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Quaternary geomagnetic field intensity: Constant periodicity or variable period?

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Abstract. Paleomagnetic results are presented from a core, KH 90-3-5, in the Melanesia basin and are correlated with the previously obtained results from two cores, KH 73-4-7, KH 73-4-8, in the same basin in a period between 0.04 Ma and 1.1 Ma. The sediments in the three cores are composed mostly of calcareous ooze. It has been shown that the variation in the saturation isothermal remanent magnetization (SIRM) in the two cores is caused neither by deposition-rate variation of magnetic minerals nor by rock-magnetic inhomogeneity but almost solely by variations in $CaCO_3$ dissolution. A close similarity between the variation in the SIRM in the two cores and the variation in the initial susceptibility (κ) in KH 90-3-5 has enabled us to correlate among the cores, and also means negligible rock-magnetic inhomogeneity in the core. A time versus depth correlation has been established from the $\delta^{18}O$ record of KH 90-3-5. The relative paleointensity record estimated from the natural remanent magnetization (NRM) normalized by κ in KH 90-3-5 and those records in the other two cores are remarkably similar, implying that the records faithfully reflect variations in relative paleointensity of the geomagnetic field for the past 1.1 Ma. We examined on the periodicity of the paleointensity records with wavelets. It is shown that periods of major changes in the records reveal continuous shifts between about 50 Ka and 140 Ka over time. We offer an alternative viewpoint about the periodicity of the paleointensity in which periods of major changes shifted continuously within the time range instead of constant periodicities.

Introduction

Spectral analysis for relative paleointensity data obtained from a deep-sea sediment core was firstly performed by *Kent and Opdyke* [1977]. They examined the periodicity of the NRM normalized by the anhysteretic remanence in the Brunhes portion of RC10-167, although it had no oxygen isotope time control, and found a broad peak centered at a period of around 43 Ka in the spectral. On the similarity of this period to that of the Earth's obliquity, they suggested a possible link between this obliquity and the generation of magnetic fields. Since this analysis, the efforts in spectral analyses for paleointensity records have focused on verifying the periodicities appearing in the Earth's orbital parameters (eccentricity, obliquity and precession) [*Tauxe and Wu*, 1990; *Tauxe and Shackleton*, 1994]. *Tauxe and Shackleton* [1994] performed a spectral analysis for a stacked record of three isotopically dated cores taken from the Ontong-Java Plateau. However, on the basis of the results that the periodicities were not recognized in the record, they suggested that the Earth's orbit didn't play a detectable role in the modulation of the magnetic field.

Apart from stationary periodicity, periodicity merely found in limited duration by extensions of traditional Fourier analysis, has been reported in some literature [*Tauxe and Shackleton*, 1994]. Wavelet analysis offers an alternative approach and is particularly useful when the amplitudes and periods of dominant cycles are time dependent. However there have been only a few reports on wavelet analysis for relative paleointensity records [*Sato et al.*, 1996]. In this paper, we apply continuous wavelet transforms to relative paleointensity records derived from three deep-sea cores.

Cores and data previously obtained from them

The three deep-sea cores examined in this study (KH 73-4-7, KH 73-4-8 and KH 90-3-5) were collected from the Melanesia basin in the western equatorial Pacific Ocean (2° 41.3' N, 164° 50.2' E, 4,160 m deep, 1° 33.2' S, 167° 38.6' E, 4,000 m deep and 4° 00.0' N, 160° 01.0' E, 3,773 m deep, respectively). The results of the transmission electron microscope examinations [*Akai et al.*, 1991] of magnetic minerals contained in the sediment coupled with the results of previously performed rock magnetic studies [*Sueishi et al.*, 1979; *Yoshida et al.*, 1985] for the cores (KH 73-4-7 and KH 73-4-8) have shown that, throughout the cores, most of the magnetic minerals are of bacterial origin, and the influences by the variations in other magnetic components are negligibly small [*Sato and Kobayashi*, 1989]. The content of magnetic mineral represented by SIRM has been shown to exhibit almost identical fluctuations even if two cores with largely different sedimentation rates are compared. It has been shown that the fluctuations are caused solely by variations in the $CaCO_3$ dissolution [*Sato et al.*, 1993]. On the basis of the SIRM correlation, the variations of the NRM / SIRM, which are thought to be the first approximation of the paleomagnetic field intensity of the two cores, were compared and a clear correlation was found [*Sato and Kobayashi*, 1989].

Paleointensity data acquisition

In this study we measured the NRM of a deep-sea sediment core (KH 90-3-5) using a SCT cryogenic magnetometer at National Institute of Polar Research and a 2G cryogenic magnetometer at Ibaraki University after an AF demagnetization of 10 mT (Figure 1a). The NRM vectors were measured for successive sequences of the core except a portion (0.057Ma to 0.543Ma) in which the measurements were achieved for one of every two specimens. Remanent intensities were corrected for

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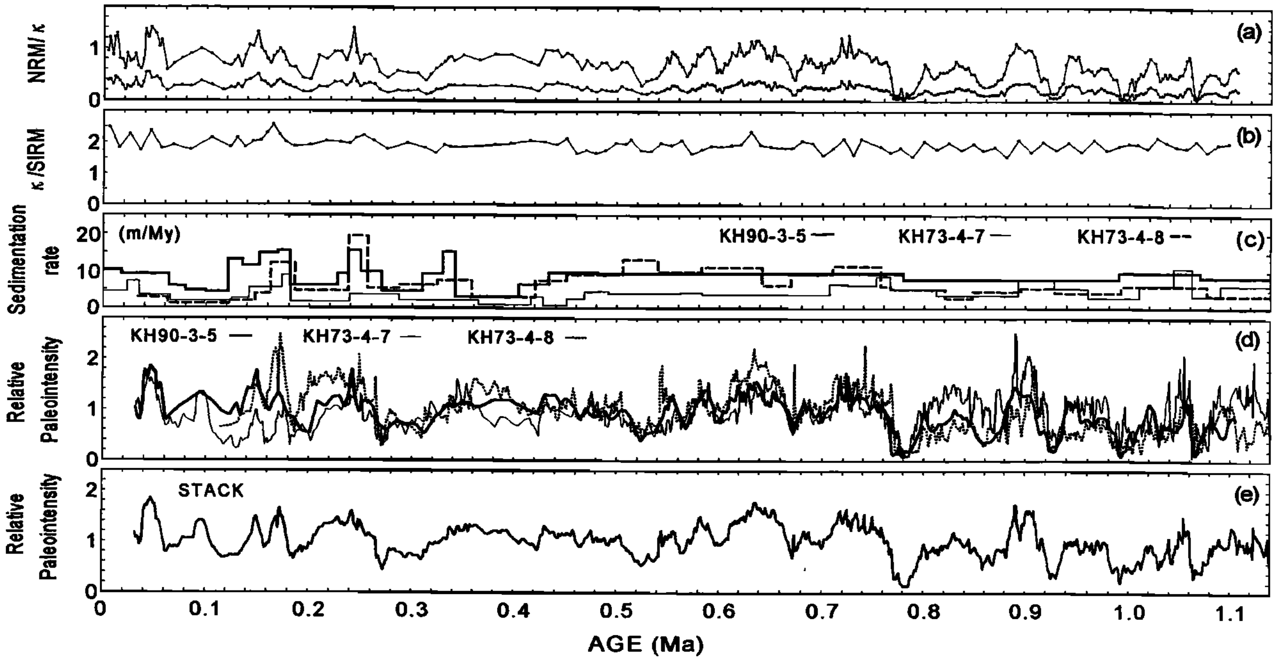

Figure 1. (a) Comparison of the NRM(10 mT) / κ record (upper) and the NRM(40 mT) / κ record (lower) for KH 90-3-5. The vertical scale is arbitrary. (b) Variations in the SIRM(1 T) / κ values for KH 90-3-5. The vertical scale is arbitrary. (c) Variations in the sedimentation rates for three cores. (d) Relative paleointensity records obtained from the NRM / SIRM values divided by the mean of the NRM / SIRM values for KH73-4-7 and KH73-4-8 and from the NRM(10 mT) / κ values divided by the mean of the NRM(10 mT) / κ values for KH90-3-5. (e) The data in (d) are averaged to give a stacked record for the three cores.

some inter-laboratory instrumental discrepancies by measuring 10 specimens using each magnetometer in this study. The fluctuation pattern of κ in the core [*Okada*, 1992] coincides well with those of the SIRM in cores KH 73-4-7 and KH 73-4-8. Good chronological control was provided by oxygen isotope stratigraphy for the upper part (top to 0.5 Ma) of the core [*Okada*, 1992]. Chronological control for the lower part (0.5 Ma to 1.1 Ma) of core KH 90-3-5 is based on magnetostratigraphy. Chronological control for the other cores is based on correlation of the fluctuation pattern of magnetic mineral content compared with core KH 90-3-5 as well as magnetostratigraphy. Variations in the sedimentation rates for three cores are shown in Figure 1c. The variations in $CaCO_3$ dissolution reflected by the fluctuations in the magnetic mineral content in the three cores will be discussed and wavelet analyses of the fluctuations will be reported elsewhere. Synchronous variations between the magnetic mineral content in these cores and $CaCO_3$ content in the eastern equatorial Pacific [*Farrell and Prell*, 1989] show that significant errors on date are not introduced by a simple estimate of age for the lower Brunhes epoch.

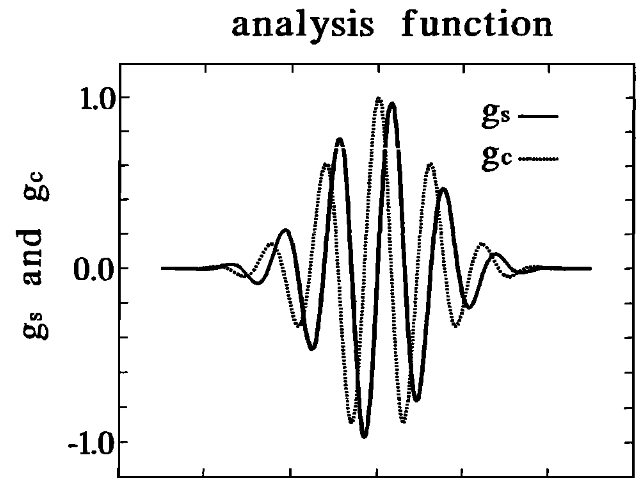

Figure 2. The modulated Gaussian wavelets used in this paper. They are sinusoids (g_s: sine, g_c: cosine) in a Gaussian envelope. The parameter n, which adjusts window width, = 2. See Bolton et al. (1995) in details.

Inhomogeneity in magnetic grain size distribution and magnetic mineralogy in core KH 90-3-5 is examined by comparison of the paleointensity signals at different steps of demagnetization (Figure 1a) and also by variations in the ratio of SIRM / κ (Figure 1b). The measurements of SIRM imparted by an DC field of 1 T and NRM after an AF demagnetization of 40 mT were made on Natsuhara Giken's SMM-85 spinner magnetometer at Hiroshima University. There are few systematic variations although some scatter in the ratio. As the correlation coefficient between κ and SIRM is high (0.98), we think the choice of a normalization parameter hardly affects the latter analysis. We note that the similarity between the paleointensity signals is also encouraging

Large scale variations with periods of 20 to 100 Ka in the ratio of NRM / SIRM or NRM / κ are quite well correlated to each other among the three cores as seen in Figure 1d. Correlation of the large scale variations can clearly be found in most of recently acquired paleointensity records [*Valet and Meynadier*, 1993; *Yamazaki et al.*, 1995]. We excluded the data from uppermost 12 - 16 cm in each core, in which large changes in relative declination were probably caused by mechanical disturbance during the coring and extraction operation [*Sato and Kobayashi*, 1989]. The horizontal component of

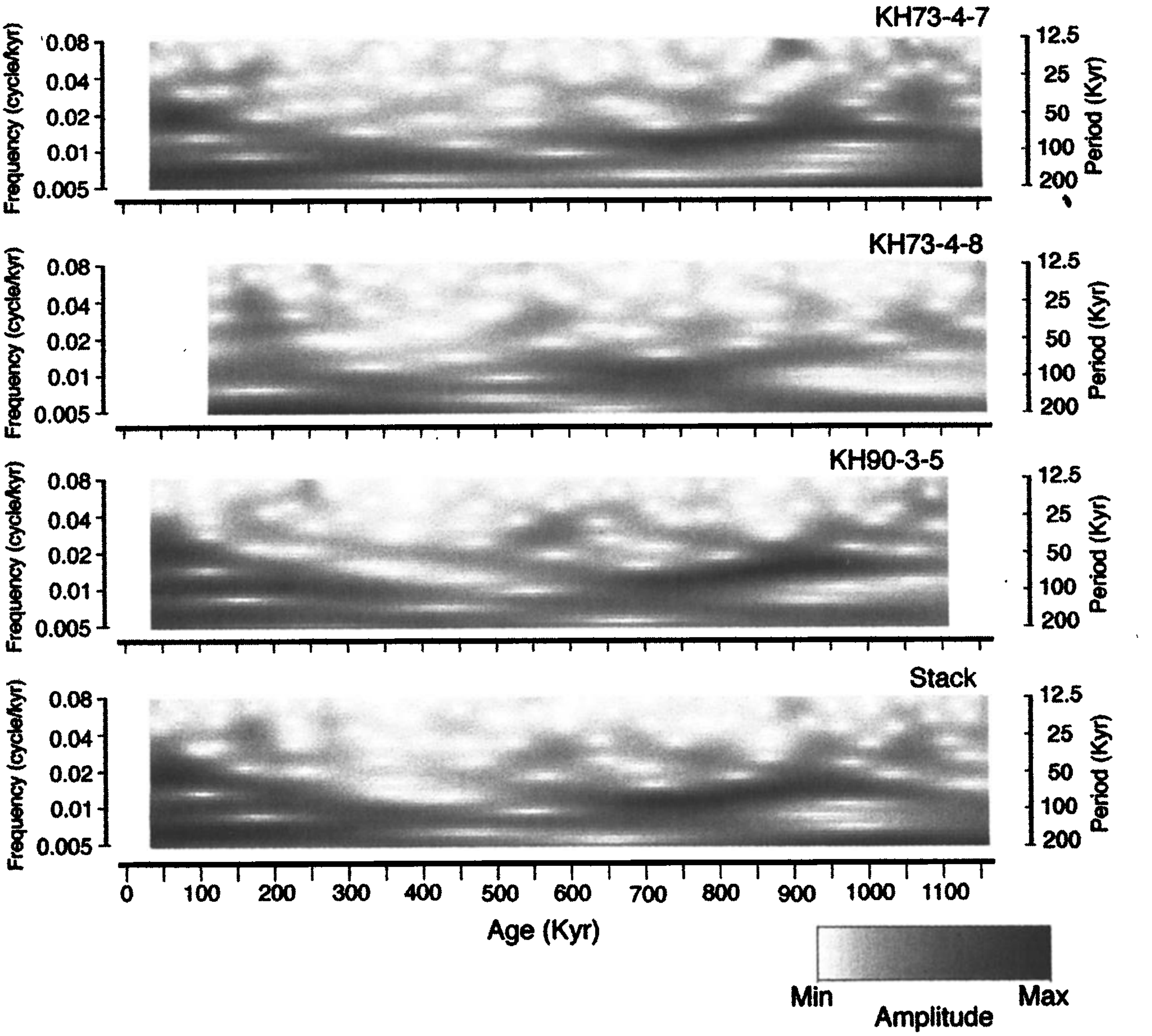

Figure 3. Wavelet transform patterns of paleointensity records from the three cores and stack. In these patterns, the wavelet coefficient is plotted as a function of period (frequency) along the vertical axis and age on the horizontal.

NRM was used in the calculation of the ratios of NRM / SIRM in cores KH 73-4-7 and KH 73-4-8. Among the three cores the sampling site of core KH 90-3-5 is the most distant from the equator. Nevertheless, nearly 90 % of inclinations are less than 10°. Therefore the influence of inclination variations to the total force of NRM is thought to be almost negligible for the other two cores.

Wavelet analyses

Wavelets are a recent tool for time-frequency analysis, exactly speaking for time-scale analysis [*Daubechies*, 1992]. The wavelet transform of a given function is defined by the expansion with respect to wavelets. Unlike the traditional Fourier transform, a wavelet basis is local, because it exist just around the origin. Also, it is granular, because its support is finite. The total family of the expansion bases is produced by dilation and translation of a basic wavelet. The expansion coefficients are the projection of a function to be analyzed at a particular frequency and time. Wavelets provide a robust multi-resolution representation; the wavelet transform offers sharp time resolution for rapidly changing components and fine frequency resolution for slowly varying components. The other advantageous feature in wavelets is the capacity they give to analyze discontinuities in transient signals; this is due to their good localization.

We used modified Morlet wavelets, which are sinusoids in a Gaussian envelop (Figure 2). The reasons for this choice are threefold: /1/ it has the least spread in both domains of time and frequency. /2/ If we use the wavelet in the continuous wavelet transform, a translation-invariant representation for comparing various time-frequency patterns is available. /3/ Fine decomposition in frequency - such as ten components per octave - is produced , and this leads to an easy-to-see visualization. Procedures for analysis using wavelets are similar to *Bolton et al.* [1995].

Results and discussion

Analyses of NRM / SIRM records from KH 73-4-7 and KH 73-4-8 and NRM / κ records from KH 90-3-5 (Figure 3) show that all frequencies have strongly time dependent amplitudes. Moreover there appears to be a clear tendency that in cores KH 73-4-7 and KH 90-3-5 a frequency of major changes shifted continuously with time, although there appeared to be some partial changes (a cycle of around 100 Ka for the last 0.25 Ma) with a constant frequency. In those cores a dominant cycle of around 70 Ka at around 1.1 Ma lengthened to around 140 Ka at around 0.6 Ma and then shortened to around 50 Ka at 0.05 Ma. In core KH 73-4-8 we can find a similar tendency from 1.1 Ma to 0.25 Ma. As the mechanical disturbance of core top in KH 73-4-8 is the largest, the reduced similarity of the top of KH 73-4-8 in the modulus plots (Figure 3) probably reflects core top distortion of the sediment.

The parameter n (= 2) in our wavelet analysis corresponds to the number of sinusoidal periods which fit between the inflection point of the Gaussian envelop (Figure 2). The good localization of the analysis enable one to recognize the variations of the dominant cycle in the original time series (Figure 1). Namely ; 3 times of approximately a 70 Ka cycle between the upper Jaramillo boundary and the Brunhes-Matuyama boundary, approximately 2 times of a 100 Ka cycle until around 0.6 Ma. Then a much longer dominant cycle can be seen with a few occurrences of short cycle until around 0.3 Ma and then conversely the cycle shortens with age.

There are one to three occurrences of the dominant cycles in each time duration of about 60 Ka to 200 Ka distinguished by magnetostratigraphy for the lower part of the core (0.5 Ma to 1.1 Ma). An error in dating of a point would induce a correspondent magnitude of error in a period only at and around the age for the point in the wavelet analysis (Figure 3). Small amplitude and/or short time-scale variations in the sedimentation rate not observed in the magnetostratigraphy and the oxygen-isotope chronology are not thought to affect the tendency of the dominant cycle change.

It is well known that a near-100 Ka cycle dominates the paleoclimate record after the mid-Pleistocene at around 0.9 Ma, and a similar tendency is found in the records of magnetic mineral content. The variable period phenomena which appears in the NRM / SIRM and NRM / κ records does not appear in the records of the magnetic mineral content. Therefore the phenomena does not originate from the content variations but probably reflects the characteristics of the geomagnetic field variation. On the other hand, more detailed rock magnetic studies would be necessary in order to find out the origin of a near-100 Ka cycle appearing the last 0.25 Ma.

The wavelet analysis presented here provides another and simple view for the time series of the paleomagnetic field intensity variations in which periods of major changes shifted continuously between about 50 Ka and 140 Ka over time instead of the constant periods determined by the Earth's orbital parameters. In order to discover whether the characteristics of variable period shown in this study are common in paleointensity variations, it is necessary to analyze records spanning periods older than 1.1 Ma as well as records obtained from different depositional environment. If the characteristics in paleointensity variations are common, the next problem may be to find what parameter determines a varying period. The range of the period in the paleomagnetic intensity variations and the variability of the period may become constraints on the dynamo theories.

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References

Akai, J., T. Sato, and S. Okusa, TEM study on biogenic magnetite in deep-sea sediments from the Japan Sea and the western Pacific Ocean, *J. Electron Microsc., 40,* 110-117, 1991.

Bolton, E.W., K.A. Maasch, and J.M. Lilly, A wavelet analysis of Plio-Pleistocene climate indicators: A new view of periodicity evolution, *Geophysical Research Letters, 22,* 2753-2756. 1995.

Daubechies, I., Ten lectures on wavelets , 357 pp., SIAM, Philadelphia, Pennsylvania, 1992.

Farrell, J.W., and W.L. Prell, Climatic change and $CaCO_3$ preservation; an 800,000 year bathymetric reconstruction from the central equatorial Pacific Ocean, *Paleoceanography, 4,* 447-466. 1989.

Meynadier, L., J.-P. Valet, R. Weeks, N.J. Shackleton, and V.L. Hagee, Relative geomagnetic intensity of the field during the last 140 Ka, *Earth and Planetary Science Letters, 114,* 39-57. 1992.

Okada, M., Late Pleistocene δ^{13}C variability in the western equatorial Pacific, Sc.D. thesis, Univ. of Tokyo, 60pp, 1992.

Sato, T., and K. Kobayashi, Long-period secular variations of the earth's magnetic field revealed by Pacific deep-sea sediment cores, *J. Geomag. Geoelectr., 41,* 147-159, 1989.

Sato, T., K. Kobayashi, and J. Akai, Variations in Fe_3O_4 and $CaCO_3$ contents in deep-sea cores from the western equatorial Pacific, *J. Geomag. Geoelectr., 45,* 125-132, 1993.

Sato, T., H. Kikuchi, and M. Okada, Secular variation of geomagnetic field and variation of paleoenvironment recorded in deep-sea sediments from the western equatorial Pacific - A wavelet analysis -, paper presented at Japan Earth and Planetary Science Joint Meeting, Toyonaka, Mar. 26 to 29, 1996.

Sueishi, T., T. Sato, N. Kawai, and K. Kobayashi, Short geomagnetic episodes in the Matuyama epoch, *Phys. Earth Planet. Inter., 19,* 1-11, 1979.

Tauxe, L., Sedimentary records of relative paleointensity of the geomagnetic field: theory and practice, *Review of Geophysics, 31,* 319-354, 1993.

Valet, J.-P., and L. Meynadier, Geomagnetic field intensity and reversals during the past four million years, *Nature, 366,* 234-238, 1993.

Yamazaki, T., N. Ioka, and N. Eguchi, Relative paleointensity of the geomagnetic field during the Brunhes Chron, *Earth and Planetary Science Letters, 136,* 525-540, 1995.

Yoshida, S., and I. Katsura, Characterization of fine magnetic grains in sediments by the susupension method, *Geophys. J. R. astr. Soc., 82,* 301-317, 1985.

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