Intensity Studies of the Archaeo-secular Variation in West Japan, with Special Reference to the Hypothesis of the Dipole Axis Rotation

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Intensity Studies of the Archaeo-secular Variation in West Japan, with Special Reference to the Hypothesis of the Dipole Axis Rotation

By

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Abstract

Archaeo-secular variation of the geomagnetic total force in Kyoto during the past 4,000 years has been revealed in the natural remanent magnetization of the various archaeologic finds of known ages with the aid of the Thelliers' method. The results show that the total force at about 2,000 B.C. and 1,000 B.C. was about 1.4 and 0.9 times as large as that at present, and at about 0 A.D. it reached a maximum value, being 1.5 times as large as that at present, and since then it showed the comparatively monotonous decrease, accompanying a little fluctuation, to that of the present.

On the other hand, summarizing the five series of intensity data so far available, the secular variation of the reduced equatorial forces for the past 2,000 years is discussed with special reference to "the hypothesis of the dipole axis rotation" proposed by KAWAI, HIROOKA and one of the present writers (1965).

I. Introduction

Through the spherical harmonic analyses of the global observation data of geomagnetism, there can be little doubt that since the middle of the 19th century the total geomagnetic force has decreased at a rate of about 5% per century. Past geomagnetic fields before the time when observations have been commenced may be estimated by archaeo- or palaeo-magnetic means. However, the intensity studies made on the palaeo-geomagnetic field are much less in number as compared with the vast accumulation of knowledges about the ancient geomagnetic direction.

In order to estimate the reliable ancient field intensity, E. and O. THELLIER (1959) proposed a step-by-step heating method based on their extensive studies of the thermoremanent magnetization (T.R.M.), and they first suggested the monotonously decreasing trend of the total intensity from 600 B.C. to the present. Recently the intensity studies in various regions of the world have been presented by several authors such as BURLATSKAYA (1962), NAGATA, ARAI and MOMOSE (1963), BUCHA (1965), WATANABE and DuBOIS (1965) and NAGATA, KOBAYASHI and SCHWARZ (1965).

Since 1963, the writers have also carried out the study of the archaeo-secular variation of the geomagnetic field intensity by means of the Thelliers' method. The baked earths specimens used in this study were collected from the old kilns excavated in West Japan, and their stability and direction of natural remanent magnetization (N.R.M.) were already described in the publication of our colleagues (KAWAI *et al.*, 1965). In this paper, the results of the archaeo-secular variation in the field intensity at Kyoto for the past 4,000 years are described.

On the other hand, soon after the publication of the present writers' preliminary report (1964) of the palaeo-intensity in West Japan KAWAI, HIROOKA and one of the present writers (1965) suggested the counter-clockwise rotation of the geomagnetic dipole axis during the past 1,500 years by analysing the results of the archaeo-secular variation so far reported by several researchers. If the newly proposed "hypothesis of the dipole axis rotation" is valid, it will be clear that several results of the archaeo-secular variation of field intensity should be much better explained by this hypothesis than the current theory. So the final discussions of this paper are paid on the question whether the hypothesis can be supported also from the viewpoint of the intensity measurements or not.

II. Specimens

Specimens used in this study are chiefly baked earths collected from the old kilns excavated from West Japan, and the ages of these kilns have been accurately estimated by K. YOKOYAMA* of Archaeological Institute of Kyoto University; these ages are ranging from the Kofun Era (the 5th century) to the Kamakura Period (the 13th century). It may be without question that the baked earths of these kilns were subjected to the repeated heatings to several hundreds centigrade, and therefore they acquired the T.R.M. under the geomagnetic field at the time of the last firing. For this reason, they are generally considered to be the most suitable specimens for investigating the archaeo-secular variation of the geomagnetic field intensity. In addition to these baked earths specimens, some potteries of older ages and some eruptive rocks of younger ages are supplied to the experiment.

Data for these specimens, including locality, estimated age and the Curie temperature of their ferromagnetic minerals are given in Table 1, and a distribution map of localities of these specimens is shown in Fig. 1. Thermomagnetic, microscopic and X-ray investigations along with the chemical analysis of the ferromagnetic minerals contained in these specimens have also been carried out. Considering

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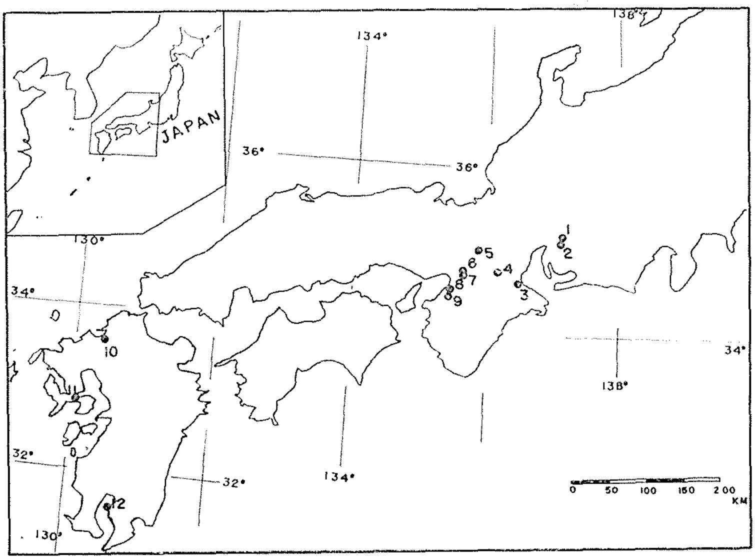


Fig. 1. A map showing distribution of the localities from which specimens were collected: sampling sites are shown in the following numbers.
1. Seto city 2. Nisshin-chō and Miyoshi-chō 3. Hisai-chō
4. Ueno city 5. Ōtsu city 6. Hiraoka city 7. Daitō city
8. Sakai city 9. Izumi city 10. Kasuga-chō 11. Isahaya city
12. Sakurajima

from the present state of our studies, most of these minerals are seemed to be so-called oxidized titanomagnetites having the spinel structure.

Several examples of the thermomagnetic curves of specimens under a strong magnetic field are shown in Fig. 2. From these diagrams and Table 1 it is found that their Curie temperatures are predominantly within the temperature range 525°–550°C. It is noteworthy, however, that these specimens are highly stable against the heat treatments in air within the limits of our experimental temperature and duration. The detailed results of the magneto-mineralogical research will be reported in the near future.

III. Method of Intensity Measurement

An accurate method of estimating the ancient geomagnetic field intensity has been established first by E. and O. Thellier (1959) through their extensive studies on T.R.M. of various potteries, bricks and baked earths. Further detailed investigation on T.R.M. has lately been advanced by C.W.F. Everitt (1961), who has established from the theoretical and experimental points of view that the intensity of

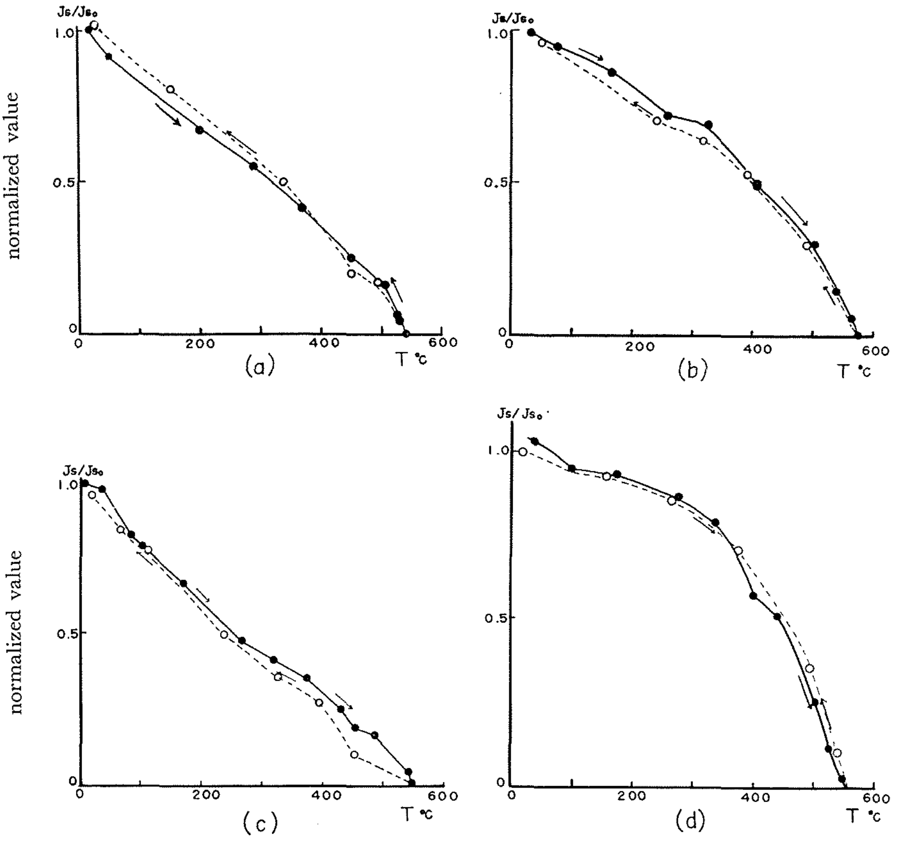


Fig. 2. Some examples of thermomagnetic curves of the specimens.
(a) 0–53 (b) Takakura (c) Hisai-3 (d) Yayoi-type pottery
—●— heating ···○··· cooling

T.R.M. and the strength of the ambient field are in a linear relation within the range of weak field of several oersteds.

The present writers have also studied the secular variation of the ancient field intensity with the aid of the Thelliers' step-by-step heating method. The practical procedures are as follows;

(i) Original N.R.M. of specimen (Jn) is measured at first, and it is expressed by the next form;

$$Jn = [F]_{T0}^{Tc} \quad (1)$$

where $[F]_{T0}^{Tc}$ denotes the total T.R.M. which was acquired under the ancient field intensity F between the Curie temperature T_c of the specimen and the room temperature T_0.

(ii) The specimen is heated up to a temperature T_1 ($T_0 < T_1 < T_c$) and then cooled to T_0 under the present laboratory field F_0. Then specimen acquires partial T.R.M. (P.T.R.M.), $[F_0]_{T0}^{T1}$ losing the demagnetized vector $[F]_{T0}^{T1}$, and the resultant vector $M_1 = \{[F]_{T0}^{Tc} - [F]_{T0}^{T1}\} + [F_0]_{T0}^{T1}$ will be measured.

According to the addition law of partial T.R.M.,

$$[F]_{T0}^{Tc} - [F]_{T0}^{T1} = [F]_{T1}^{Tc} \tag{2}$$

Substituting $[F]_{T1}^{Tc} = \Delta Jn(T_1)$ and $[F_0]_{T0}^{T1} = Jt(T_1)$, then it becomes

$$M_1 = \Delta Jn(T_1) + Jt(T_1) \tag{3}$$

where $\Delta Jn(T_1)$ is the remainder of Jn after the partial demagnetization up to T_1, and $Jt(T_1)$ is the newly acquired P.T.R.M. between T_1 and T_0.

(iii) The specimen is set in a reversal position so as to acquire a new partial T.R.M. antiparallel to the direction of $Jt(T_1)$. After the inverse set the specimen is again subjected to the heating-cooling treatment as in the process (ii). Then, the following resultant vector M_2 will be measured;

$$\begin{aligned} M_2 &= \{[F]_{T0}^{Tc} - [F]_{T0}^{T1}\} - [F_0]_{T0}^{T1} \\ &= \Delta Jn(T_1) - Jt(T_1) \end{aligned} \tag{4}$$

(iv) From (3)+(4) and (3)−(4), the next equations are obvious.

$$(M_1 + M_2)\tfrac{1}{2} = \Delta Jn(T_1) \tag{5}$$

$$(M_1 - M_2)\tfrac{1}{2} = Jt(T_1) \tag{6}$$

(v) When the similar processes are carried on in every temperature range, $T = T_1$, $T = T_2, \cdots$, $T = T_n, \cdots (T_0 < T_1 < T_2 < \cdots < T_n < \cdots < T_c)$, the corresponding values of $\Delta Jn(T_n)$ and $Jt(T_n)$ will be given.

Thus, the all sets of intensity values of $\Delta Jn(T_n)$ and $Jt(T_n)$ are plotted on a diagram, where the abscissa gives $Jt(T)$ and the ordinate $\Delta Jn(T)$. If the factors concerned to the acquisition of T.R.M. remained invariable throughout the heat experiments of the same specimen, $[F]_{T0}^{Tn} / [F_0]_{T0}^{Tn}$ is proportional to F/F_0, therefore all the plots of $\Delta Jn(T_n)$ *v.s.* $Jt(T_n)$ must fall on a straight line. From the slope of this line the ratio of F to F_0 can be successfully determined. If the contained ferromagnetic minerals were changed in the course of the experiment, the linear relation can not be held, and such a datum must be omitted after the Thelliers' criteria.

IV. Results of the Intensity Measurements

More than 70 specimens were submitted to the intensity measurements, of which a typical example is shown in Fig. 3. The specimen shown in this example was collected from the kiln, 0–53 (of the Table 1), of which age was estimated to be 1,000±20 years A.D.. Upper diagram of the figure shows the variation of the remanent direction during a run of experiments plotted on the Schmidt's projection. It is found from the diagram that the direction of remanence measured during an experimental run moves regularly along the great circle containing directions of both the original remanence and the geomagnetic field at the laboratory. From

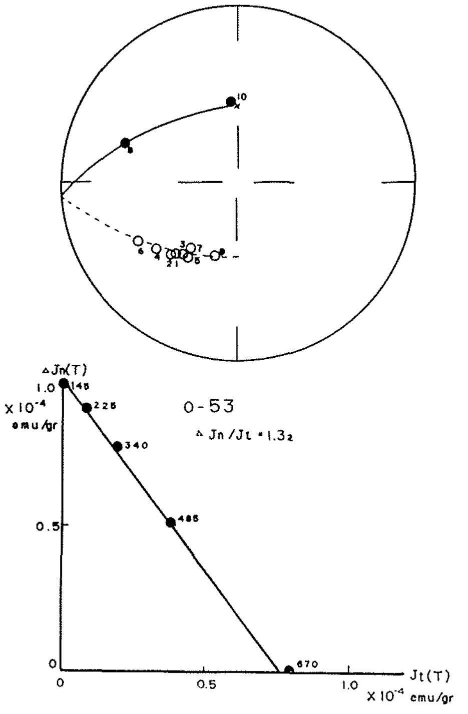


Fig. 3. A result of the intensity measurements showing the change of remanent direction during a run of experiments plotted on Schmidt's net (in upper diagram), where cross mark indicates the direction of laboratory field. The numerals nearby solid and hole circles represent the order of successive experiments:

1, 20° 2–3; 145° 4–5; 225° 6–7; 340° 8–9; 485° 10; 670°C.

●: lower hemisphere ○: upper hemisphere

Lower diagram shows the relation of $\Delta Jn(Tn)$ *versus* $Jt(Tn)$. The numerals nearby solid circles represent the temperature of heat-treatment in centigrade.

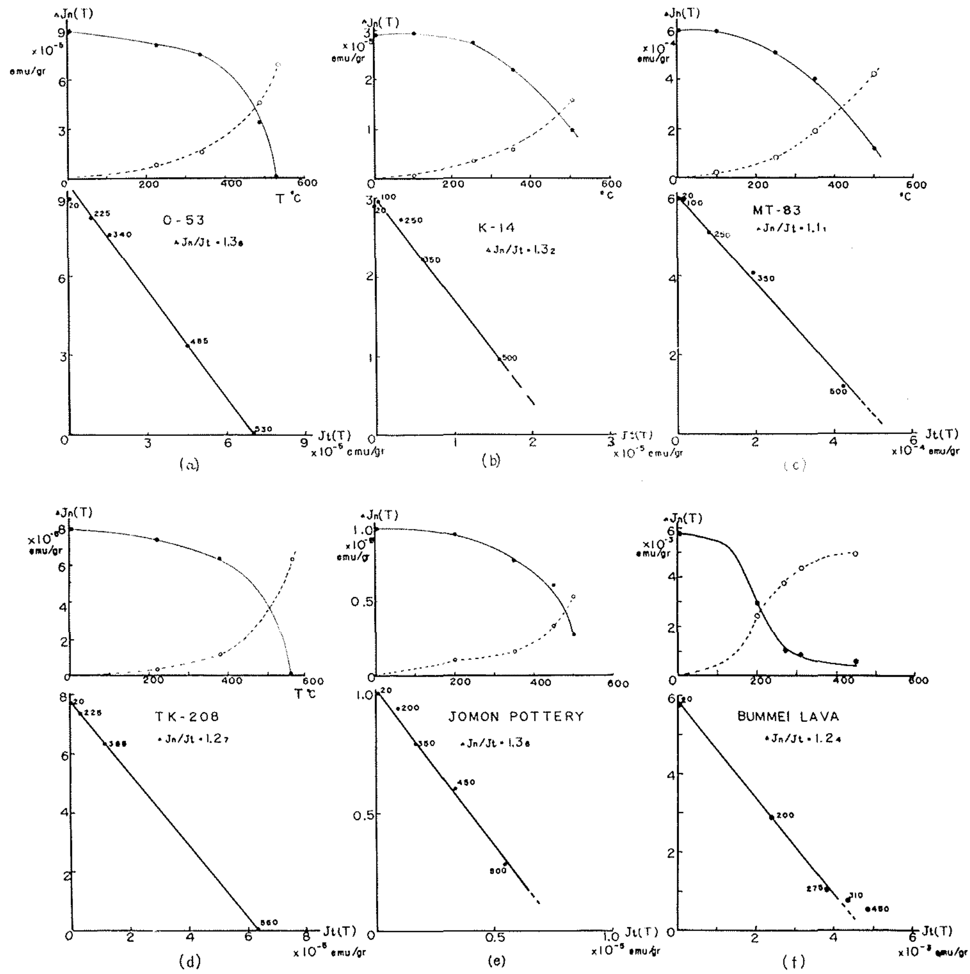


Fig. 4. Some examples of the intensity measurements. Upper diagram shows the relation between the demagnetization of the original N.R.M. (full line) and the acquired P.T.R.M. (broken line), and lower diagram shows the relation of $\Delta Jn(Tn)$-$Jt(Tn)$.
(a) 0–53 (b) K-14 (c) MT-83 (d) TK-208 (e) Jomon-type pottery (f) Bummei-lava in Sakurajima

this fact it is confirmed that the experiment has gone under the fully satisfied condition. On the other hand, the calculated values of the $\Delta Jn(T_n)$ and $Jt(T_n)$ at each temperature are plotted in the lower diagram. As mentioned in the previous chapter, the slope of the line gives the ratio of the ancient geomagnetic field intensity to that of the present, and it is estimated to be 1.32 in this example.

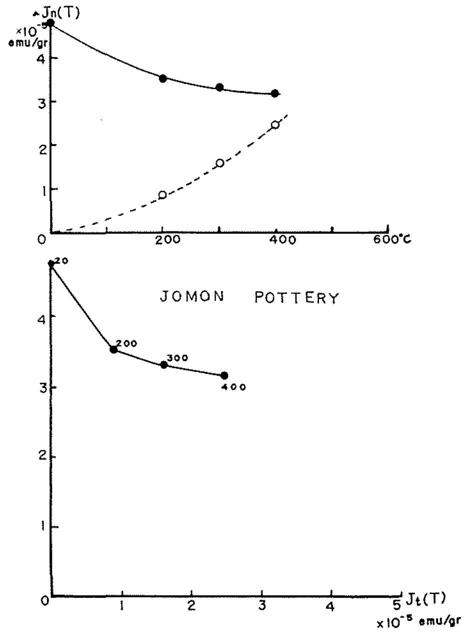


Fig. 5. An example showing the intensity measurements without success.

Some of other results are shown in Fig. 4. In this figure, the full lines and the broken lines of the upper diagrams show the demagnetization curves of original N.R.M. and the magnetization curves newly acquired in the laboratory field . In addition to these good examples, one of unsuccessful examples giving a non-linear relation in $\Delta Jn(T_n)$-$Jt(T_n)$ plots is shown in Fig. 5. This non-linear phenomenon can be interpreted as due to chemical or other changes of the ferromagnetic minerals during the heating process. Such specimens are excluded in this study, and thus excluded specimens in the present study amount to one-thirds of the whole specimens treated. It was pointed out also by NAGATA *et al.* (1963) that some of the ancient potteries gave similar non-linear relation in their measurements especially in higher temperature, and for this reason these potteries were presumed by them to have baked at a temperature appreciably below their Curie temperature.

Table 1. Data of specimens including the estimated age, material and the ratio of the ancient geomagnetic total force (F) to that at present in Kyoto ($Fo_{(1965)}=0.466\Gamma$).

Site	Locality	Material	T°C	Age	Number of specimen	F/Fo
Sakurajima	Kagoshima	andesite	380	1780 ± 5 A.D.	1	1.1
Sakurajima	Kagoshima	andesite	510	1470 ± 5 A.D.	1	1.2
Fusō-3	Seto	baked earth	515	1280 ± 50 A.D.	4	1.23 ± 0.01
0-53	Nisshin	baked earth	530	1000 ± 20 A.D.	4	1.26 ± 0.02
K-14	Miyoshi	baked earth		960 ± 20 A.D.	4	1.45 ± 0.03
MT-83	Sakai	baked earth		810 ± 10 A.D.	1	1.40 ± 0.19
K-84	Miyoshi	baked earth	525	800 ± 10 A.D.	1	
KM-13	Izumi	baked earth	535	780 ± 20 A.D.	1	1.35 ± 0.06
Sakai-48	Sakai	baked earth	510	750 ± 40 A.D.	1	
MT-21	Sakai	tile		720 ± 20 A.D.	5	1.43 ± 0.04
I-17	Nisshin	baked earth		690 ± 10 A.D.	2	1.21 ± 0.06
Takakura	Sakai	baked earth	550	650 ± 50 A.D.	2	1.48 ± 0.10
MK-8	Sakai	baked earth	500	540 ± 40 A.D.	4	1.46 ± 0.03
TK-47	Sakai	baked earth	525	520 ± 20 A.D.	1	
Hisai-3	Hisai	baked earth	540	480 ± 10 A.D.	1	1.44 ± 0.06
TK-208	Sakai	baked earth		470 ± 30 A.D.	2	
	Ueno	clay idol		380 ± 20 A.D.	2	1.35 ± 0.09
	Hiraoka	pottery		220 ± 20 A.D.	2	1.41 ± 0.01
	Kasuga	pottery		100 ± 50 A.D.	1	1.4
	Daitō	pottery	555	100 ± 50 B.C.	1	1.6
	Ōtsu	pottery	525	900 ±100 B.C.	2	0.93 ± 0.01
	Isahaya	pottery		2000 ±200 B.C.	4	1.35 ± 0.02

V. Discussion and Conclusions

1) The secular variation of the geomagnetic total force at Kyoto

The ancient intensity ratios determined by the above-mentioned method are summarized in Table 1, in which only the data of 47 specimens with higher reliability out of 73 total specimens are listed. From this result the secular variation of the total force at Kyoto for the last 4,000 years can be traced and the specimens of much older ages are now under investigation.

From the value of F/F_0 given in Table 1 and the present total force at Kyoto, $F_{0(1965)}=0.466\Gamma$, the ancient geomagnetic field intensity F can be calculated. It is needless to say that the reduction of the data obtained from various sites to a standard point (Kyoto; 135.8°E, 35°N) for comparison must be taken into consideration; the following dipole formula is used for the reduction of the present study.

$$F_0 = F'(1+3\,cos^2 p_0)^{\frac{1}{2}}(1+3\,cos^2 p')^{-\frac{1}{2}}$$

where F_0 is the reduced field intensity, p_0 is the geomagnetic colatitude of standard point (Kyoto; $p=64°$), F' the measured intensity and p' the geomagnetic colatitude of the sampling site. In fact, the reductions for almost all the sites are neglisible since their latitudes are nearly comparable to that of Kyoto as shown in Fig. 1.

Thus obtained secular variation of the geomagnetic total force at Kyoto for the last 2,000 years is shown in Fig. 6, where the abscissa shows the ages in year A.D. and the ordinate the intensity of the geomagnetic field in gauss. From this figure and Table 1, the following facts may be remarked.

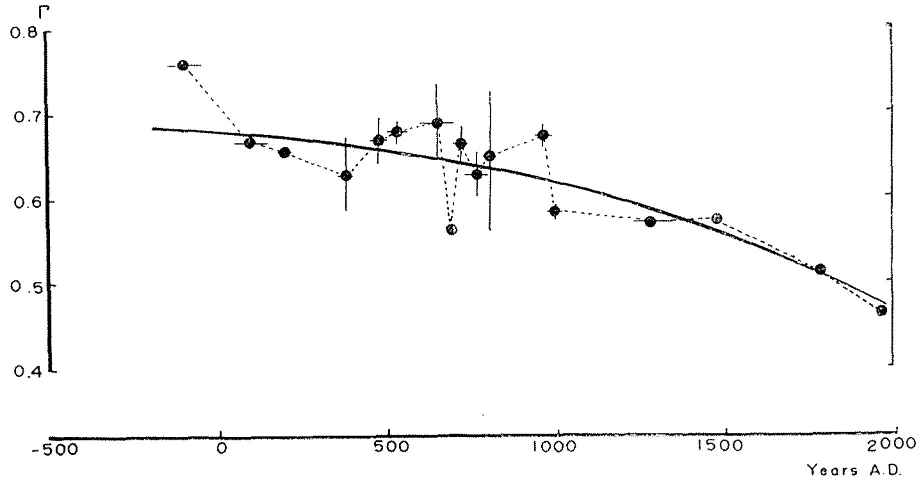


Fig. 6. Secular variation of the total force during the last 2,000 years at Kyoto. The cross lines on the solid circle illustrate the errors of estimated age and standard deviation of intensity value respectively. The decreasing trend of observed data is drawn by a thick line.

i) The total geomagnetic force in Kyoto at about 4,000 years ago was about 1.4 times as large as that at present, while at about 3,000 years ago it reached the minimum intensity of 0.9 times of the present intensity.

ii) Then the total force increased to the maximum value at about 2,000 years ago, being about 1.5 times as large as that of the present, and since the time its intensity decreased monotonously to that of the present.

Comparing the present results at Kyoto with those by NAGATA *et al.* (1963) at Tokyo, it may be noticed that the first conclusion stated above shows a slight discrepancy with those by them, and that the second conclusion is in good agreement; namely the two mean curves for the past 2,000 years are nearly comparable irrespective of their different undulatory time-variations suggesting some nondipole effects. Furthermore, the mean decreasing trend in Kyoto also shows a striking similarity to those obtained from some distant regions in the world; *e.g.* Paris, Tbilisi and Czechoslovakia. From this fact it may be said that these common trends of decrease found in measured intensities certainly suggest the secular variation of the dipole field proper.

2) The secular variation of the equatorial force during the last 2,000 years

The results of the secular variation of the geomagnetic total force in historic era have been published by several authors at the following sites; *i.e.* Paris (E. and O. THELLIER, 1959), Tbilisi (S. P. BURLATSKAYA, 1962), Tokyo (T. NAGATA, Y. ARAI and K. MOMOSE, 1963) and Peru (T. NAGATA, K. KOBAYASHI and E.J. SCHWARZ, 1965). To compare the present study with these data resulted from the various sites having different longitudes and latitudes, all of these data are reduced to the values at the geomagnetic equator.

It is generally accepted from the direct observation that the axis of the dipole has not changed appreciably for the last 120 years. On the other hand, KAWAI, HIROOKA and one of the present writers (1965) lately proposed a hypothesis of the counter-clockwise rotation of the dipole axis by summarizing the data of the archaeo-secular variation in direction reported by several authors. Consequently, the next two kinds of reduction should be taken into consideration: *i.e.* the case 1; on the basis of the commonly believed theory that the dipole axis has been unchanged

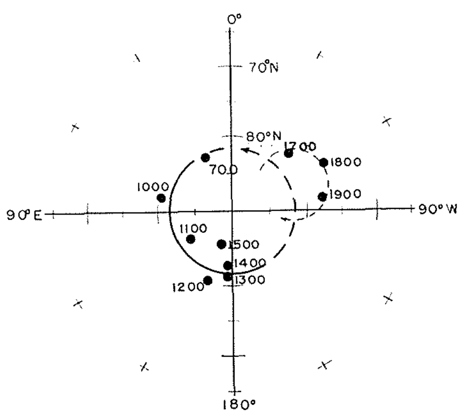


Fig. 7. Assumed rotation of the pole position transcribed from the diagram by KAWAI *et al.* (1965).

during the last 2,000 years, and the case 2; the dipole axis has undergone the counter-clockwise rotation reported by KAWAI *et al.* (1965), whose orbit of the pole shift of the dipole axis is transcribed in Fig. 7.

When the earth's magnetic field is approximated by the dipole field, the geomagnetic total force at any site (F_{ob}) can be reduced to that of the geomagnetic equator (F_{eq}) by the following equations,

$$F_{eq} = F_{ob}/(1+3\cos^2\theta)^{1/2} \quad (1)$$

$$\sin\varphi = \sin\varphi_0 \cos\theta + \cos\varphi_0 \sin\theta \cos D \quad (2)$$

$$\sin(\lambda-\lambda_0) = \sin\theta \sin D/\cos\varphi \quad (3)$$

where θ and (φ_0, λ_0) denote the geomagnetic colatitude and the geographical coordinates at a given site, and (φ, λ) is the pole position of the dipole axis. Taking the standpoint of the case 1, the value of θ remains constant with time, whereas of the case 2, the value of θ regularly changes with time.

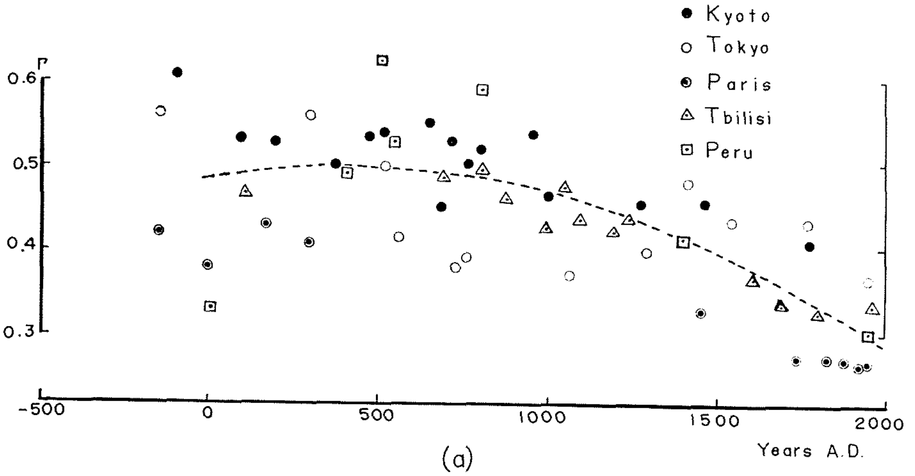
Thus reduced geomagnetic equatorial forces basing on the different hypotheses are drawn in Fig. 8–a (case 1) and Fig. 8–b (case 2). The mean curves for these plots of the diagrams determined by the method of least squares are expressed by the next two quadratic equations, which are drawn by a broken line on the respective diagram.

$$F = 48350+6.84\,t-0.00826\,t^2 \text{ gamma } (\pm 540\text{: p.e.}) \quad \text{(in Fig. 8–a)}$$

$$F = 48150-1.21\,t-0.00379\,t^2 \text{ gamma } (\pm 500\text{: p.e.}) \quad \text{(in Fig. 8–b)}$$

where F denotes the mean geomagnetic equatorial force at a given time t (in years A.D.).

As especially seen in the upper diagram, the values obtained at Paris give, as a whole, much lower ones than the mean curve, while those obtained by the present writers give rather the higher ones; and then, the data obtained by NAGATA *et al.* (1963) show a roughly sinusoidal curve with a considerable amplitude, extending over the two limits of values mentioned above. Furthermore, the data obtained from Tbilisi show a good approximation to the mean curve. It is also found in the upper diagram that the most of data at Paris and Kyoto fall on respective side of the mean curve. This seems highly improbable in the presumption that either negative or positive field of the non-dipole has prevailed in each site through the last 2,000 years. This contradiction is lessened in the lower diagram (case 2). At a first view, however, a pair of diagrams generally show much similarities in their patterns excepting a small differences; *e.g.* the mean curve in the upper diagram has its maximum at about 400 A.D., while in the lower diagram the maximum intensity occurs at about 0 A.D. Another important fact to be mentioned is that the geo-



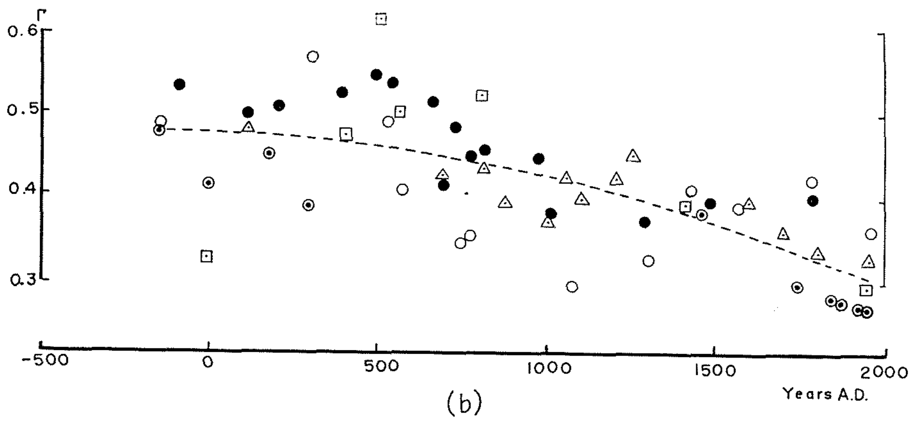


Fig. 8. The secular variation of the geomagnetic equatorial force during the last 2,000 years obtained from the five series of available results;
(a): on the assumption that the dipole axis has not appreciably changed during the time,
(b): on the assumption of the counter-clockwise rotation of the dipole axis.

magnetic equatorial force at 2,000 years ago was about 1.6 times as large as that at present, and that the mean decreasing rate of the force seems to be nearly concordant with that of the last century deduced from the direct observation. Furthermore, it is worthy of note that the various intensity data could be equally accepted, whichever hypothesis might be taken into consideration, because of the similarities found in these two diagrams.

On the other hand, when the geomagnetic equatorial force and the geomagnetic colatitude of a site are known, the expected total force at that site

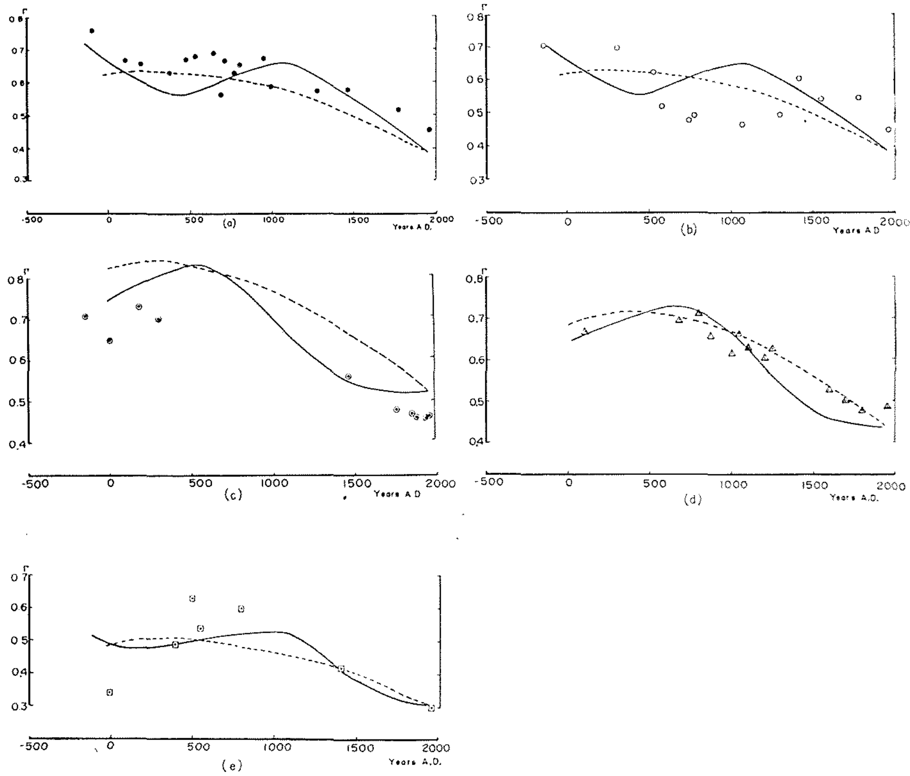


Fig. 9. Comparison of the measured palaeo-intensity data with the variations of geomagnetic total force for the last 2,000 years inferred from the two different ideas. Broken line; the expected variation of the total geomagnetic force according to the case 1 (see chap. **V**). Full line; that according to the case 2.
a) Kyoto (after Sasajima and Maenaka) (b) Tokyo (after Nagata, Arai and Momose) (c) Paris (after Thelliers) (d) Tbilisi (after Burlatskaya) (e) Peru (after Nagata, Kobayashi and Schwarz)

can be computed by means of the equation V-(1). These results of computation at Kyoto, Tokyo, Paris, Tbilisi and Peru are respectively drawn on the diagrams of Fig. 9(a)-(e). In this figure, a full line and a broken line indicate the probable secular variations of the total force basing on the two different interpretations mentioned above; *i.e.* full line indicates the variation in the case 2, and broken line that in the case 1. From these diagrams, it can easily be recognized that the observed intensity data in these sites are better approximated by the full line than the broken line. If we go into further details, it may be found that the data obtained from Kyoto, Paris and Peru are respectively in excellent fit to the full line, but those from Tokyo and Tbilisi do not always show a good agreement to the full line.

It must be admitted that the problem is not entirely solved yet, but from these considerations, it may be concluded that "the hypothesis of the dipole axis rotation" can not be denied but rather strongly supported by the already reported results of the intensity measurements. Further data in the other regions of the world will be desired in the near future to solve these problems.

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