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Effects of variable sedimentation rates and age errors on the resolution of sedimentary paleointensity records

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[1] Synthetic, u-channel records of relative paleointensity have been generated with a numerical model simulating the recording process in sediments, variable quality age control and variable sedimentation rates, over a time interval of 500 ky. Simulation results indicate that paleointensity records with mean sedimentation rates up to 15 cm/ky can reflect geomagnetic dipole intensity fluctuations, with some amplitude differences between individual records of nongeomagnetic origin. This study confirms that relative paleointensity records have great potential as a stratigraphic tool and that a stratigraphic precision of a few thousand years can be achieved with records characterized by high sedimentation rates. Spectral analyses suggest that caution should be used when interpreting the power spectra of individual records and that stacked records should be favored. Stacked u-channel records with mean sedimentation rates of 1 cm/ky do not provide reliable spectral information on the dipole intensity for wavelengths shorter than 25–50 ky, and their utility is limited to long-term trends in paleointensity. For higher sedimentation rates, the range of spectral information depends on the stack resolution (sedimentation rates) and the age model. The best results are, predictably, obtained with high sedimentation rates and excellent age control. In these cases, the power spectra are reliable for wavelengths as short as 4 ky.

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1. Introduction

[2] Considerable information has been gathered in the past few decades on the time variations of the geomagnetic field [*Dormy et al.*, 2000; J.-P. Valet, Time variations in geomagnetic intensity, manuscript submitted to *Review of Geophysics*, 2001, hereinafter referred to as Valet, submitted manuscript, 2001]. For timescales ranging from a few thousand to a million of years, most of this information has been provided by continuous records of relative geomagnetic paleointensity obtained from marine sediments [e.g., *Channell et al.*, 1997, 1998; *Channell and Kleiven*, 2000; *Guyodo et al.*, 1999, 2001; *Lehman et al.*, 1996; *Meynadier et al.*, 1992, 1994; *Schneider and Mello*, 1996; *Stoner et al.*, 1995, 2000; *Tauxe and Wu*, 1990; *Tauxe and Shackleton*, 1994; *Tric et al.*, 1992; *Valet and Meynadier*, 1993; *Yamazaki et al.*, 1995]. Those records have permitted significant progress in our understanding of the geomagnetic field behavior during polarity reversals, during geomagnetic excursions, or within periods of stable magnetic polarity (see review in Valet [submitted manuscript, 2001]). The recent development of global paleointensity composites (Sint-200, Sint-800) showed that paleointensity features with wavelengths of a few tens of thousand years can be correlated worldwide [*Guyodo and Valet*, 1996, 1999]. This property of geomagnetic paleointensity has been used to develop age models in cases where the use of more traditional dating techniques is limited [*Stoner et al.*, 1998]. For shorter wavelengths, recent studies of high-resolution paleointensity records spanning the last ~100 ky indicate that millennial-scale correlation can be achieved, at least regionally [*Laj et al.*, 2000] and probably globally [*Channell et al.*, 2000; *Stoner et al.*, 2000]. However, those high-resolution correlations are difficult to test independently because alternative dating techniques such as oxygen isotope stratigraphy have a lower resolution than the paleointensity variations recorded in those sediments. In addition, amplitude differences are present among records with apparently correlative features, which could be lithologic in origin, but also geomagnetic in nature, as those records have sedimentation rates that should in principle allow sampling of nondipole (local) geomagnetic intensity variations.

[3] Over longer timescales, comparisons of relative paleointensity records have generated controversy. There has been lively debate about the interpretation of an asymmetrical saw-tooth pattern in paleointensity records that has been explained as a property of the geodymamo [*Valet and Meynadier*, 1993; *Meynadier and Valet*, 1996; *Meynadier et al.*, 1994, 1998] or as an artifact of the magnetization acquisition process [*Kok and Tauxe*, 1996; *Mazaud*, 1996a]. Another controversy surrounds the interpretation of cycles in paleointensity power spectra, some of which correspond to periods of the Earth's orbital parameters [*Channell et al.*, 1998; *Yamazaki*, 1999; *Yokoyama and Yamazaki*, 2000] but may be explained by climatic/lithologic "contamination" [*Guyodo et al.*, 2000] or by aliasing of the geomagnetic signal by coarse sampling of the field [*Teanby and Gubbins*, 2000].

[4] In the present paper, we explore the effects of age inaccuracies on the power spectra of sedimentary paleointensity records characterized by unstable sedimentation rates. Using a numerical model, we simulate records with mean sedimentation rates ranging from 1 to 15 cm/ky. We investigate (1) whether sedimentation rates fluctuations and age errors are sufficient to explain the amplitude differences observed between paleointensity records, (2) to what extent individual records reflect global geomagnetic fluctuations, and (3) how much confidence should be placed in the power spectra of paleointensity records.

2. Construction of the Model

[5] We have developed a numerical model simulating the deposition, magnetization acquisition, and paleomagnetic measurement of marine sediments characterized by variable sedimentation rates. The initial "geomagnetic" intensity signal, or reference signal, is the same for all experiments, and consists of a 500 ky long time series with intensity variations that are believed to represent (statistically) geomagnetic intensity changes [*Constable and Parker*, 1988]. This initial signal was constructed assuming that the value of each Gauss coefficient of the

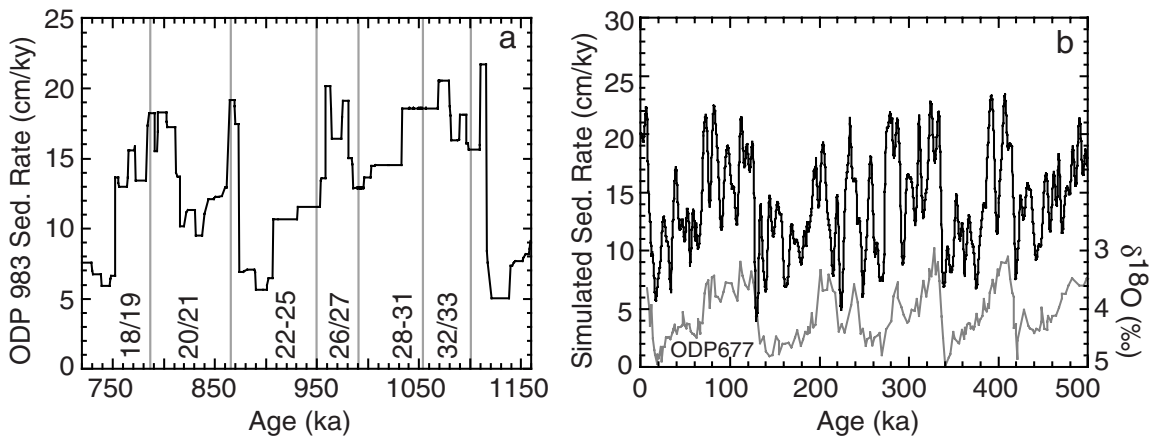

Figure 1. (a) Sedimentation rates calculated at ODP Site 983. The vertical lines (in gray) indicate the location of major glacial to interglacial transitions. The numbers located between the lines correspond to the oxygen isotope stages (redrawn from *Channell and Kleiven* [2000]). (b) Example of sedimentation rates simulated with the numerical model. ODP Site 677 benthic $\delta^{18}O$ record [*Shackleton et al.*, 1990] is shown at the bottom, to illustrate the fact that the simulated sedimentation rates vary on a glacial/interglacial time-scale.

geomagnetic field at a specific time is a fraction of its value at a preceding time, plus a random contribution from a white noise spectrum [*Mazaud et al.*, 1996b]. The fraction of the value retained between successive terms depends on the correlation time of each coefficient (millennial for the dipole field, and centennial for the nondipole field) [*Constable and Parker*, 1988; *Hulot and Le Mouël*, 1994; *Hongre et al.*, 1998; *Mazaud et al.*, 1996b].

[6] Our numerical model is composed of four consecutive steps for each simulation: (1) conversion of the "geomagnetic" reference time series into a depth series, (2) acquisition of the magnetization and alteration of the magnetic signal, (3) measurement of u-channel samples, and (4) conversion to a time series using an age model.

2.1. Variable Sedimentation Rates

[7] The first step in each simulation consists of converting the age-scale into a depth-scale using the appropriate sedimentation rate transfer function. This simulates the deposition of sediment on the seafloor and instantaneous orientation of the magnetic mineral grains with the geomagnetic field. In natural pelagic marine environments, sedimentation rates vary significantly from one geologic setting to another, with average values ranging from less than one to more than ten centimeters per thousand years. They are affected by several parameters including variations in paleoproductivity in the oceans, ice sheet variability, or fluctuations of the carbonate compensation depth (dissolution). Overall, one can expect sedimentation rates for the past few million years to be variable on a glacial/interglacial time-scale. A good example is provided by a study at Ocean Drilling Program (ODP) Site 983 in the time interval 0.7–1.1 Ma [*Channell and Kleiven*, 2000]. The age model in this interval at Site 983 was derived by tuning the precession cycles (20 ky) present in its $\delta^{18}O$ record to those of the ice volume model of *Imbrie and Imbrie* [1980]. The tuning was obtained by correlating the outputs of a Gaussian filter applied to both records and centered at 0.05 ± 0.02 ky^{-1}. The resulting sedimentation rates averaged ~14 cm/ky, with values ranging from 5 to 22 cm/ky, and a standard deviation of ~4 cm/ky (i.e., ~30% of the mean sedimentation rate), with lower rates during glacials (Figure 1a). Sedimentation rates probably change significantly over time intervals of only a few thousand years. For traditional matching of the Site 983 $\delta^{18}O$ record to a reference $\delta^{18}O$ record, the time step separating two tie-points would exceed 10 ky. Averaging sedimentation rates between tie-points, for intervals with significant changes in sedimentation rates, would lead to large chronological errors.

[8] We have attempted to take this variability into account in the numerical model. For each simulation, a sedimentation rates transfer function is constructed from a random time series with fixed

mean (in the 1–15 cm/ky range) and standard deviation (30%), which is multiplied by a weighting function favoring higher sedimentation rates during interglacial periods. An example of such sedimentation rates is shown in Figure 1b. In this example, the average sedimentation rate is 14 cm/ky. Note that the range of sedimentation rate values (4–24 cm/ky) in this example is comparable to that of ODP Site 983 (5–22 cm/ky) (Figure 1a).

2.2. Postdeposition Remanence Acquisition

[9] The model also simulates the acquisition of a stable magnetization by the sediment. This is achieved by convolution of the initial signal with a "lock-in" function corresponding to a postdepositional remament magnetization (pDRM) acquisition process. The actual shape and extent of the pDRM function is uncertain [e.g., *Kent*, 1973; *Verosub*, 1977; *Hyodo*, 1984; *Hoffman and Slade*, 1986; *Katari et al.*, 2000], but it seems reasonable to assume that the lock-in of the magnetization is somewhat progressive. Magnetic grains at the top of the sedimentary column, where the water content is high and the sediment relatively unconsolidated, are able to rotate and reorient themselves along magnetic field lines. In contrast, magnetic grains located in the underlying sediment, depending on their size and shape, will be unable to rotate due to the progressive dewatering of the sediment. A simple model of pDRM consists of an exponential function [*Hyodo*, 1984], which has been used in recent studies modeling postdepositional magnetization acquisition processes [*Meynadier and Valet*, 1996; *Mazaud*, 1996a; *Teanby and Gubbins*, 2000]. *Teanby and Gubbins* [2000] also added an 8 cm uniform mixing layer (magnetization = 0) at the top of the sedimentary column, which was intended to simulate bioturbation at the sediment/water interface. A recent redeposition study suggested that, at least for some lithologies, intergranular interaction could reduce significantly the extent of pDRM, and bioturbation may not enhance, but rather disrupt, the remanent magnetization below the sediment/water interface [*Katari et al.*, 2000]. The conclusions of this recent paper are in agreement with studies by *Tauxe et al.* [1996] and *Hartl and Tauxe* [1996] but contradict previous results [*deMenocal et al.*, 1990; *Lund and Keigwin*, 1994; *Kent and Schneider*, 1995]. In the present paper, we chose to follow an approach where the pDRM function is simply given by an exponential. The parameters in this equation were selected so that 50% of the magnetization is locked within 10 cm (lock-in-depth) below the sediment/water interface, and 100% within 1 m. In Figure 2, we have plotted the results of paleointensity simulations obtained over a 100 ky long time interval showing sufficient variability, with lock-in-depths of 1 and 10 cm, and constant sedimentation rates of 1 cm/ky and 15 cm/ky. An increase in pDRM, simulated by greater lock-in-depth, results essentially in a decrease in the amplitude of high frequencies in the paleointensity record and acts as a low-pass filter on the geomagnetic paleointensity record. A significant fraction of the filtering is also achieved by lowering the mean sedimentation rate, as can be deduced from the difference in resolution between the records at 15 and 1 cm/ky. Ideally, one should be able to take a few sedimentary paleointensity records and compare their resolutions with those of the simulation. This would provide a calibration of the pDRM required in the model to fit the real data. However, as discussed in the section 2.1, sedimentation rates at one site are not uniform over a time interval long enough to sample the entire spectrum of geomagnetic field intensity variations. Therefore the extent of pDRM-induced filtering in real paleointensity record would be difficult to distinguish from that induced by sedimentation rates fluctuations. In addition, pDRM effects are probably dependant on the sediment lithology, and intergrains interaction [*Lu et al.*, 1990]. Despite this frustrating situation, we attempted a qualitative comparison with the results from ODP Site 983 for which the sedimentation rates are well constrained. We selected the interval (780–880) ka, which corresponds to a period of stable magnetic polarity. Over this interval, the mean sedimentation rate is 15.1 cm/ky, with values ranging from 7 to 19 cm/ky. The amplitude of the short-term oscillations appears to be lower than obtained in the simulation with a 1 cm lock-in-depth, suggesting the presence of some pDRM-induced filtering of the signal. The presence of pDRM at Site 983 is also suggested by the shape of the paleointensity power spectra, the

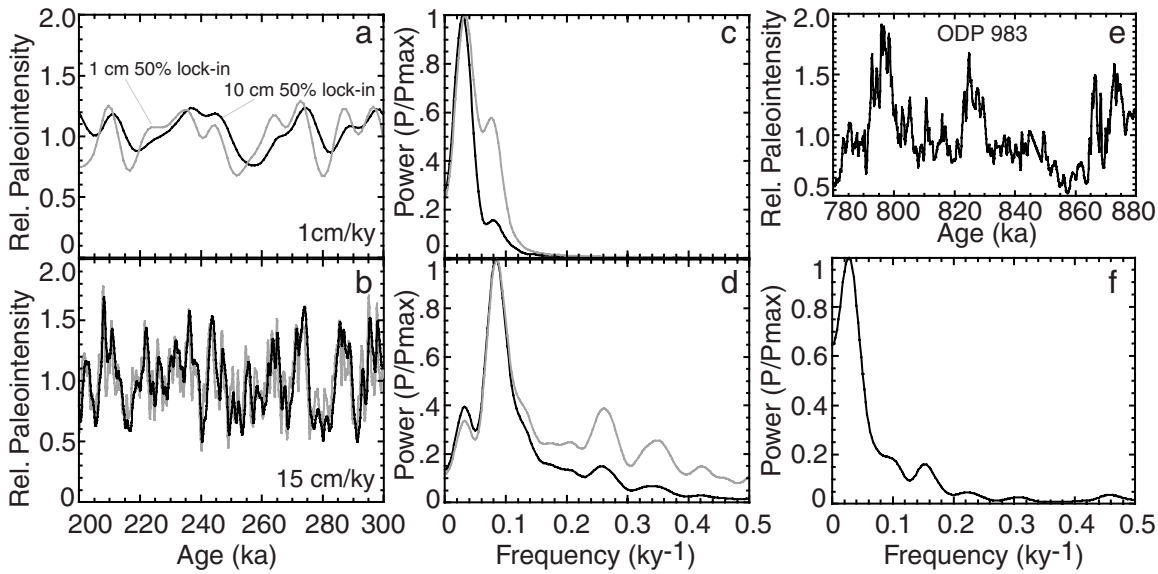

Figure 2. 100 ky-long relative paleointensity simulations with constant sedimentation rates of (a) 1 cm/ky and (b) 15 cm/ky, and (c, d) their respective power spectra. Gray curves correspond to simulations performed with a 1 cm lock-in-depth, while black lines correspond to simulations done with a 15 cm/ky lock-in-depth. (e) Paleointensity at ODP Site 983, for a 100 ky long time interval of stable magnetic polarity, and (f) associated power spectra. The confidence interval on the power spectra at the 95% confidence level is given by the relation: $0.49 < dP/P < 3.08$.

shape being closer to the one derived from the simulation with a 10 cm lock-in-depth. Over the frequency range shown in Figure 2, the power spectrum of the 1-cm lock-in-depth simulation does not drop below 5% of its maximum value, whereas those of Site 983 and of the 10-cm lock-in-depth simulation are both attenuated to this level for frequencies higher than 0.3–0.4 ky^{-1}. Therefore we chose the conservative approach and incorporated a 10 cm lock-in-depth in the model.

[10] Subsequent to the acquisition of magnetization, the model simulates the measurement of u-channel samples with a cryogenic magnetometer, with a down core measurement stepsize of 1 cm. The signal is subsampled at intervals of 1 cm after convolution with the response function of a 2G-Entreprises u-channel magnetometer, which is a Gaussian function with a maximum half-width of about 6 cm. The top-most part of the record is subsequently removed, as the sediment is not consolidated and the magnetization acquisition only partial over this interval.

2.3. Different Age Models

[11] In the final step of the simulation, the paleointensity records are dated using age models of variable quality. Previous studies simulating the acquisition or measurement of magnetization in marine sediments have considered constant sedimentation rates and therefore ideal dating. This situation is highly unlikely in reality, since most paleomagnetic and paleoceanographic studies report records characterized by variable sedimentation rates. For marine sediments, the age model is usually derived by correlation of oxygen isotope ($\delta^{18}O$) data at a specific site to a reference record of known age. Tie-points between the $\delta^{18}O$ record and the reference record, and the step between tie-points, will depend on the resolution of sampling and the overall quality of the isotopic record. This procedure assumes constant sedimentation rates between tie-points. If the actual sedimentation rates vary on a timescale shorter than the time step between tie-points (typically a few tens of thousand years), age offsets (of a few thousand years) are generated.

[12] In our simulations, we used four age models of variable resolution. Examples of these age models are shown in Figure 3, where the apparent sedimentation rates resulting from the age models are compared to the actual sedimentation rates used to construct the initial depth-scale (as described in

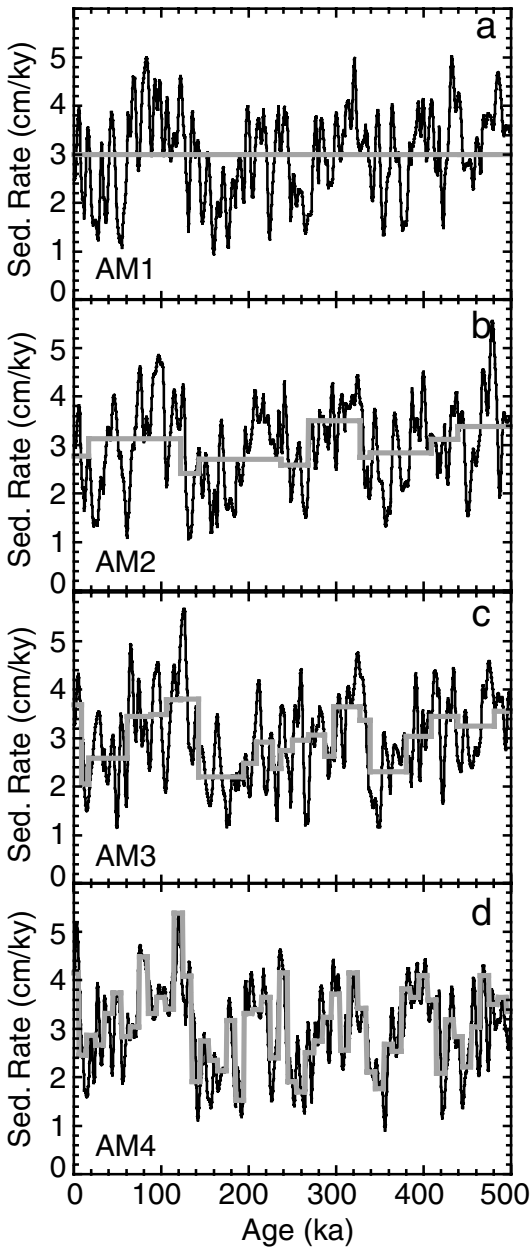

Figure 3. Examples of apparent sedimentation rates (in gray) derived from the age models (a) AM1, (b) AM2, (c) AM3, and (d) AM4 used in the simulations, and compared to the actual (initial) sedimentation rates (in black).

section 2.1). In the first age model, AM1, only two tie-points have been used. This could correspond to an age model based on magnetic polarity stratigraphy, where no isotope data are available and only the location of the magnetic polarity boundaries can be used to date the sediment. The second age model, AM2, represents a low-resolution correlation between $\delta^{18}O$ data, where only the terminations between glacial and interglacial periods have been correlated. The reference curve utilized here is the benthic $\delta^{18}O$ record of ODP Site 677 [*Shackleton et al.*, 1990]. The AM2 age model corresponds to an age model based on a $\delta^{18}O$ record obtained from a low-resolution sampling of the sediment or on a $\delta^{18}O$ record that is difficult to correlate unambiguously to the reference. In the third age model, AM3, additional tie-points have been introduced. This corresponds to a medium-high resolution correlation of $\delta^{18}O$ records. The last age model, AM4, corresponds to that obtained with a "tuning" of the $\delta^{18}O$ records, using the orbital precession cycles. This type of age model requires high-resolution $\delta^{18}O$ records, of excellent quality. Evidently, an age-model based on only a few tie-points will yield less variable apparent sedimentation rates, which could be wrongfully interpreted as the result of uniform sedimentation (Figure 3).

2.4. Comparison With Real Data

[13] In the model described in the section 2.3, the magnetic properties (magnetic mineralogy, grain size and shape, and concentration) and the response function of the sediment have been assumed constant throughout the entire sequence. However, natural sediments display variations in these parameters, which influence the natural remanent magnetization (NRM) of the sediment. Ideally, paleointensity records are obtained by normalizing the NRM with a magnetic parameter reflecting variations in concentration of the grains that carry the NRM. If the normalization has been done correctly, the resulting record should display geomagnetic paleointensity changes (see review by *Tauxe* [1993]). A compilation of 18 paleointensity records for the last 200 ky (Sint-200) [*Guyodo and Valet*, 1996] showed that these globally distributed records recover a consistent global paleointensity record. However, the correlation between the records is imperfect, and the disparity accounts for the ~10% uncertainty associated with the compilation [*Guyodo and Valet*, 1996]. These differences could be due to uncertainties in chronologies but also to inadequacy of the normalization procedure resulting in uncompensated lithologic variability.

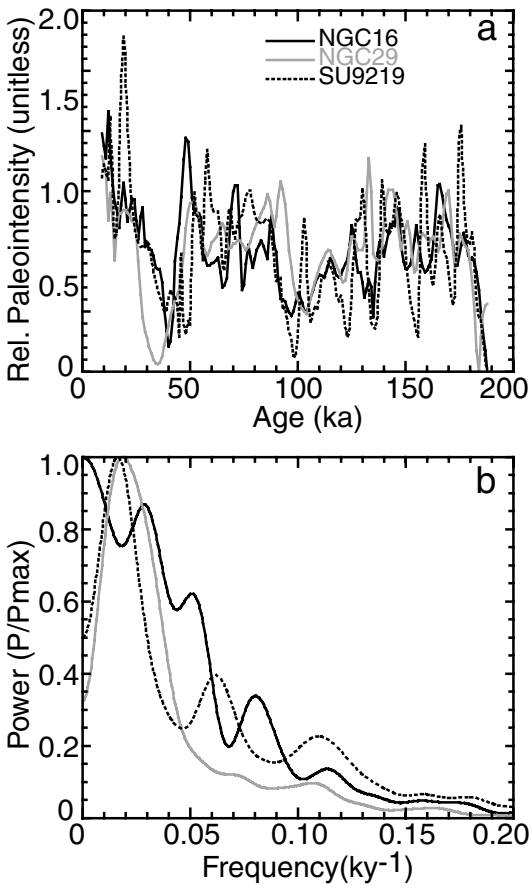

Figure 4. (a) Comparison of three real paleointensity records over a 200 ky long time interval and (b) their respective power spectra. The confidence interval on the power spectra at the 95% level is given by the relation: $0.49 < dP/P < 3.08$.

[14] In Figure 4, we plot three paleointensity records of mean sedimentation rate around 3 cm/ky [*Lehman et al.*, 1996; *Yamazaki and Ioka*, 1994], which were extracted from the database used to construct Sint-200 [*Guyodo and Valet*, 1996]. These records have been put on a common timescale using oxygen isotope stratigraphy, with a resolution similar to an AM3 age model [*Guyodo and Valet*, 1996]. Most of the features can be matched among the records, but they display significant differences in amplitudes. In addition, although they display the same succession of paleointensity features, their power spectra do not agree well with each other. We tested whether or not our model could reproduce those differences. The results are shown in Figures 5a and 5b, where we have plotted the outputs of three simulations obtained with a mean sedimentation rate of 3 cm/ky for a 200 ky time interval. The age model for these simulations is AM3, which has similar resolution to the age models of data presented in Figure 4. Amplitude differences among the simulated records (Figure 5a) are much less marked than in the case of the real records (Figure 4). On average, the amplitude difference in relative paleointensity among the simulated records is about a third of that of the real records. In addition, the power spectra of the simulated records are very similar to one another, with a mean difference in power of ~30%, in contrast with those of the real data that show an average difference in power of ~60% (Figure 5b). This suggests that the differences in paleointensity induced by age errors are not sufficient to explain the differences among real records at these mean sedimentation rates. These differences probably reflect imperfect normalization due to lithologic variability. Geomagnetic variability is unlikely to provide the explanation. At mean sedimentation rates of 3 cm/ky, nondipole (local) geomagnetic intensity variations are unlikely to be recorded because, according to some authors, the nondipole components vary on a centennial scale [*Hulot and Le Mouël*, 1994; *Hongre et al.*, 1998]. In order to simulate uncompensated lithologic variability, a small overprint (~10% of the standard deviation of each paleointensity record) has been added to the simulations. This secondary signal is different for each simulation and is generated from a random iterative process with wavelengths ranging from a few centimeters to several meters. The paleointensity simulations obtained with this revised model (Figures 5c and 5d) display differences in amplitude and power spectra that are closer to those of the real data (Figure 4) and are therefore considered to be more realistic.

3. Results

3.1. Individual Records

[15] The model was used to simulate u-channel paleointensity records over a time span of about 500 ky, with mean sedimentation rates ranging from 1 to 15 cm/ky. For each mean sedimentation

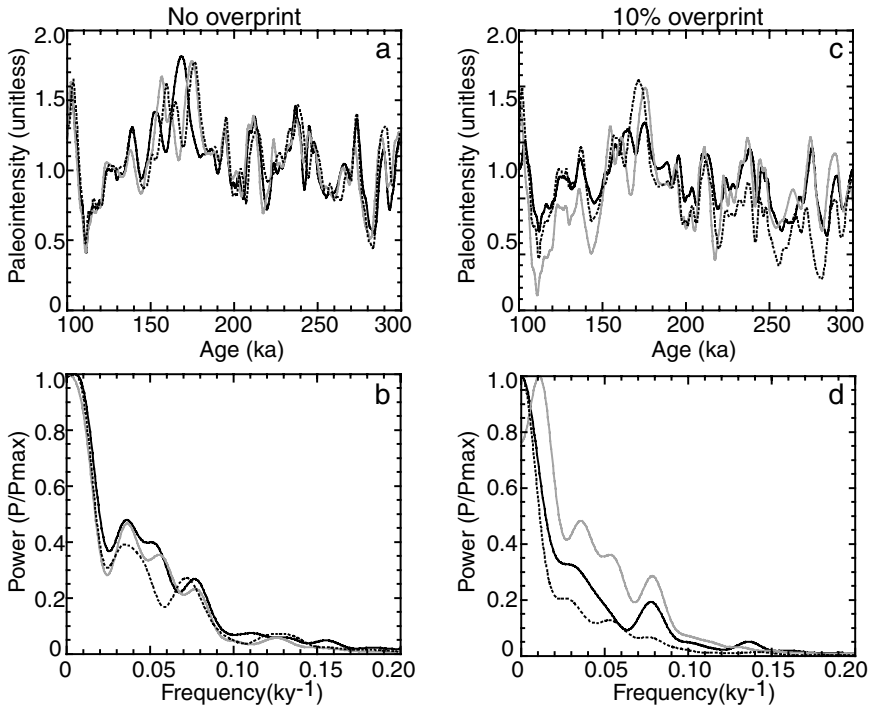

Figure 5. 200 ky simulations of paleointensity records with mean sedimentation rates of (a) 3 cm/ky and (b) associated power spectra. (c, d) The same as Figures 5a and 5b, with an additional 10% overprint. The confidence interval on the power spectra at the 95% level is given by the relation: $0.49 < dP/P < 3.08$.

rate, 10 simulations were performed. The results obtained for the mean sedimentation rates of 1, 7, and 15 cm/ky are shown on Figure 6, over the time interval common to all the records. As expected, a decrease in the dispersion of the data is noticed with increasing age model resolution (Figure 6). The low-resolution records seem to remain unaffected by changes in quality of the age model. For age models AM2, AM3, and AM4, there is a significant decrease in dispersion with increasing sedimentation rates. The problem inherent in the age models could be corrected if the signal was sufficiently preserved to allow positive recognition of paleointensity features among the records. This is explored in Figure 7a for the age model AM3. In this case, records characterized by very high mean sedimentation rates (e.g., 15 cm/ky) show features that can be uniquely correlated to dipole variations of geomagnetic field intensity, although there are some differences in amplitude. In Figure 7a, relative variations of the axial dipole intensity are estimated by filtering wavelengths shorter than 2000 years from the reference geomagnetic signal. As mentioned above, nondipole components and equatorial dipoles are believed to have time constants of about 150 years and 500 years, respectively [*Hulot and Le Mouël*, 1994; *Hongre et al.*, 1998; *Dormy et al.*, 2000]. Our simulations suggest that paleointensity records with mean sedimentation rates up to 15 cm/ky display essentially global geomagnetic time variations associated with the main axial dipole. This result tends to support previous findings that imply that paleointensity records from the North Atlantic to the South Atlantic oceans can be correlated [*Channell et al.*, 2000; *Stoner et al.*, 2000]. Maximum offsets between the synthetic records and the reference geomagnetic variations are less than 4-5 ky (Figure 7a). They are sufficiently small to allow correct matching of dipole variations from one record to the other. Therefore one could use high-resolution relative paleointensity records to develop a global geomagnetic paleointensity stratigraphy, at a resolution of a few thousand years. One application would be to provide important information about leads and lags between paleoclimatic proxies in different regions of the globe.

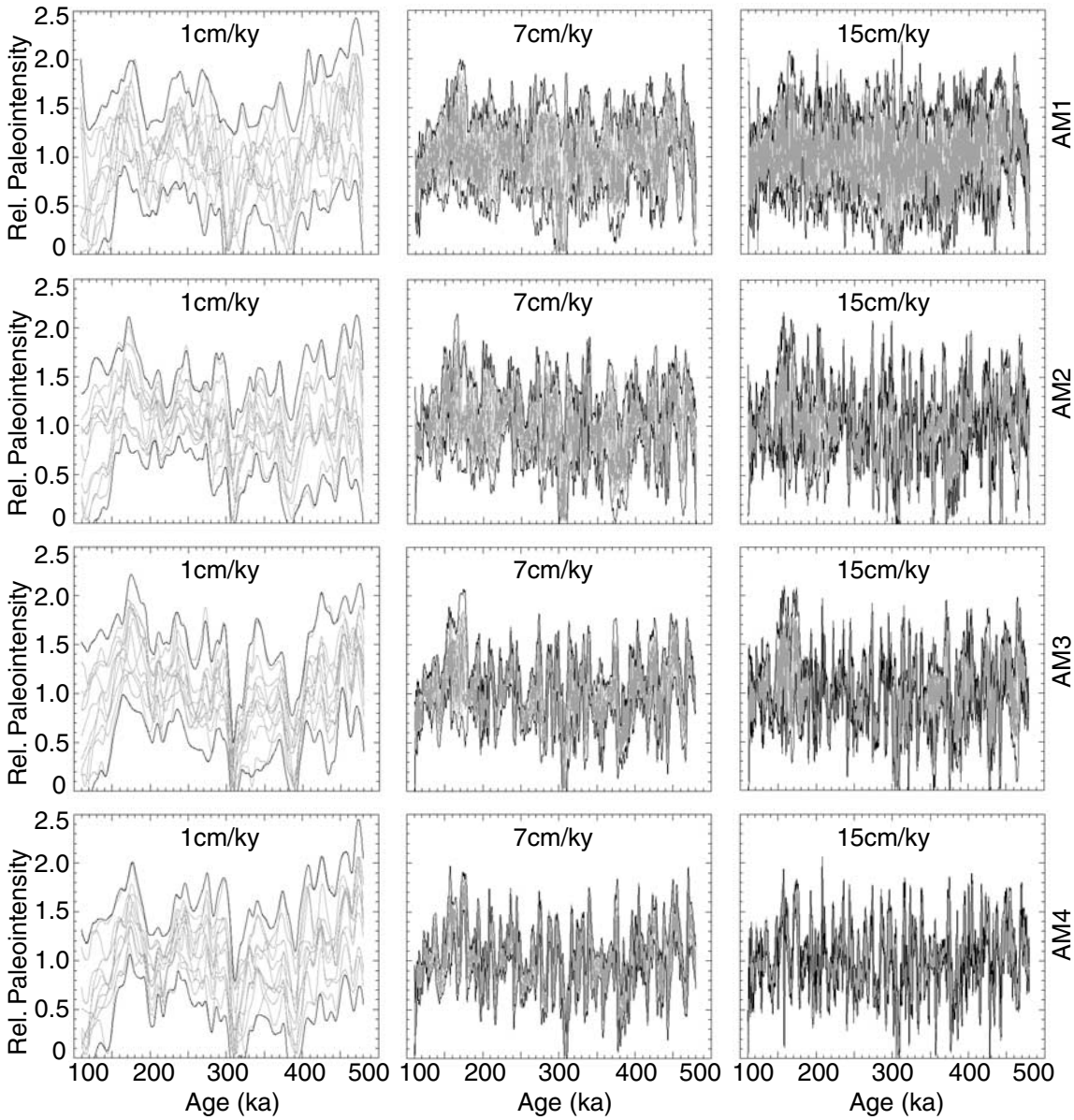

Figure 6. Paleointensity records simulated for mean sedimentation rates of 1, 7, and 15 cm/ky and the age model AM3 over the 110–480 ka time interval. The records are represented on their common interval (110–480 ka). The black lines represent the 2-sigma standard deviation of the distribution of paleointensities for each mean sedimentation rate.

[16] Records with medium- to high-sedimentation rates (e.g., 7 cm/ky) can also be correlated to one another and to the axial dipole signal with confidence (Figure 7a). For low-sedimentation rates (e.g., 1 cm/ky), recognition of reference geomagnetic features is very poor. Essentially, only the major dips (like the one at 310 ka) and broad trends in the initial reference geomagnetic model are recorded. For these low sedimentation rate simulations, offsets between the simulations and the reference geomagnetic intensity can be greater than 10 ky. Direct correlation of low sedimentation rate simulations with higher sedimentation rate simulations is difficult. When simulated records characterized by different quality age models are compared (Figure 7b), the correlation is not easy to establish. In particular, it is difficult to correlate simulated records with drastically

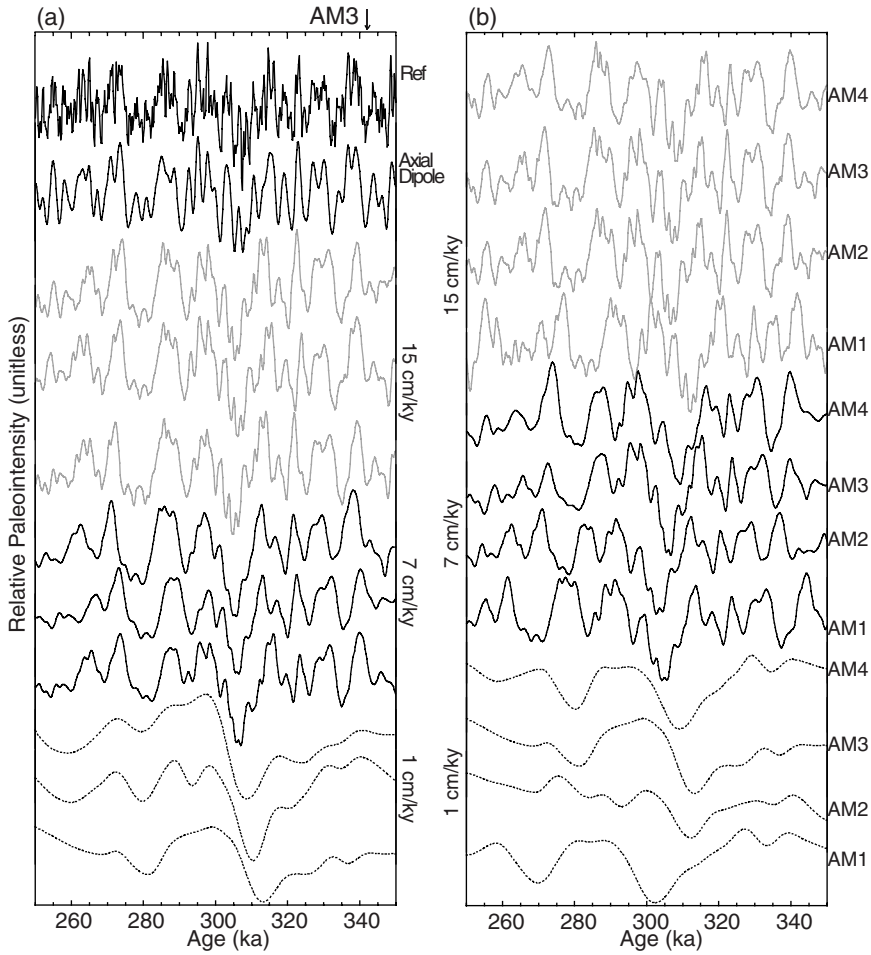

Figure 7. (a) Comparison of simulated records of paleointensity with the reference geomagnetic signal (at the top) from which they are derived. The age model is AM3. A "dipole" curve is also figured, which was obtained by applying a low-pass filter (>2 ky) to the reference curve. (b) Comparison of simulated paleointensity records for different age models.

different mean sedimentation rates (e.g., 1 versus 7 cm/ky), and age control of variable quality. If such correlation had to be attempted, the best approach would be to intercorrelate the low-resolution paleointensity records, and then correlate them to records of progressively increasing resolution and age control.

3.2. Individual Power Spectra

[17] Subsequently, we investigated the effects of unstable sedimentation rates on the power spectra of individual records, for the four age models. Figure 8 represents the power spectra of the individual paleointensity records for mean sedimentation rates of 1, 7, and 15 cm/ky. The spectra were obtained with the Blackman-Tukey method in the software Analyseries [*Paillard et al.*, 1996]. Besides the obvious differences in the frequency range of the power spectra for different mean sedimentation rates, the power spectra vary significantly among records of similar resolution and age model. This could result in serious problems when interpreting individual power spectra in terms of geodynamo behavior. A smaller dispersion among the spectra is found for paleointensity records with high mean sedimentation rates and very good age control (AM4). In this case, most of the power spectra display a somewhat comparable succession of spectral peaks. However, they are affected by significant differences in the relative amplitudes of those spectral peaks from one record to another.

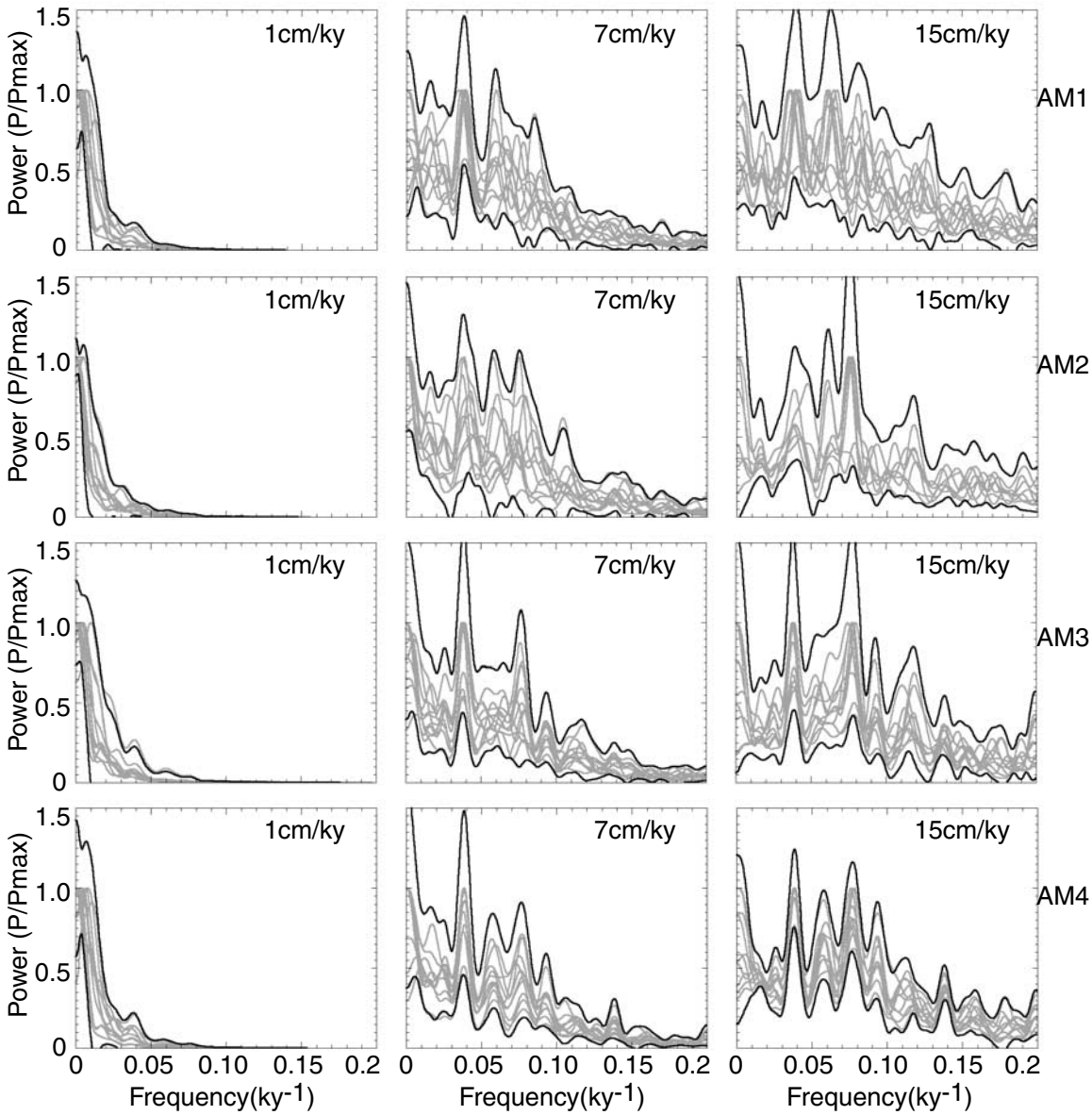

Figure 8. Power spectra of the records shown on Figure 6. The black lines represent the 2-sigma standard deviation of the distribution of power spectra for each sedimentation rate. The confidence interval on the power spectra at the 95% level is given by the relation: $0.49 < dP/P < 3.08$.

[18] As a consequence, caution should be used when interpreting the power spectra of individual records of relative paleointensity, even when they are well dated. A more conservative and probably safer approach would be to consider either a compilation of a sufficient number of individual power spectra or the power spectra of a compilation of paleointensity records. These methods yield average power spectra, which should reflect the spectral information common to all the records and hopefully converge toward the power spectrum of the actual geomagnetic field.

3.3. Stacking the Records

[19] Compilations of the individual power spectra, as a function of mean sedimentation rate, ranging from 1 to 15 cm/ky, are represented by color maps in Figure 9. Alternatively, Figure 10 displays the power spectra derived from stacking the 10 paleointensity simulations. Comparison with the refer-

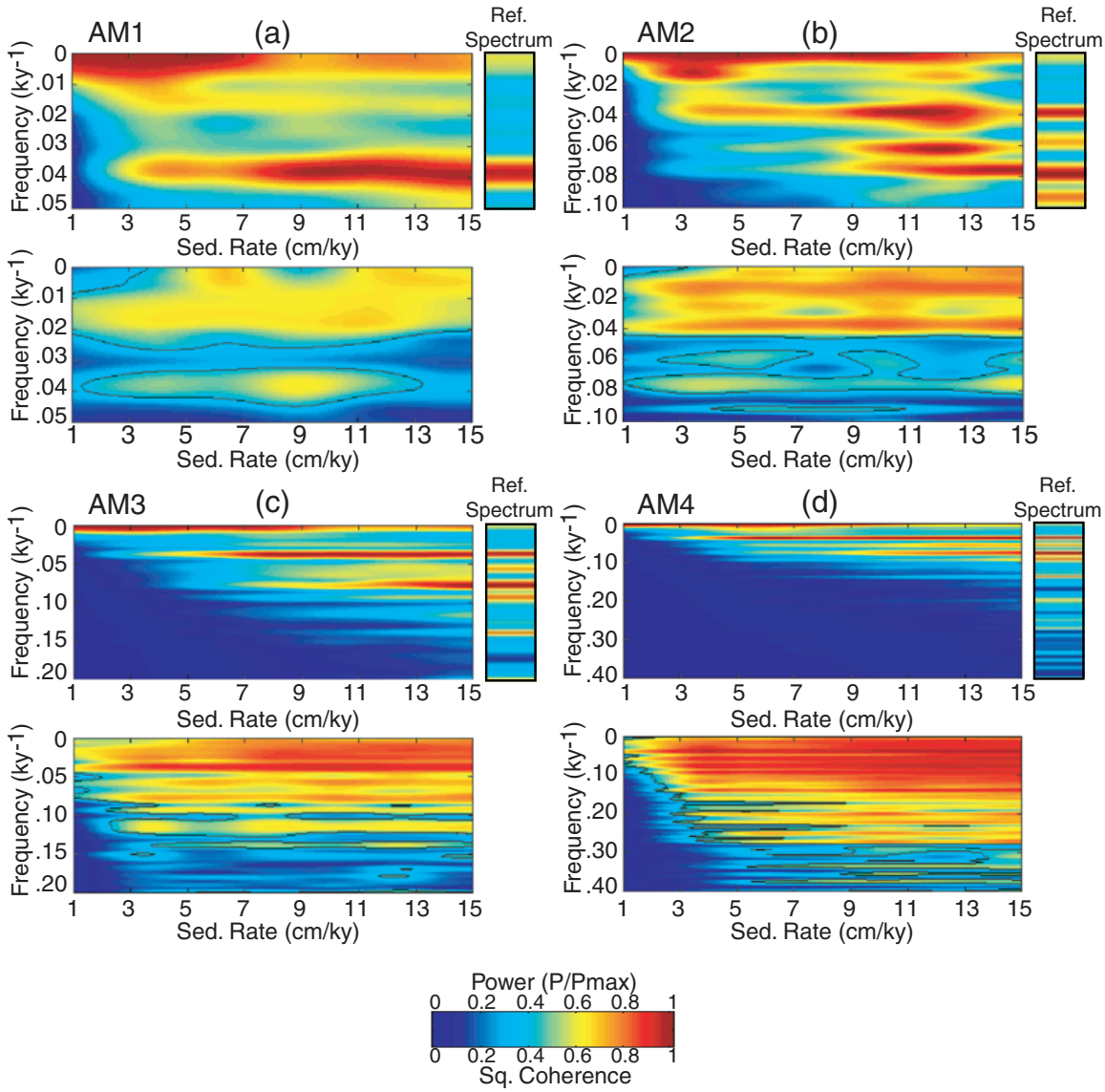

Figure 9. (a) Top panel color maps of the compilation of power spectra, as a function of mean sedimentation rates ranging from 1 to 15 cm/ky for the age model AM1 (top panel). The power spectra can be compared to the reference spectrum (vertical color bar). Color maps of the compilation of squared coherences between the paleointensity and the reference signal, as a function of sedimentation rate, for the age model AM1 (bottom panel). The black line corresponds to the 95% significance level. (b, c, d) The same as Figure 9a for the age models AM2, AM3, and AM4, respectively. The frequency scales vary from one subplot to the other, depending on the range of frequency where the signal is significant.

ence power spectrum can be done by visual match (Figures 9 and 10), as well as by calculation of the coherence function between the compilations and the reference geomagnetic signal. Figures 9 and 10 show similar results, although the spectra are sharper (better recognition of the features present in the reference spectrum), and the values of the coherence are higher in the case of the power spectra derived from stacking compilations of paleointensity records (Figure 10). In both cases, significant differences are observed between results obtained with different age models. Naturally, compilations obtained from records dated with a low-resolution age model (e.g., AM1) incorporate records with significant age offsets, which tend to reduce the time resolution of the compilation

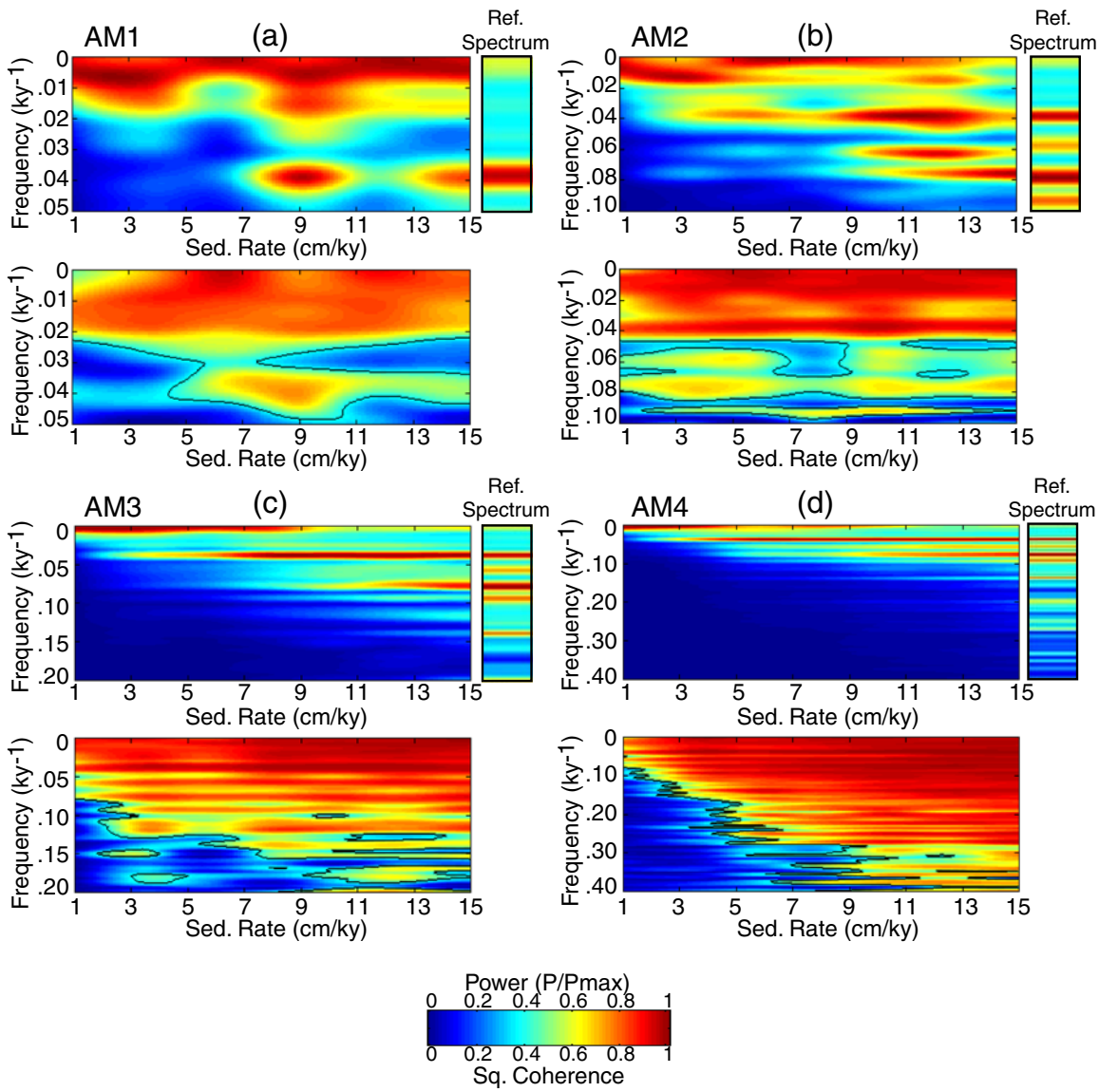

Figure 10. (a) Color maps of the power spectra of the stacked records, as a function of sedimentation rates ranging from 1 to 15 cm/ky for the age model AM1 (top panel). The power spectra can be compared to the reference spectrum (vertical color bar). Color maps of the squared coherence between the stacked paleointensity records and the reference signal, as a function of sedimentation rate, for the age model AM1 (bottom panel). The black line corresponds to the 95% significance level. (b, c, d) The same as Figure 10a for the age models AM2, AM3, and AM4, respectively. The frequency scales vary from one subplot to the other, depending on the range of frequency where the signal is significant.

(Figure 10a). For these records, there is little resemblance between the power spectra and the reference spectrum, for all sedimentation rates. For this age model, it is impossible to find any paleointensity feature of wavelength shorter than 25–50 ky that is coherent (at the 95% significance level) with those of the reference geomagnetic model. The coherence increases with improving age models and increasing sedimentation rates. When the age control is excellent and the mean sedimentation rate is 15 cm/ky, paleointensity features as short as 2–3 ky are coherent with the geomagnetic field at the 95% significance level. These results are summarized in Figure 11a, which displays the location of the 95% significance level as a function of the sedimentation rate for the four

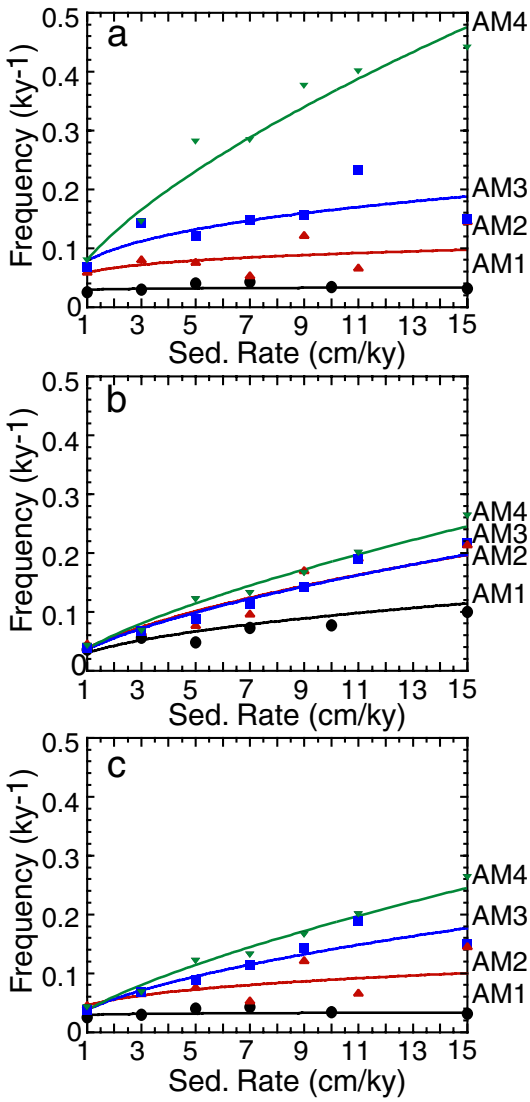

Figure 11. (a) Maximum frequency range of the coherence (at the 95% significance level) between the stacked paleointensity records and the reference signal, as a function of the sedimentation rate. (b) Limit of the 80% attenuation of the power spectra, relative to the reference spectrum. (c) Minimum value of either the frequency at which the coherence with the reference signal is lost (at the 95% level), or at which the 80% attenuation is reached.

age models. Because the 95% significance level depends slightly on the power spectra, those limits have to be taken as estimates (within a few 10^{-3} ky^{-1}). AM1 is characterized by almost no variation, while there is an increase in the frequency domain of coherence with increasing sedimentation rates for the other age models. For age models AM2 and AM3, the increase is much slower than for AM4, and some "plateau" (at ~10 ky for AM2 and ~6–8 ky for AM3) is reached for mean sedimentation rates higher than about 7 cm/ky. These estimates are based on the existence of coherence between the paleointensity and the reference geomagnetic signal with values above the 95% significance level. However, the actual power in those spectral bands may be too attenuated with respect to the reference spectrum to provide a reliable estimate. This point is illustrated in Figure 12, where we plot the power spectrum of a compilation of paleointensity records with mean sedimentation rate of 9 cm/ky (age model AM4). In this example, there is coherence between the compilation and the geomagnetic signal for frequencies up to ~0.28 ky^{-1} (i.e., wavelengths shorter than ~3.5 ky). However, the power spectrum at that point is characterized by values that are less than 5% of the maximum value. In addition, the relative changes in amplitude for consecutive peaks in the power spectrum do not match those of the reference spectrum and therefore would not provide reliable information on the geomagnetic field. An alternative way to examine these results is to plot the relative change in power spectrum between the original geomagnetic signal and the paleointensity stack (Figure 12c). It is possible to separate regions where the paleointensity power spectrum has been amplified relative to the reference spectrum, and where it has been attenuated (Figure 12c). The region where the correlation with the reference spectrum is unclear (Figure 12a) corresponds to an attenuation of the original power spectrum greater than ~80% (Figure 12c), and to a slight decrease in the coherence, although it is still above the 95% significance level (Figure 12b).

[20] We used this additional criteria to redefine the maximum range of frequencies where reliable power spectra can be obtained from compilations of paleointensity records, and plotted the results in Figure 11b. The main observation is that values obtained for the different age models appear to be more grouped (at least for AM2, AM3, and AM4) than previously and vary almost linearly with the sedimentation rate. This result is not surprising, since the degree of attenuation of the power spec-

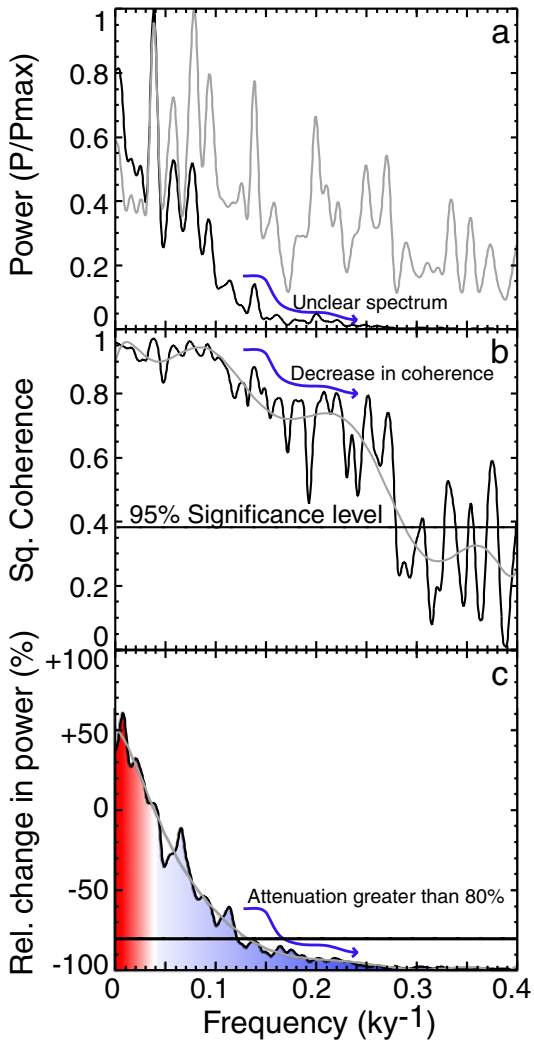

Figure 12. (a) Power spectrum of a compilation of paleointensity records with a mean sedimentation rate of 9 cm/ky (in black) and the age model AM4. The power spectrum of the reference signal is represented in gray. The confidence interval on the power spectrum at the 95% level is given by the relation: $0.49 < dP/P < 3.08$. (b) Squared coherence between the compilation and the reference signal. (c) Relative change in power between the paleointensity power spectrum and the geomagnetic reference. Positive values represent a relative amplification, and negative values a relative attenuation. The gray curves represent best polynomial fits to the data.

trum should depend essentially on the degree of filtering of the original time series (i.e., the reference signal), which to a first approximation is a function of the sedimentation rates. Finally, for a particular power spectrum, the maximum extent of reliability will be either the 80% spectral attenuation limit or the 95% significance level of coherence with the reference signal, whichever is the lowest. Those values are represented in Figure 11c. The dependence on the age model is not as strong as in Figure 11a, particularly going from AM3 to AM4. Compilations of paleointensity records with low mean sedimentation rates (i.e., 1 cm/ky) provide spectral information about geomagnetic intensity variations with wavelengths larger than 25–50 ky, independent of the age-model. For higher sedimentation rates, the limit depends on the quality of the age model and on the mean sedimentation rate. A moderate mean sedimentation rate of 5 cm/ky would yield information on the dipole for timescales down to ~8 ky with very good age control (AM4) or down ~16 ky with a less detailed age model (AM2). For high mean sedimentation rates of 15 cm/ky, the limit is extended down from ~10 to ~4 ky, depending on the age model.

4. Conclusion

[21] We have developed a numerical model simulating u-channel paleointensity records from a reference signal containing intensity variations similar to those of the geomagnetic field. The output of our model confirms that age inaccuracies cannot explain most of the dispersion observed among existing records of similar resolution and that some level of lithologic influence has to be considered. Comparison of records with mean sedimentation rates up to 15 cm/ky show that they all display dipole paleointensity variations that can be traced from one record to another with confidence, provided that the difference in mean sedimentation rates does not exceed a few centimeters per thousand years. Even when the records have been dated with high-resolution correlation of $\delta^{18}O$ records, offsets of geomagnetic features between records of a few thousand years are common and are of the same order as those observed between published paleointensity records [e.g., *Stoner et al.*, 1998; *Channell et al.*, 2000]. Owing to amplitude differences and age offsets between records, individual power spectra display significant discrepancies, which could lead to misinterpretation of some spectral peaks in term of geodynamo behavior. The accuracy of the power spectra increases when paleointensity records are stacked and the over-

prints attenuated by the stacking process. Evidently, this procedure (and our model) assumes that the overprints are random and not coherent between sampling sites. If a fraction of the individual overprints were a global climatic signal or if the records were affected by a long-relaxation-time viscous remanent magnetization overprint [e.g., *Kok and Tauxe*, 1996; *Meynadier et al.*, 1998], the task would be much more difficult. Hopefully, different sediment types and sedimentary environments will have sufficiently different lithologic influences. In any case, we recommend that compilations obtained from records at different locations and with different lithologies should be preferred to individual records.

[22] We compiled simulated records with mean sedimentation rates ranging from 1 to 15 cm/ky and characterized by age models of variable quality. The power spectra obtained from those compilations reflect more or less that of the reference signal. However, some disparities exist between records of different sedimentation rates and age-control. When the sedimentation rates decrease, the intensity of the low-frequency variations is progressively amplified (i.e., overestimated) relative to the actual geomagnetic signal, and the high-frequency signal is attenuated (i.e., underestimated). Independent of the age model, very low-resolution records (i.e., 1 cm/ky), may provide spectral information on the field for frequencies lower than $\sim$0.02–0.04 ky^{-1} (25–50 ky). Therefore their use is limited to questions regarding the general, long-term tendency of geomagnetic paleointensity. For instance, they should not be used to assess the possible influence of orbital parameters such as the obliquity (41 ky) or the precession (23 ky) on the geodynamo. An increased resolution may be achieved with the measurement of discrete samples taken at 1-cm intervals, which would remove the filtering induced by the response function of the u-channel magnetometer. The same spectral limit is obtained for compilations derived from low-resolution age-models (e.g., those based only on magnetic polarity stratigraphy). For mean sedimentation rates higher than 1–2 cm/ky, the spectral information depends on the quality of the age-model. For instance, a compilation of records with mean sedimentation rates of 7 cm/ky can provide reliable information for time-scales as short as $\sim$25 ky for a low resolution age-model and up to $\sim$7 ky in the case of a high-resolution age-model. For compilations of very-well dated sequences with mean sedimentation rates of 15 cm/ky, the power spectra provide reliable information for frequencies up to $\sim$2.5 ky^{-1} ($\sim$4 ky). At present, the only "global" compilation available to perform such spectral investigations is the Sint-800 stack, which integrates 33 records of relative paleointensity over the last 800 ky [*Guyodo and Valet*, 1999]. However, the actual resolution of the curve is rather difficult to assess, as the stack is constructed from paleointensity records with mean sedimentation rates ranging from 1 to 13 cm/ky but is probably comparable to a mean sedimentation rate of a few centimeters per thousand years. The stack may be close to the limit of resolution necessary to firmly address questions regarding the presence of characteristic times or orbital frequencies in the geodynamo. In the present paper, we use the Blackman-Tukey spectral method, which has been employed in recent paleomagnetic and paleoceanographic studies [e.g., *Channell and Kleiven*, 2000]. Alternative, data-adaptive methods such as wavelet analysis [*Guyodo et al.*, 2000] may provide a more efficient treatment of the problem. Nevertheless, the situation should improve with the production of new compilations of high-resolution paleointensity records, with excellent age control, and from a variety of marine environments.

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