J. Geomag. Geoerectr., 36, 45-62, 1984

Possibility of Reconstruction of the Past Geomagnetic

Field from Homogeneous Sediments

Masayuki HYODO

Cryogenic Center, Kobe University,
Nada, Kobe 657, Japan

(Received February 6, 1983; Revised November 10, 1983)

Magnetizing process of a sediment is formulated using a linear system theory. Remanent magnetization is represented as a convolution integral of geomagnetic field variation and a moment fixing function. The formulated model predicts that a field variation is deformed by filtering to be recorded in magnetization of sediments, and that the original field is deduced from the record of magnetization by a deconvolution method. Application of the model to the magnetization data of a core of shallow water sediment reveals that the remanent intensity variation may reflect the intensity reduction due to the cancellation of magnetic moments aligned in various directions
rather than decrease in a field intensity. Width of magnetizing zone is inferred to be unexpectedly small from results of measurement of magnetization and laboratory experiments. The half fixing depths, at which a half of magnetic moments in a horizon
is locked in, seem to cluster around 10cm or less.

1. Introduction

Natural remanent magnetizations (NRM) of lake and shallow water sediments have been measured to investigate geomagnetic secular variations. Many cores of deep-sea sediment have also provided long-period changes of the earth's field. In these studies natural sediments have been often used as good memory storage of the past geomagnetic field because they are preferable to igneous rocks and archeomag-netic samples owing to the chronological continuity of sediments. The essential assumption in these treatments is that the sediment faithfully preserves the change of geomagnetic field, which should be experimentally tested.
IRVING (1957) has discussed with the post depositional detrital remanent magnetization (PDRM) model that the magnetization of natural sediments is acquired accurately in alignment with a direction of an ambient field without any inclination error. The model was confirmed experimentally with both synthetic and natural sediments (IRVING and MAJOR, 1963 ;KENT, 1973). We also have some observed data from lake sediments which support the PDRM model. Two cores of sediment from lake St. Croix have the same magnetic records of high degree of correspondence in the magnetization directions (LUNT et al., 1976). Similar curves of directional changes in remanence have been observed in many cores from several

45

46 M. HYODO

lakes in Britain (TURNER and THOMPSON, 198 1), although they show somewhat lower degrees of correspondence than that of lake St. Croix. Moreover, the observed paleo-inclinations are close to the values calculated at the site with a central dipole field. These facts suggest that sediments acquire the remanences controlled by the ambient field and could carry the same record of magnetization when they meet some conditions.

We cannot easily conclude that a PDRM points to the true direction of a past geomagnetic field even if several sediment columns bear the same records of changes in remanent magnetization. Each record may have undergone the same deformation to deviate from the true field direction. Another question is that there has been no observation of the same records of magnetization in sediments whose past de-positional environments differ largely, in particular, accumulation rates are ex-tremely different. The author discusses modification of a geomagnetic field variation recorded in a continuous sample of sediment on the basis of the experimental results on the mechanism of remanence acquisition.

2. Description of PDRM

Magnetic grains in a sediment are free to rotate in the water-filled voids of matrices even after deposition and are aligned along the external magnetic field. As the voids are gradually reduced by the weight of the overlying sedimentary column, the grains become hard to move and eventually cease to rotate, leaving the magnetization directions parallel to the ambient field. The fixing of a magnetic grain is attained by a balance of two opposing forces; a magnetic torque and a mechanical resistance. The magnetic torque is expressed by a vector product of the magnetic moment of the particle and the external field. The mechanical resistance is caused by viscosity of the surrounding fluid and a friction with void wall. The particle is fixed when the resistant force predominates the magnetic torque. YASKAWA (1974) postulated only an increase of viscosity due to compaction as a factor determining the depth of fixing of magnetic grains. OTOFUJI and SASAJIMA (1981) demonstrated that a magnetic particle rotation does not occur steadily but in a halting fashion and that the rotation is dominantly controlled by a maximum friction with matrix grains but not by the viscosity.
Experimental tests have been attempted by several investigators. They can be classified into three types. (a) A long column of sediment is formed grain-by-grain
deposited during a long term (LφVHE, 1974, 1976; BARTON and MCELHINY, 1979), (b)

A slurry is poured into a container or a short column. The PDRM component was measured at various depths in a short column (TUCKER, 1980). The degree of compaction was replaced with a water content of a sample (PAYNE and VEROS 1982). (c) A specimen is compressed using an apparatus (HAMANO,1980; OTOFUJI and SASAJIMA, 1981). A sediment was compacted with various degrees which correspond to depths in a natural sediment. Partial magnetization acquired over some degree of compaction was measured.
Three characteristic features of depositional detrital remanent magnetization

Possibility of Reconstruction of the Past Geomagnetic Field 47

(DRM) have been revealed from these experimental results. The first is that most of the remanences of sediments are ascribed to PDRM components. Second, in a uniform field the magnetization acquired in each depth decreases as depth goes down. The change appears to represent an exponential decrease with depth. HAMANO (1980) discussed on a red clay that the magnetization acquisition starts from the depth of 15cm, half of the total remanence being acquired at 80cm depth, and is completed at 2.5m. The third is that the partial PDRM acquired in some compaction range has an additive property (OTOFUJI and SASAJIMA,1981). If apartial magnetization acquired in a uniform field over the depth range from do to d1 (do <d1) is denoted by Mdo, partial magnetizations M do, M 1 and Mao have the following relation;

This law was realized even when the field direction was reversed or the field strength was changed during the compaction process. This fact leads to a possibility that the magnetization of sediment can be represented by a superposition of components acquired in different ages.

3. A Linear System Model

Let's consider a thin sediment sheet produced for unit time width in a long core with unit cross section. It contains magnetic grains of various sizes with different intensities. The sediment sheet is subjected to a gradual compaction after deposition and then the void volume formed by relatively large grains, in which smaller magnetic particles can rotate to align along the ambient field, is reduced with time. The following increases in viscosity of fluid and in friction with void wall cause blocking of magnetic particles. The magnetic particles do not cease to rotate simultaneously, but they are partially fixed in various stages of different degrees of compaction. The resultant magnetization of the sediment is the sum of the magnetic moments of particles gradually fixed. To express the change of the partial fixing quantitatively, we define a function r(t); the amount of magnetic moment blocked at tin a unit sediment sheet. The r(t) can approximately be expressed by an exponential function according to Hamano's experiment, i.e.

r(t)=Ce-At (1)

r(t)=0(t<t0) (1.1)

(1.2)

(1.3)

48 M. HYODO

(1.4)

where coefficients A and C are constants, t0, t1 and t2 (t0<t1<t2) represent times of onset of magnetization, completion in the fixing of a half magnetic moments and end of the moment fixing. The integral value of r(t) is normalized by m0, amount of the total magnetic moment to be fixed in a uniform field of intensity f0. Equation 1 is shown in Fig. 1 being integrated. The dotted line represents the experimental result in which the end of moment fixing was confirmed. There is a small discrepancy below 1.5m between the curves from experiment and approximated by an exponential, however, its contribution to the total remanence is expected small.
Assuming that the axis of magnetic moment fixed at t is aligned in parallel with the geomagnetic field and each moment is additive, the magnetization of a unit sediment sheet of age i, which has been exposed to a geomagnetic field variation f(t)
from τ years ago through to present, can be expressed as follows

(2)

where m(τ) is the magnetization and t shows the age axis which has its origin in the

sediment/water interface and increases downward. The schematic view of Eq. 2 is illustrated in Fig. 2. The curve off (t) on the left shows the geomagnetic field vector corresponds to the age of each horizon in the sediment column. Since the unit
sediment sheet ofage τ, expressed by a shaded portion in Fig. 2, acquires remanent magnetization through a duration from to to t2 after deposition, namely, from t=τ

-t0 to t=τ-t2 , the moment fixing function r(t) is given as drawn in Fig. 2. This model implies that the magnetization of a sediment can be calculated by a convolution integral of a magnetic field variation f (t) and the moment fixing function r(t). And then it suggests two important features of magnetization acquired in a magnetic field always changing. One is that the direction of magnetization does not coincide with that of the external field unless f (t) is unchangeable in direction or r (t) is

Fig. 1. Moment fixing function. The solid line shows an exponential curve. The dotted line shows a
curve from experiment.

Possibility of Reconstruction of the Past Geomagnetic Field 49

Fig.2. A schematic view ofthe present model. Thef{t)shows a secular variation ofgeomagnetic
field vector. The r(i-t)represents a moment fixing function. The shaded area shows the unit
sediment sheet of age τ.

the Dirac's δ-function. The other is that the magnetization intensity is shown by a

product of the component proportional to the field intensity and the component of intensity reduction caused by the cancellation due to the superposition of magnetic moments aligned in various directions. The latter component results from the integral of the directional change of field.

4. Effect of Moment Fixing Function r(t)

Considering the four associated conditions of Eq.1, the integral limits of Eq. 2
can be extented as:

(3)

where fe(t)=m0/f0f(t). Since Equation 3 is a convolution integral, it can be described by spectra using the Fourier transform as:

M(ω)=Fe(ω)R(ω) (4)

where M(ω),Fe(ω) and R(ω) are spectra of m(t), fe(t) and r(t), respectively. Equation
4 shows that the. spectrum of magnetization M(ω) can easily be calculated only by multiplying Fe(ω) by R(ω), whereas in the space domain the magnetization m(t) is obtained by filteringfe (t) with a filter r(t). The R(ω) provides us detailed properties of the filter.

50 M. HYODO

If we put to=osince to《t2, Equation l becomes as:

r(t)=Ae-At(A=ln0.5/T1/2) (5)

where T112 is a period for the fixing of a half magnetic moment. Thus the moment fixing function r (t) can be determined by only T112, i.e. only the condition (1.3) is enough for the determination of r (t).
Since r (t)=0 when t<0, the Fourier transform of r (t) becomes as:

R(ω)=1/(1+(ω/A)i) (6)

To examine the properties of R(ω) in detail, we separate it into real part and

imaginary part, which show an amplification and a phase lag, respectively. The amplitude spectrum becomes as:

(7)

and the phase spectrum becomes as:

θ=tan-1(αT1/2/T) (8)

where T=2π/ω. Equations 7 and 8 show that both spectra are functions with respect

to (T1/2/T), the ratio of the half fixing period to the wavelength of the field variation. Figure 3 shows the two spectra. We also simulated the effect of the filter with respect to the function from experiment in which remanence acquisition terminates at the depth 250cm. Both the amplification and the phase lag of the filter from experiment show almost the same change to those of an exponential one, although small fluctuations occur in the curve of phase lag. If we adopt a linear function instead of an exponential, a more pronounced fluctuation, whose frequency is determined by the width of moment fixing zone, will grow up in both the amplification and the ph tse lag. Anyway the using of an exponential is appropriate for the approximation of the moment fixing function.
According to secular variations of geomagnetic field from archeomagnetism

(HIROOKA, 1971; KOVAGHEVA, 1980), there is no directional offset over 20° from a

mean direction. Therefore, we can regard the change of declination and inclination approximately linear to the orthogonal axis. Then the amplitude attenuation and the phase lag shown in Fig. 3 are applicable to the deformation of declination and inclination curves. As shown in Fig. 3, the large (T1/2/T) causes a large amplitude attenuation and a large phase lag in declination and inclination. If the T1/2 is kept constant, the components of higher frequency are more deformed. On the other hand, the large T1/2, which is equivalent to a small depositional rate, causes a large deformation. For instance when T1/2=500yr, the directional change of T=500 yr

Possibility of Reconstruction of the Past Geomagnetic Field 51

Fig. 3. Amplification and phase spectra of the filter R. The true lines show the spectra of Eqs. 7
and 8. The dotted lines show the spectra on a function from experiment.

is deduced to 0.13 and its phase is delayed with 115 yr and that of T=250 yr to 0.25 and with 53 yr. Thus a secular variation of the earth's field is recorded being modified variously by different filters.

5. Application

The model presented above quantifies deformation of a secular variation recorded in sediments, predicted from an assumption that remanence of the sediments possesses the three characteristic features of PDRM as shown by the laboratory experiments (see in chapter 2). Two major features expected on the geomagnetic secular variation recorded in a long sediment column are; (a) modification of declination and inclination by amplitude attenuation and phase lag and (b) intensity variation resulting from the cancellation of magnetic moments aligned in the opposite directions. We apply the model to data from natural sediments in order to examine the significance of the feature (b) and estimate the width of remanence acquisition zone.

52 M, HYODO

5.1 Effect of cancellation of magnetic moments
The above characteristic (b) has already been discussed by other investigators on remanent intensity in a polarity transition zone. But cancellation in the magneti-zation intensity during a period with the same polarity has never been considered. A core of shallow water sediment, which is unconsolidated and composed of silt and clay, was taken from Osaka Bay (HYODO and YASKAWA,1980). Itis considered to have been deposited after the Holocene transgression. The coring was made with a giant corer 20cm in diameter. Therefore several specimens were collected from each horizon and then the dispersion of magnetization in each depth could be calculated.
The average α95 is 14.7°, which is almost equal to the value ofother cores ofsediment

from the Inland Sea, Japan (HYODO et al., 1983a, 1983b, 1983c). It is a little larger than that of lake sediment (HORIE et al., 1980; HYODO and YASKAWA, 1983). The magnetization was measured with a superconducting magnetometer of SCT. The stability of magnetization was confirmed with the AF-demagnetizer of rotating field designed for soft materials (MATSUDA et a!.,1981). The results of measurement are shown in Fig. 4 and Fig. 5 (a).
The declination and inclination logs in Fig. 5 (a) are those of magnetizations averaged in each horizon. The young sections shallower than about 3m are consistent with archeomagnetic curves (HYODO and YASKAWA, 1980). The inclination
of overall mean is 52.3°, which is close to the value 54.0°, the inclination of the

geocentric axial dipole field expected at the site latitude. Intensity curve of saturation isothermal remanent magnetization (SIRM) in a field of 3000 Oe is almost flat, attaching two small peaks, and then represents an inconsistent change with the NRM intensity curve (Fig. 4).

Fig. 4. Results on the remanent intensity in the core OS2. The SIRM is obtained in a field of 3000
Oe. Each curve is smoothed by an operation of 5-points running mean.

Possibility of Reconstruction of the Past Geomagnetic Field 53

Fig. 5. Calculation of the intensity reduction due to cancellation during a period with the same polarity. (a) Directional change of magnetizations in the core OS2. (b) Directional change of
the virtual geomagnetic field variation deduced by a deconvolution with Z1/2=10cm. (c)
Intensity variations due to cancellation calculated with the virtual fields. The right figure shows
21/2 used in each calculation. (dotted line; 50-95% moment fixed, solid line; over 95% fixed)
Each variation curve is smoothed by an operation of 5-points running mean.

The observed declination and inclination curves must have been subjected to amplitude attenuation and phase shift passing through a filter. Then we calculate a virtual geomagnetic secular variation from the magnetization data by deconvolution. Equation 4 can be transformed as

Fe(ω)=M(ω)/R(ω). (9)

Using Eq. 9, we obtain the field spectrum Fe (ω) from the magnetization spectrum M(ω) and then the inverse Fourier transform of Fe(ω) provides the virtual

geomagnetic field secular variation fe(t) whose directional swings and fluctuations grow up. Through this calculation all magnetization intensities were set to 1, and since a depth axis was used instead of time, a half fixing depth Z1/2 was replaced with

54 M. HYODO

the T112. Figure 5 (b) shows the virtual geomagnetic secular variation deduced by the method with the filter of Z1/2=10cm. Second, magnetizations were calculated carrying out the integration of Eq. 2 with the virtual geomagnetic secular variation and the same response r(z) used in the deconvolution. Intensities of the virtual geomagnetic fields were again reset to 1. The intensity variations of magnetization calculated on the responses of Z1/2=5, 10, 20 and 40cm, are shown in Fig. 5 (c). These procedures have some inconsistencies. The virtual geomagnetic field variation was calculated with the observed magnetization intensity of which was assumed to be constant. Furthermore the intensity of the virtual geomagnetic field was regarded as uniform when the magnetization was calculated. These calculations, however, yield the minimum estimate of intensity reduction of magnetization due to the cancellation effect. If an intensity variation of geomagnetic field is taken into account, a much more decrease in magnetization intensity will be calculated. Therefore this method can test whether or not the component of the cancellation effect is negligibly small.
The inverse filtering in the above procedures of calculation should carefully be
operated, since the 1/R(ω) amplifies high frequency components. Although the

spectra of Nyquist frequency and over were removed, it is possible that noises are amplified. Then we remove the high-frequency components of the directional change of magnetization by an operation of 3-points running mean and recalculate the intensity change due to the cancellation by the above method. Figure 6 shows the result compared with the intensity variation calculated with the original data without any high-cut filtering. The result indicates that the high-cut operation causes the decrease in components by cancellation, especially in the amplitude. The high-frequency change of field direction clearly plays an important role in the intensity reduction due to cancellation. Hence the intensity curve in Fig. 5 (c) were calculated using the original magnetic data without any high-cut operation.
The results have revealed that the intensity reduction due to the cancellation effect is unexpectedly large. It gives rise to a reduction of as much as 50% even when the filter of 21/2=10cm is used. As the half fixing depth goes down, the intensity curve becomes smooth and the general intensity level descends. Thus it is clarified

Fig. 6. Contribution of high frequency changes of field direction to the intensity reduction due to cancellation. (a) Intensity variation calculated with the directional data smoothed by an
operation of 3-points running mean. (b) Intensity variation calculated with the original data.

Possibility of Reconstruction of the Past Geomagnetic Field 55

that the intensity variation due to the superposition of magnetic moments aligned in various directions is not so small. Moreover, the curve of calculated intensity is quite similar to that of the observed intensity. In particular, a remarkable coincidence is shown between the curves of the NRM/SIRM and the calculated intensity with Z1/2 of 10cm.

5.2 Estimation of half fixing depth for natural sediments
We try to estimate half fixing depth 2112 of natural sediments. A clear value for 21/2 is provided by the remanent intensity of deep sea sediments. It shows a progressive decrease prior to a polarity transition and an immediate recovery after that. The intensity drop shows a convex decrease and the following recovery a concave increase. These features are not only observed in natural deep-sea sediments (OPDYKE et al., 1966; HARISON and SOMAYAJULU, 1966; KOBAYASHI et al., 1971) but also explained by some models (LOvLIE, 1976; NIITSUMA, 1977; OTOFUJI and SASAJIMA, 1981). The present model is applied to the magnetization data of the core KH 68-4-20 (KOBAYASHI et al., 1971). The remanent intensities and polarities determined from directions of remanence are shown in Fig. 7 (a). Intermediate directions of magnetization are not observed at the positions of polarity transition. Four successive polarity changes occur during the depth from 3.52m to 5.50m. The two reversals at 3.52-4.10m and 4.75-5.50m are paleontologically interpreted as the Kaena and the Mammoth events. Their ages determined from volcanic rocks (LABRECQUE et al., 1977) are shown in Fig. 7 (b). The intensity drop at the reversals, caused by only the cancellation of magnetic moments aligned in the opposite directions, is calculated using Eq. 2 with a field expressed by the polarity change in Fig. 7 (b) assuming that the depositional rate is constant at 7.6mm/103 yr. The calculations were carried out with respect to four kinds of responses with Z1/2 =10, 20, 40, and 80cm (Fig. 7 (c)). The results represent that the shape of intensity pattern considerably changes with 2112. The uppermost intensity peak in the three successive ones diminishes as Z1/2 becomes large. The peak disappears completely when Z1/2 reaches the width of the Kaena event. Then positions of polarity boundary are shifted downward depending on Z1/2. The result of calculations reveals that a polarity transition is recorded being shifted downward by Z1/2 and a small event shorter than 21/2 is not recorded in magnetization direction, although the trace still remained in intensity. The intensity pattern with Z1/2 of 20cm seems to fit best the observed one. Thus the remanent intensity drop during a reversal can be explained by only the cancellation effect on the assumption that the field intensity is constant. According to some studies with volcanic rocks and intrusions, the intensity of the earth's field is decreased at a polarity transition. However, we can not know if the duration of the field intensity decrease is as long as those recorded in sediments, since the studies on polarity transition zone with igneous rocks can not be made on time axis. Width of a remanent intensity drop at a single reversal in sediments is usually less than 50cm. No matter how fast a sediment is accumulated, the drop width in the sediment does not extend beyond this value. This fact suggests that the remanent intensity drop during a reversal in sediments is independent on the field intensity. If the intensity change

56 M. HYODO

(a)

(b)

(c)

Fig. 7. Intensity reduction due to cancellation in the polarity transition zone. (a) Magnetization intensities of deep sea sediment of the core KH-68-4-20 (after KoBAYASHI et al., 1971). (b)
Polarity change of the input field. (c) Intensity patterns calculated with a field of the polarity
change shown in (b). The right figure represents Z1/2 used in the calculation of each curve.

consists of only the cancellation effect, a quite small Z1/2 is enough to produce the intensity drop. Even the response whose Z1/2 is only 12cm can produce the intensity drop more than 10% over the width 30cm. Many drops which extend over 10cm or less were observed in densely measured cores of deep sea sediments (SATO,1980). To make out an intensity drop of 10cm-width, 2.5cm is enough for the half fixing depth. Thus the small value 10cm or less is generally appropriate for 2112 of deep sea sediments.

Possibility of Reconstruction of the Past Geomagnetic Field 57

6. Discussion and Conclusion

The model is characterized by proposing a moment fixing function. Although
the function is provided by an exponential in the present study, it may take other forms. For example, the Dirac's b function is possible to be taken if all magnetic

particles are simultaneously fixed, or it may not show a monotonous decrease but any others like bimodal changes. But no experimental result which suggests these functions has been obtained. As discussed above, the change of the moment fixed in a horizon of a sediment column is controlled by a size distribution of magnetic and nonmagnetic grains, their shapes, magnetization intensities of them, properties of interstitial fluid, sedimentation rates, and intensity of geomagnetic field. All but the last two factors show physical properties of sediment. Assuming that the moment fixing can be expressed by an exponential function on every sediment, the half fixing depth 21/2 can be regarded as one of the physical properties of sediment. According to an experiment remagnetizing natural sediments in a laboratory, a sediment rich in sand shows a high possibility of remagnetization (PAYNE and VEROSUB,1982). This fact suggests that the sand-rich sediment has a high value of Z1/2. We can infer that a sediment, whose grain size distributes widely, would have a larger half fixing depth than an even-grained sediment. The value 10cm or less has been estimated for Z1/2 of deep sea sediments. We rather wish to know if the Z1/2 of lake and shallow water sediments is as small as that of deep sea sediments. Some experiments with lake deposits have shown that few realignments of magnetic grains occur in a sediment redeposited. If the 21/2 is 2cm, for example, the 82% magnetic moment in a horizon is to be fixed on the depth 5cm beneath the sediment/water interface. It would be difficult to detect the mechanism of PDRM in detail with these sediments. In Britain

and Japan, the secular variations of geomagnetic field, which coincide with those from archeomagnetism, have been obtained from lake sediments and shallow water sediments (CREER et a1.,1972; HYODO and YASKAWA, 1980). These facts also indicate that Z1/2 is small. Thus we can interpret by the small half fixing depth many observed data from lake and shallow water sediments, and many results of laboratory experiments with these sediments.
Let us consider a possibility to obtain a secular variation of geomagnetic field from sediments. The effect of the filter r(t) is described with depth axis in Fig. 8. Amplification and phase lag of a secular variation of the earth's field, whose wavelength is expressed in centi-meter, are shown on several half fixing depths. When Z1/2 is 40cm, the significant attenuation in amplitude and phase lag occur throughout the wavelength range from 0 to 400cm, their grades depending on the wavelengths. Therefore, these sediments do not preserve accurate paleo-field direc-tions. On the other hand, when Z1/2 is 5cm, the deformation due to the filter becomes small; on the components of wavelength over 50cm, the decrease in amplitude is less than 20% and phase lag is only 4 to 6cm, both curves of which are flat throughout the wavelength range more than 100cm. The geomagnetic field direction appears to be recorded faithfully in a sediment of small Z1/2. When we discuss the high-frequency

58 M. HYODO

Fig. 8. Amplification and phase lag due to the filter R.

component of the wavelength less than 50cm, however, we should take the effect of the filter into consideration.

On the remanence preserved in sediments of large Z1/2, some problems can be inferred. When a field variation is recorded in sediment columns of different

depositional rates, the recorded signals are not only different in wavelength but also subjected to different filterings. These two sediments have distinct variations of magnetization, even if their half fixing depths are the same. This result may cause the fact that no good coincidence exists in secular variation curves of the earth's field from various sediment cores of quite different depositional rates. Curves of declination and inclination, whose wavelengths of main spectra are extremely different from each other, are recorded with some difference in their phase lags. This matter provides us with some warning in using the declination and inclination curves of remanence in sediments as a time scale. When depositional rates or half fixing depths vary with depth in a sediment column, it is quite difficult to reconstruct the original field variation from the magnetization of the sediment.
We have found that the intensity reduction due to cancellation is too large to be neglected even on the period with the same polarity. Then we consider how

Possibility of Reconstruction of the Past Geomagnetic Field 59

significantly this component contributes to the magnetization intensity of natural sediments.

Three components can be considered for the primary magnetization intensity of sediments; the content of magnetic minerals, the intensity of paleo-geomagnetic field and the intensity reduction due to cancellation. Since the first component can be rejected by normalizing the intensity of NRM by the SIRM intensity, we discuss only the last two components. Only the archeomagnetism at present can provide the intensity change of paleofield over the past several thousands years. Figure 9 shows

Fig. 9. Comparison of three kinds of intensity changes. Variation of the geomagnetic field intensity from archeomagnetism in Japan and the Middle East (after SAKAt, 1981) (top).
Variation curve of NRM/SIRM of the core 0S2 (middle). Intensity change due to the cancellation calculated with Z1/2=10cm (bottom).

60 M. HYODO

the paleofield intensities from archeomagnetism in Japan and Middle East (SAKAI, 1980), the observed intensity curve NRM/SIRM and the intensity variation due to only the cancellation effect calculated with the response of Z1/2=10cm, in comparison. The archeomagnetism represents a high field period whose peak is around 1500 yr B.P. and a long duration of low field from 3000 yr B.P. through back to 6000 yr B.P.. This trend is similar to that from archeomagnetism in south-eastern Europe (KOVACHEVA,1980), although they have some discrepancy in the positions of the high peak. Three horizons in the NRM/SIRM curve, whose sediment ages are determined by 14C dating, are contrasted to the paleofield intensity in Fig. 9. These two curves do not coincide with each other in the position of high peak and have different trends. We can easily recognize that the NRM/SIRM is rather analogous to the calculated intensity than the archeomagnetic paleointensity. In particular, the general trend of increasing with depth and the positions of small peaks and valleys below 4m quite well correspond to each other. This fact might suggest that the component of cancellation effect greatly contributes to the magnetization intensity of sediments, far from being negligible. But we must note that the amplitudes of intensity drops due to cancellation are somewhat small for explaining the observed intensity change completely by only the calculated intensity. Although we do not know whether or not the NRM/SIRM consists of only the magnetization intensity calculated from the directional change of magnetic field vector, some improvement may be needed in the present model, or we should consider that some alterations like drying would have occurred in the NRM intensity. Anyway the remanent intensity of sediment does not directly reflect a field intensity, but strongly depends on the change in the field direction. Moreover, the remanent intensity does not still coincide with the field intensity from archeomagnetism even after removing the component due to cancellation with the linear system model. In order to establish the method to deduce a geomagnetic secular variation correctly from the remanence of sediments by deconvolution, the intensity problem must be solved perfectly. The future experi-ments and observations will provide a solution.
In conclusion the paleomagnetic signals recorded in sediments are subjected to some deformations resulting from the effect of the filter r(z). For a precise paleomagnetic study on field variations, it is preferable to use homogeneous sediments with smaller half fixing depths, deposited at a high uniform rate of sedimentation.

The author wishes to thank Professor K. Yaskawa for his encouragement and sug-gestions. He is indebted to Drs. Isezaki and J. Matsuda for valuable discussions and comments.

REFERENCES

BARTON, C.E. and M.W. MCELHINY, Detrital remanent magnetization in five slowly redeposited long cores of sediment, Geophys. Res. Lett., 6, 229, 1979.
CREEK, .M., D.L. GRoss, and J.A. LINEBACK, Origin of regional geomagnetic variations recorded by Wisconsin and Holocene sediments from Lake Michigan, U.S.A. and Lake Windermere, England, Geol. Soc. Amer. Bull., 87, 531, 1976.

Possibility of Reconstruction of the Past Geomagnetic Field 61

HAMANO, Y., An experiment on the post-depositional remanent magnetization in artificial and natural sediments, Earth Planet. Sci. Lett., 51, 221, 1980.
HARRISON, C.G.A. and B.L.K. SOMAYAJULU, Behavior of the earth's magnetic field during a reversal, Nature, 212, 1193, 1966.
HIROOKA, K., Archeomagnetic study for the past 2000 years in southwest Japan, Mem. Fac. Sci. Kyoto Univ., 38,167, 1971.
HORIE, S., K. YASKAWA, A. YAMAMOTO, T. YOKOYAMA, and M. HYODO, Paleolimnology of Lake Kizaki, Arch. Hydrobiol., 89, 407, 1980.
HYODO, M. and K. YASKAWA, Geomagnetic secular variation recorded in the stable magnetic remanence of the young sediments collected from Osaka Bay, J. Geomag. Geoelectr., 32, 581, 1980.
HYODO, M. and K. YASKAWA, Paleomagnetism of a core from Lake Yogo, Mem. Grad. School Sci. & Technol., Kobe Univ., 2, to be submitted, 1983.
HYODO, M., H. MORINAGA, H. NISHIMURA, and K. YASKAWA, Paleomagnetism of a core from Osaka Bay II, Mem. Grad. School Sci. & Technol., Kobe Univ., 2, to be submitted, 1983a.
HYODO, M., J. MATSUDA, N. ISEZAKI, and K. YASKAWA, Paleomagnetism of a core from the Inland Sea, Japan (Seto Naikai) I, Mem. Grad. School Sci. & Technol., Kobe Univ., 2, to be submitted, 1983b. HYODO, M., F. MURATA, T. TSUCHIYA, H. INOKUCHI, and K. YASKAWA, Paleomagnetism of a core from the Inland Sea, Japan (Seta Naikai) II, Mem. Grad. School Sci. & Technol., Kobe Univ., 2, to be submitted, 1983c.
IRVING, E., The origin of the paleomagnetism of the Torridonian Sandstone series of northwest Scotland, Philos. Trans. R. Soc. Lond. A, 250, 100, 1957.
IRVING, E. and A. MAJOR, Post-depositional detrital remanent magnetization in a synthetic sediment, Sedimentology, 3, 135, 1964.
KENT, D.V., Post-depositional remanent magnetization in deep-sea sediment, Nature, 246, 32, 1973. KOBAYASHI, K., K. KITAZAWA, T. KANAYA, and T. SAKAI, Magnetic and micropaleontological study of deep-sea sediments from the west-central Pacific, Deep-Sea Res., 18, 1045, 1971.
KOVACHEVA, M., Summarized results of the archeomagnetic investigation of the geomagnetic field variation for the last 8000 yr in south-western Europe, Geophys. J. R. Astr. Soc., 61, 57, 1980. LABRECQUE, J.L., D.V. KENT, and S.C. CANDE, Revised magnetic polarity time scale for late Cretaceous and Cenozoic time, Geology, 5, 330, 1977.
LOVLIE, R., Post-depositional remanent magnetization in a re-deposited deep-sea sediment, Earth. Planet. Sci. Lett., 21, 315, 1974.
LOVLIE, R., The intensity pattern of post-depositional remanence acquired in some marine sediments deposited during a reversal of the external magnetic field, Earth Planet. Sci. Lett., 30, 209, 1976. LUND, S.P., D. BOGDAN, S. LEVI, S.K. BANERJEE, and A. LONG, Continuous geomagnetic record for the past 10,000 years from Lake St. Croix, Minnesota, EOS (Trans. Am. Geophys. Un.), 57, 910, 1976. MATSUDA, J., M. HYODO, H. INOKUCHI, N. ISEZAKI, and K. YASKAWA, A new alternating field demagnetizes for paleomagnetic studies without rotation of specimen, J. Geomag. Geoelectr., 33, 161, 1981.
NIITSUMA, N., Zone-magnetization model and depth lag of NRM in deep-sea sediments, Rock Magn. Paleogeophys., 4, 65, 1977.
OPDYKE, N. D., B. GLASS, D. HAYS, and J. H. FOSTER, Paleomagnetic study of Antarctic deep-sea cores, Science, 154, 349, 1966.
OTOFUJI, Y. and S. SASAJIMA, A magnetization process of sediments; laboratory experiments on post-depositional remanent magnetization, Geophys. J. R. Astr. Soc., 66, 241, 1981.
PAYNE, M. A. and K. L. VEROSUB, The acquisition of post-depositional detrital remanent magnetization in a variety of natural sediments, Geophys. J. R. Astr. Soc., 68, 625, 1982.
SATO, T., Paleomagnetic field intensity obtained by use of deep-sea cores of Quaternary, PhD. Thesis, Osaka Univ., Osaka, Japan, 1980.
SAKAI, H., Variation of the geomagnetic field intensity deduced from archeological objects, Rock Magn. Paleogeophys., 7, 61, 1980.

62 M. HYODO

TUCKER, P., A grain mobility model of post-depositional realignment, Geophys. J. R. Astr. Soc., 63,149,
1980.

TURNER, G.M. and R. THOMPSON, Lake sediment record of the geomagnetic secular variation in Britain during Holocene times, Geophys. J.R. Astr. Soc., 65, 703, 1981.
YASKAWA, K., When did magnetization fix in loose sediment?, Rock Magn. Paleogeophys., 2, 15, 1974.