current.

2. Case of Kitan Strait

(a) Observation with the geomagnetic torsion balance

In the present case a simple type such as shown in Fig. 1 is treated out of many types of magnetic torsion balance. The principle is to eliminate the general diurnal or stormy variations of a large amplitude with gentle gradient and small curvature by making the magnetic moment of two magnets (Ml and Mr) as equal as possible, but to detect any local disturbances of a minute amplitude, with a sharp gradient and a large curvature. Two small permanent magnets of KS steel with 4 mm-diameter and 25 mm-length are fixed at both ends of an aluminum pipe of 1.5 mm-diameter and 27 cm-length, being oppositely oriented with respect to their magnetic poles, as

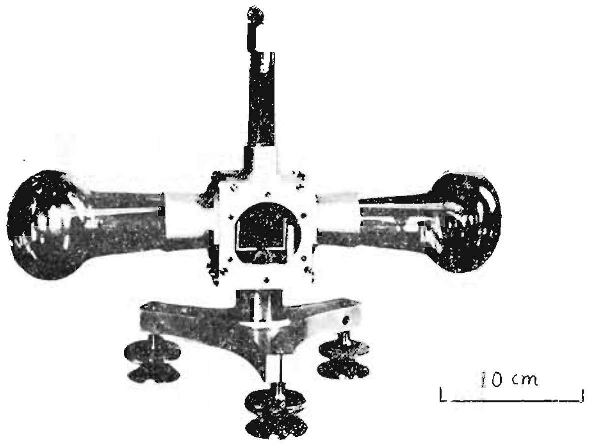

Fig. 1a. Magnetic torsion balance.

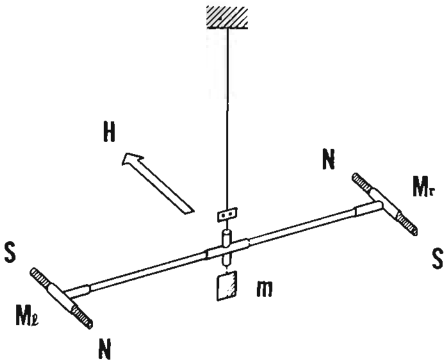

Fig. 1b. Principle of magnetic torsion balance.

schematically shown in Fig. 1b. This system of magnets is suspended by a thin strip of phosphorbronze with 9 cm-length and 1.5 c.g.s./radian/cm-torsional rigidity, and all parts packed air tight in an aluminum and glass case, as seen in Fig. 1a. The magnetic moments of both magnets are nearly 63.4 c.g.s. unit and adjusted to the order of 8×10^{-3} in the ratio of the difference between the magnetic moments of the two magnets (Ml-Mr) to the original Ml. This order of compensation is far from being satisfactory, and it is to be reduced to less than 10^{-6} for perfect elimination of diurnal and stormy variations.

A practical observation was made at Kada seashore ($\lambda=135°04'$E, $\varphi=34°17'$N) 20 m off and 12 m above sea-level of the Kitan Straits, as shown in Fig. 2. The observation room was an ordinary small underground room of brick, and the observation with the above described magnetic torsion balance was concurrently carried out with the ordinary magnetic variometer for declination during one year period from July 1947 to July 1948.

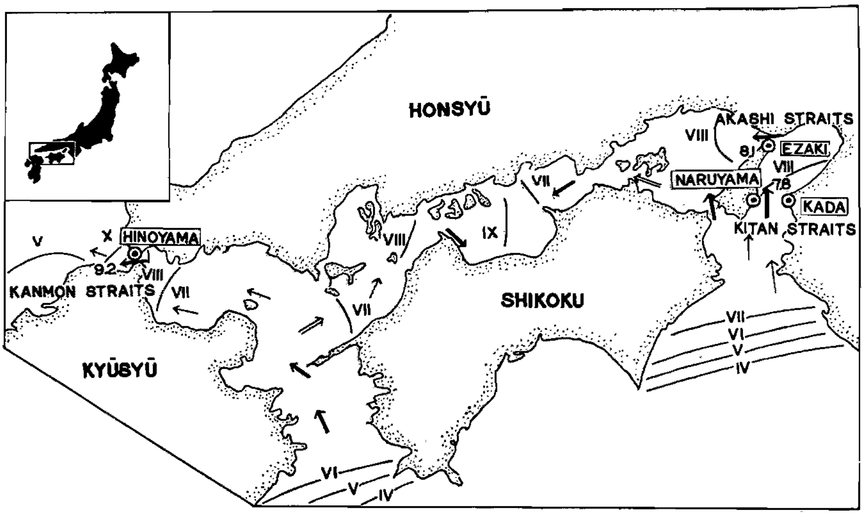

Fig. 2. Observation stations and co-tidal current chart (semi-diurnal)
→ 1-2 knots, ⇨ 2-3 knots, ➡ over 3 knots.

The period of free oscillation of the magnet-system, the optical distance in photographic recording, and the instrumental sensitivity, were estimated as 6 m 10 s, 312 cm, and 0.029 γ/mm/27 cm for gradient of the magnetic field in EW direction. The period of free oscillation of the magnet system was theoretically calculated as 8 m 50 s when the two magnets perfectly compensated. The last mentioned sensitivity was experimentally determined by applying a magnet of known-magnetic moment placed several meters distant from the instrument in the EW direction. But in practice, the variation recorded in the magnetogram was never discriminated whether it was caused by variation of the gradient or curvature of the magnetic field. The optical distance and sensitivity of the declinometer used for comparison was 182 cm and consequently 0′.96/mm respectively in the present case. The magnetograms thus obtained were shown in Fig. 3, as an example, for periods of February 29–March 7, and March 7–March 14, 1948. As represented in the Figure, the usual diurnal variation of declinations was also recorded in the magnetic torsion balance in the reduced value of about 1/2 and the opposite sense compared with that in the ordinary declinometer. The reason of opposite sense could easily be explained by reason of a reflecting mirror of 45°-orientation placed between the magnetic torsion balance and the recording equipment placed orthogonally to each other. Declination variations of usual

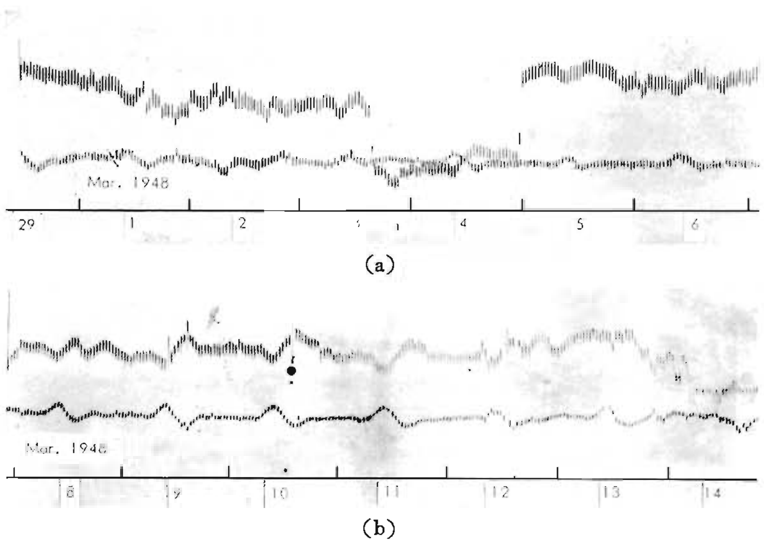

Fig. 3. Magnetograms by magnetic torsion balance (upper) and declinometer (lower).

types observed in the magnetic torsion balance were certain to be caused by a remaining feeble imaginary magnet deduced from an imperfect compensation of the two magnets, and the reason for the nearly same amplitudes recorded in both instruments in spite of the large optical distance of the magnetic torsion balance in nearly twice that of the declinometer, offered an interpretation that the magnetic moment of the remaining imaginary magnet was so weak as to be reducedly influenced by the torque of the thin suspension strip, whereas the rotational motion of magnet in the declinometer was entirely free from the effect of the suspension strip. In connection with this the magnetic moment of the magnet in the declinometer was 650 c.g.s. unit and the torsional rigidity, 0.24 c.g.s./rad./6 cm.

As is clearly seen in the magnetograms inserted as examples in Fig. 3, a complex wavy motion was observed in addition to the ordinary diurnal variation of declination. In connection with this, a test observation with the same torsion balance but with substitution of a non magnetic material (copper) for the magnets in the same weight was made, and it was ascertained from this experiment that this magnetic torsion balance was little gravitationally influenced by the tidal change of sea water in Kitan Straits. Taking the circumstances above described into consideration, the following procedure was provisionally applied to detect the influence of ocean tides upon the geomagnetic variation in the present case. Namely, during the suitable quiet period of one month from March 5 to April 3, 1948, the hourly values observed by the magnetic torsion balance, were read, and the corresponding values of declination observed by the declinometer were subtracted from them taking into consideration the difference in sensitivity of the two instruments. The values thus calculated were harmoniously analysed, giving, in this way, the following numerical result for the M_2-component,

$$0.34\,\text{mm}\cos(2t-9.1^h)\ \text{for eastward deflection.}$$

On the question whether this geomagnetic variation of tidal period was caused by the difference of magnetic field intensity or the curvature at two points of the magnets, or by deflection of the remaining imaginary magnet originating from imperfection of the compensation, no definite way of judging was yet possible. At any rate it could correctly be said that the variation above stated was certainly caused by the ocean tides of a neighbouring strait, and had no connection with the variation of the L_2-term judged from the points of amplitude and phase angle. Should the above result be tentatively expressed as geomagnetic variation of the declination, due to a feeble remaining imaginary magnet or variation in the difference of geomagnetic field at two points of magnet-orientation by the geomagnetic gradiometer, the following numericals would ensue.

As M_2-variation of geomagnetic declination : $3.0\gamma\cos(2t-9.1^h)$ for eastward deflection

As M_2-variation of geomagnetic gradient : $0.01\gamma\cos(2t-9.1^h)$ for 27 cm-span

(b) Simultaneous observations of geomagnetic declination

As described in the preceding section, effects of ocean tides upon the geomagnetic field at a neighbouring seashore station was certainly observed. In the present section such effect is discussed from another standpoint. Simultaneous observations with the geomagnetic declinometer were carried out since September 1954, at two stations of Kada and Naruyama, their positions being illustrated in Fig. 2. They are situated at opposite sides of the Kitan Straits, both observation rooms being small and underground of brick building. It is to be remarked that the station of Kada in the present case was nearly 3 km southward from the station mentioned in the preceding section. Instruments were geomagnetic variometer for declination of ordinary type, the suspended magnet being a KS-steel magnet of 6 mm-diameter, 75 mm-length, and 700 c.g.s.-magnetic moment, and the suspension strip being phosphorbronze strip with 75 mm-length and 1.5 c.g.s./rad./cm-torsional rigidity. The optical length in photographical recording was kept at exactly 400 cm at both stations, and the photographic papers were exchanged once a day, their time pitches being 22.5 mm/hour and 23.0 mm/hour for the stations of Kada and Naruyama respectively. The magnetograms thus obtained at the two stations were shown, as an example, in Fig. 4. As

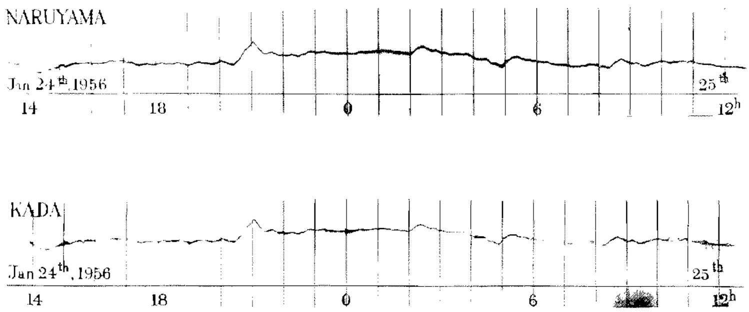

Fig. 4. Magnetograms by declinometer observed at Naruyama and Kada.

clearly seen in the Figure, the mode and amplitude of variation at the two stations were well in accord with each other even in detailed points. In the present treatment, the hourly values at Kada were subtracted from those at Naruyama, applying fine adjustment for perfect elimination of geomagnetic diurnal and stormy variations. These procedures were applied independently of the data of each month, and the results obtained in this way for the suitably quiet day were tabulated as in the following.

From the above table the total effect for declination was roughly estimat-

Component tides: H cos (nt-κ)

Epoch	M_2		S_2		K_1		O_1	
	H	κ	H	κ	H	κ	H	κ
1956 I. 16–II. 14	0'.0343	8.0^h	0'.0067	10.3^h	0'.0130	13.6^h	0'.0156	5.0^h
II. 14–III. 14	290	8.3	202	8.8	167	9.7	84	14.1
III. 25–IV. 23	284	8.5	122	8.0	155	10.5	78	9.0
Mean	0'.0306	8.3	0'.0130	9.0	0'.0151	11.3	0'.0106	9.4

ed for the semidiurnal component (M_2, S_2,……) as 0'.1 for double amplitude and 8h for phase lag. It is to be remarked that the positive values in cosine-form in the above table meant a westward magnetic deflection at Naruyama or a eastward magnetic deflection at Kada. Concerning the results above described it would be correctly emphasised that the effects of the ocean tides upon the magnetic field at the two stations were clearly observed, though in minute amplitudes, because three values calculated independently from three months' data showed a satisfactorily good coincidence, especially for M_2-component, in amplitude and phase angle.

It was a hard task to clarify the source and mechanism of this effect of the ocean tides in a pricise manner, but, in this section, some considerations upon them will be mentioned briefly. As deductable from the tidal current chart represented in Fig. 2, this effect was reasonably interpreted as intimately related to the action of oceanic tidal current of the Kitan Straits, because the time of maximum amplitude for the M_2-component observed from the present simultaneous observation with the geomagnetic declinometer nearly coincided with that of the maximum speed of the tidal current. Consequently, it was convenient to calculate approximately to what degree the tidal current affected the geomagnetic field of neighbouring station. As deduced from the tidal chart and bathygraph around the Kitan Straits, the circumstances were greatly different at the two stations, Kada and Naruyama, the mean sea depth, the direction and maximum speed of tidal current near the places, Kada and Naruyama, being 30 m and 100 m for depth, NNE and NNW for direction, and 1 m/sec and 4 m/sec for current speed, respectively. Under these circumstances a magnetic field caused by the tidal current of sea water in the earth's main magnetic field, was roughly estimated.

The problem of tidally induced electric current in water and earth near the channel or strait was first discussed early by M. Faraday in 1832, and since that day many observations followed for measuring the potential difference between a pair of electrodes properly laid across the channel or strait. Recently, a detailed study on this problem was made by N. F. Barber (1948) and an observational and theoretical treatment, especially taking the conductivity of the channel bed in consideration, was made by M. S. Longuet-Higgins (1949) and (1954). Recently T. Kiyono investigated the same phenomenon from the point of underwater electric cable (1959). In the present case a very rough estimation was made of magnetic field induced by the tidal current of the Kitan Straits assuming that an electric current in the water was produced by the tidal motion of water in the earth's magnetic field as an electric sheet current of a infinite area.

Denoting E, v, z, σ, j, D, J and ΔH as the electromotive force, speed of tidal current, vertical component of earth's main magnetic field, specific electric conductivity, specific electric current, thickness of water in tidal current, intensity of electric sheet current, and the magnetic field caused by the tidal current, their relations were defined as follows, after manner of treatment as in the dynamo-theory of geomagnetic daily variation

$$E = vz$$
$$j = \sigma E$$
$$J = \sigma ED$$
$$\Delta H = 2\pi J,$$

and their practical values in the present case were approximately determined as

	near Kada	near Naruyama
v	100 cm/sec	400 cm/sec
z	0.35 Gauss	0.35 Gauss
σ	3.4×10^{-11} e.m.u.	3.4×10^{-11} e.m.u.
D	3×10^{3} cm	1×10^{4} cm

From these, all expressed in e.m.u.

	near Kada	near Naruyama
E	35	140
j	1.19×10^{-9}	4.76×10^{-9}
J	3.57×10^{-6}	4.76×10^{-5}
ΔH	2.36×10^{-5}	30.0×10^{-5}

In the present case the value of ΔH meant the additive magnetic field, whose direction is coincident with that of tidal current, had 2.4γ for Kada and 30γ for Naruyama respectively, and these being caused by electric sheet current of orthogonal direction to that of tidal current induced by the tidal current of electrically conductive sea water in the vertical geomagnetic field.

Practically, the electric current system induced in the water was never considered to be an electric sheet current of infinite area. Moreover, the semi conductive strait-bed and side rock, though their conductivities were far smaller than that of sea water (e.g. $\sigma = 10^{-15} \sim 3\times10^{-14}$ for granite, $2\times$

$10^{-14} \sim 10^{-12}$ for consolidated sedimentary rock), affected the form of the electric current system in water, and greatly reduced its electric current intensity. In the present case the affected ΔH for variation of the declination was $\Delta H \sin Q$, where Q meant the angle between the magnetic meridian and the direction of tidal current of water. If Q be tentatively assumed as 20° eastward at Kada and 20° westward at Naruyama, the magnetic effect of deflecting the declinometer to E at Kada was roughly estimated as 0.8γ, and that to W at Naruyama 10.4γ, thus giving of a variation of declination in the values would be greatly reduced by the above mentioned effect of semiconductive rock and other various effects, but it was to be emphasised that the roughly calculated effect of the oceanic tidal current would approximately explain the observed values at the two stations in the point of order of magnitude of variation, and especially of the direction of deflection.

In the following chapters, the observational data obtained with geomagnetic declinometer at the areas of Akashi Straits and Kanmon Straits are discussed, these areas being comparatively suitable for study on the effect of oceanic tidal current upon the geomagnetic variation than those of Kitan Straits above described. Moreover it must strongly be mentioned that the data obtained at Kanmon Straits are highly reliable, because one observation room in this case is underground room beneath the strait.

3. Case of Akashi Straits

The direction of tidal current in case of the former observation at Kitan Straits is nearly NNW-SSE, and consequently, its effect upon the geomagnetic variation of declination is certainly expected to be small. But in the present case of Akashi Straits, the direction of tidal current is nearly in W-E as seen in Fig. 2, and its effect is presumed to be considerably larger compared with the former case. Under these circumstances the simultaneous observations with two geomagnetic variometers of declination were made during the two months' period of October 10-December 12, 1956 at two places of Ezaki and Kada. At Ezaki was a point at the southern coast of Akashi Strait, but at Kada not a point near Akashi Strait. At Kada it was a point at the eastern coast of Kitan Straits, the same point as already described in the preceding section, and was selected from two reasons; one, there was no suitable observation station at the northern coast of Akashi

Straits, two, Kada was ascertained to be little affected by tidal current effects upon geomagnetic variation as already mentioned. The observation point at Ezaki was composed of Ezaki Lighthouse close to the strait, only 10 m distant, and 1.5 m above the sea level. The observation point at Kada was 70 m distant from the eastern seashore of Kitan Straits and 30 m above the sea level. The longitude and latitude of both stations were read 135°00′E and 34°36′N for Ezaki and 135°04′E and 34°16′N for Kada respectively, their relative position and chart of tidal current near both straits being shown in Fig. 2.

The instruments used in the present case were the same as in case of Kitan Straits of the preceding section, the method of recording and analysis also were similar to the former case. The magnetograms obtained at two stations are shown, as an example, in Fig. 5.

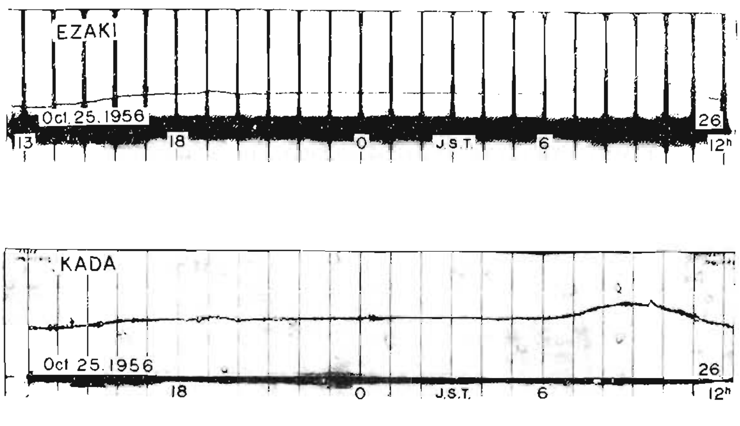

Fig. 5. Magnetograms by declinometer observed at Ezaki and Kada.

Concerning the process of analysis, the difference between the hourly read values of the data obtained at Kada and Ezaki were first calculated. The data used in analysis were those of one month at two stations during the period of October 11–November 9, 1956. It was ascertained after the first stage of analysis that the difference thus calculated showed a considerably large remaining daily variation. It indicated that the amplitudes of daily variation at both stations were not quite the same. This difference of amplitude at both stations was considered to be probably caused by the difference of their latitudes (34°16′ for Kada and 34°36′ for Ezaki), the difference of their geomagnetic elements (0.31 gauss for H at Kada 0.26 gauss for H at Ezaki), the difference of surrounding geological and topographical conditions for geomagnetic variation, and the like. Taking these particular circumstances into consideration, the following procedure was specially applied to the present analysis. Namely a mean curve of remaining daily variation was, as the first step, calculated by averaging the 30 values for each solar hour in the difference value already obtained. And next, their mean hourly values of remaining daily variation were subtracted from the hourly value of difference of the data between two stations above calculated. The remaining hourly values thus obtained were harmoniously analysed in an usual process. Both curves of the mean daily variation and the harmonious-

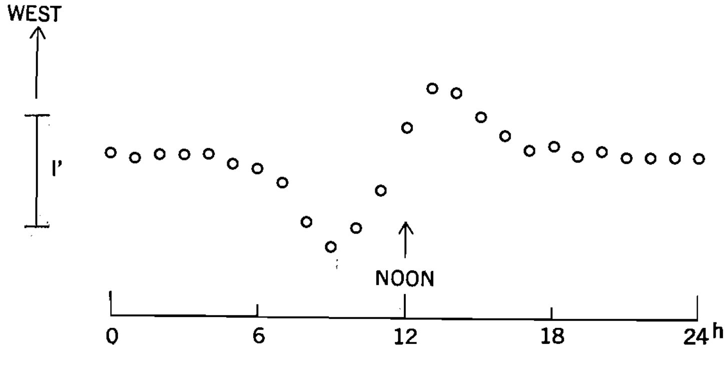

Fig. 6. Solar diurnal variation observed at Ezaki.

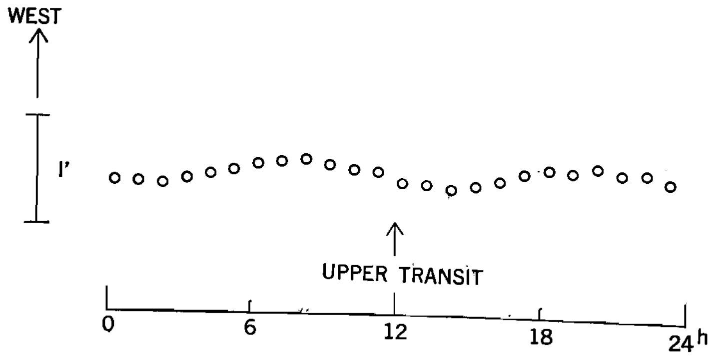

Fig. 7. Lunar semi-diurnal variation observed at Ezaki.

ly analysed value for M_2-component are shown in Fig. 6 and Fig. 7. The lunar-semidiurnal variation is clearly shown in Fig. 7, its amplitude being 0.13′ in declination and 1.2γ in field intensity.

The lunar-semidiurnal variation (M_2-component) of geomagnetic declination obtained by the analytical process above described was reasonably interpreted as caused by the effect of tidal current at Akashi Straits upon the geomagnetic element at Ezaki. This was ascertained by the following brief calculation ; namely, the same calculation as used in case of Kitan Straits was also effectively applied to the present case.

Denoting E, v, z, σ, j, D, J and ΔH as the electromotive force, speed of the tidal current, vertical component of earth's main magnetic field, specific electric conductivity, specific electric current, depth of water in tidal current, intensity of the electric sheet current, and the magnetic field caused by the tidal current, their relations were defined as follows :

$$E = vz$$
$$j = \sigma E$$
$$J = \sigma ED$$
$$\Delta H = 2\pi J,$$

and their practical values in the present case were

$$v = 150 \text{ cm/sec}$$
$$z = 0.35 \text{ gauss}$$
$$\sigma = 3.4 \times 10^{-11} \text{ e.m.u.}$$
$$D = 7 \times 10^3 \text{ cm.}$$

From this the change of geomagnetic horizontal intensity caused by tidal current expressed in e.m.u. would mean

$$\Delta H = 8.0 \times 10^{-5}.$$

The difference of ΔH-values between those obtained from the observation (1.2γ) and the calculation (8.0γ) was reasonably explained by the following interpretation. The electric current induced by motion of the sea water in the geomagnetic field formed a sheet of solenoidal current, and consequently the induced magnetic field in this case was mainly in the interior of this solenoidal sheet. Moreover the value of 8.0γ above calculated should greatly be reduced in practical case of taking the electric conductivity of the rock of sea shore and the bottom of strait into consideration. Because the simple calculation above described was obtained in case of neglect of electric resistance of rock, and practically the induced electric circuit was formed by connecting the sheet of sea water and layer of the surrounding rocks.

Next, concerning the phase of observed lunar-semidiurnal variation, the time of maximum westward deflection at Ezaki was 8.3h. On the other hand the time of the most rapid westward tidal current in Akashi Straits is 8.1h as seen in Fig. 2. Thus the analysed value showed a good agreement with the practical one in the points of phase and direction of tidal current. Mention be made that the induced geomagnetic effect by tidal current observed at Ezaki was observed as an external magnetic field of solenoidal electric current caused by tidal motion of the sea water, because the direction of induced magnetic flux in solenoid was, in the present case, from W to E, resulting in an eastward deflection of declinometer in time of westward maximum tidal current (8.1h).

In the present case the effect of tidal current of Akashi Straits upon the geomagnetic field of the surrounding area was rather clearly observed. Speaking in detail the observed amplitudes of the induced geomagnetic variation for declination showed 0.03′ (ΔD) or 0.28γ (ΔH) at Naruyama near Kitan Straits, and 0.13′ (ΔD) or 1.2γ (ΔH) at Ezaki near Akashi Straits respectively. Under these conditions the data obtained at Ezaki and Akashi Straits were certainly to be regarded trustworthy. But it had left yet something to be desired in the point that an induced geomagnetic effect concerned was the external magnetic field of solenoid of induced electric current, precise calculation of which is very difficult. In this stage an observation at the point in the solenoid of induced electric current in the strait was further strongly desirable to treat the present study in a physically rigorous manner. Then a similar observation operated in an under sea bottom tunnel at Kanmon Straits is given in detail in the next section.

4. Case of Kanmon Straits

Kanmon Straits between Honshu Province and Kyushu Province is famous for its rapid tidal current, its position and tidal current charts being shown in Fig. 2. Early in 1943, an underground tunnel for railway was constructed beneath the strait, and another underground tunnel for general traffic was also constructed in our observation period of 1959. Same type observations as at those places that had been described were carried out at two points under and near Kanmon Straits. Namely one (named Tunnel Observatory) was in the pilot tunnel for the new main tunnel above mentioned, and another (named Hinoyama) on the top of a hill near the strait in Simonoseki City, as shown in Fig. 8. One would remark that the observation room in the pilot tunnel was selectively situated in the part of non-reinforced concrete of tunnel to avoid the magnetic effect of steel skelton. The longitude and latitude of two points were roughly 130°57′E and 33°57′N ; and their mutual horizontal distance was 700 m. Their heights from sea level were −45 m for Tunnel Observatory and 90 m for Hinoyama, and their horizontal com-

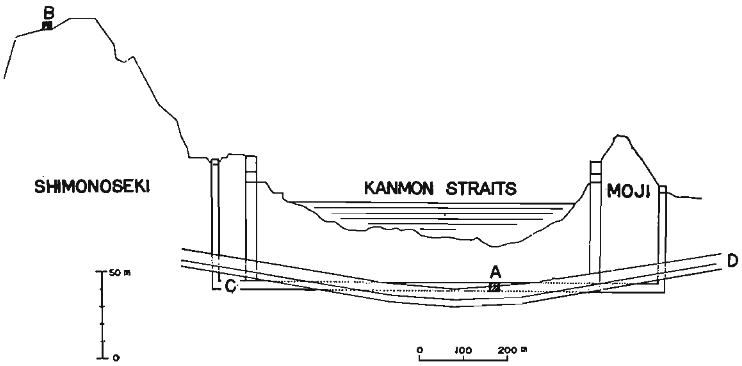

Fig. 8. Section of Kanmon Straits.
A : Tunnel Observatory B : Hinoyama Observatory
C : Pilot tunnel D : Main tunnel

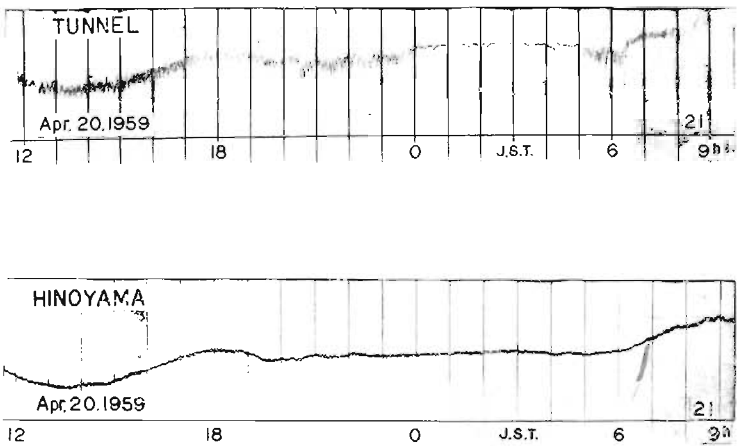

Fig. 9. Magnetograms by declinometer observed at Tunnel and Hinoyama.

ponents of geomagnetic intensity were 0.31 gauss and 0.32 gauss respectively.

The period of observation was 1.5 months during March 25–May 10, 1959, and the method and instrument used in the present observation were all identical with the preceding two cases. Examples of magnetogram observed at two points are shown in Fig. 9. It is clearly seen, as in Fig. 9, that the point of Tunnel Observatory was greatly, magnetically disturbed, especially in daytime, by the effect of an intense traffic in the public road tunnel which runs parallel to the pilot tunnel concerned as shown in Fig. 8, the distance between two tunnels being only about 10 m.

Taking those conditions into consideration the usual analytical process, which was applied for the two preceding cases, was repeated. Namely the difference between the raw hourly values during one month from March 26 to April 24, 1959 observed at Tunnel Observatory and Hinoyama, was first calculated. The result was, as expected, greatly disturbed in the form of sud-

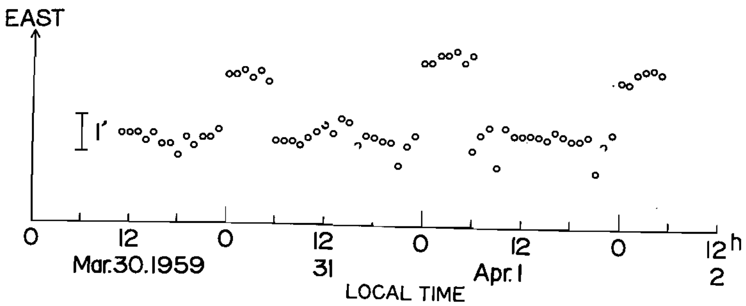

Fig. 10. Difference value of declination between those observed at Tunnel and Hinoyama.

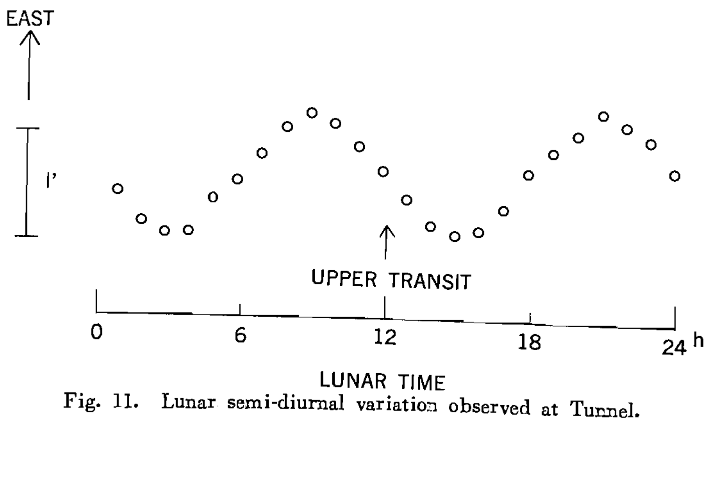

Fig. 11. Lunar semi-diurnal variation observed at Tunnel.

den jumps as shown in Fig. 10. After suitable correction for these disturbances considered to be caused by an artificial origin, the smoothed data were harmoniously analysed in an ordinary method. The result arranged in lunar time was plotted as in Fig. 11, and had also a semi-diurnal variation clearly seen. Phase and amplitude of this M_2-component were 8.8h (maximum eastward deflection) and 1.1′ for ΔD or 10γ for ΔH respectively.

In the present case the time of maximum westward tidal current was nearly 9.0h after the upper culmination of the moon over the meridian of 135°E (Japanese Standard Meridian), as seen in Fig. 2. The direction of maximum deflection in this case was eastward in time of maximum westward tidal current, showing an induced geomagnetic variation observed at Tunnel Observatory which was certainly the induced magnetic field inside the solenoid of electric current in the strait.

Concerning the amplitude of induced geomagnetic variation of declination observed at Tunnel Observatory, its value of 1.1′ (ΔD) or 10γ (ΔH) was exceedingly larger than those observed in the preceding two cases (0.03′ or 0.28γ at Naruyama and 0.13′ or 1.2γ at Ezaki). This was rightly expected from two conditions that the Kanmon Straits was famous for its high speed of tidal current, moreover nearly in the direction of E-W, and one of the present observation points was certainly in the electric current solenoid in the strait. As first step for discussion, the same calculation as the two preceding cases was made under an assumption that an electric current circuit induced by motion of the sea water was entirely in the sea water of the strait, and the calculation resulted as in the following :

Speed of tidal current (v) = 260 cm/sec

Vertical intensity of geomagnetic field (z) = 0.35 gauss

Specific electric conductivity of sea water (σ) = 3.4×10^{-11} e.m.u.

Thickness of water in tidal current (D) = 1.5×10^{3} cm

Horizontal component of induced magnetic field (ΔH) = 30×10^{-5}

But, in the present case, the expected amount of induced magnetic variation must be calculated for an electric current circuit formed by sea water, rock of two opposite sides, and the bottom rock in the strait. This problem was in detail treated by M. S. Longuet-Higgins in (1948) and (1954), and, in the present case, the value of specific electric conductivity of surrounding rock was calculated to give an observed value of 10γ as an induced magnetic field inside its electric current solenoid caused by a tidal motion of the sea water in the strait. Namely, following the treatment described in Longuet-Higgins' paper, the total current J flowing round the circuit was approximately denoted by the formulae,

$$J=\frac{l\cdot E}{Ri+Re}$$

where l, E, Ri and Re denoting the width of strait, induced voltage difference, internal resistance on the part of sea water, and external resistance on the part of bed rock respectively. And moreover

$$E\simeq vz,\qquad Ri\simeq \rho l/D,\qquad Re\simeq \rho'$$

where, v, z, l, ρ, D and ρ' represented velocity of tidal current, vertical component of geomagnetic force, width of strait, specific resistivity of sea water, its depth and specific resistivity of bed rock, respectively. In the present case,

$$v=260\ \text{cm/sec}$$
$$z=0.35\ \text{gauss}$$
$$l=600\ \text{m}$$
$$\rho=30\ \text{ohm-cm}$$
$$D=15\ \text{m}.$$

From these and the formula of $\Delta H=2\pi J$, we obtained the value of ρ' in case of $\Delta H=10\gamma$ as

$$\rho'=2.4\times10^{3}\ \text{ohm-cm}$$

This value of ρ' is considered to be comparatively low, but value of the same order was frequently observed in case of geoelectric exploration. For the sake of a reference the value of ρ' obtained by Longuet-Higgins in case of English Channel was $1.3\sim2.7\times10^{4}$ ohm-cm in case of observation of earth electric current. The difference of ρ'-values between two observations of our case and Longuet-Higgins' is reasonablly interpreted as caused by the different conditions of Kanmon Straits from English Channel, and moreover difference in method of observation, namely one being a geomagnetic method and the other an earth current method.

In summary the induced magnetic variation caused by the tidal current was observed with a variometer of declination at these places near Kitan Straits, Akashi Straits and Kanmon Straits. Especially at Kanmon Straits, the observation was made at point underground room of bed rock, and the quantitatively reliable value of induced magnetic variation was obtained, thus giving a dependable value of electric resistivity of the bed rock.

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