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Why are geomagnetic excursions not always recorded in sediments? Constraints from post-depositional remanent magnetization lock-in modelling

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Abstract

Many geomagnetic excursions have been documented during the Brunhes Chron. However, high-resolution paleomagnetic studies of sediments often provide evidence of few (if any) excursions. We have investigated the reasons for this observation by modelling the post-depositional remanent magnetization (PDRM) lock-in process. A cubic lock-in function produces more rapid lock-in compared to linear and exponential functions proposed in the literature. We therefore used a cubic function to model "best-case" scenarios for the quality of the paleomagnetic record when a high-frequency geomagnetic input signal is convolved with the sediment lock-in function for a wide range of sedimentation rates. Even for a lock-in depth of 10 cm, where 95% of the PDRM is locked in 5 cm below the surface mixed layer, an input signal containing abundant excursions (with 1-kyr duration) is smoothed so drastically at low sedimentation rates (1–3 cm/kyr) that no excursions are recorded. Excursions are further attenuated by increasing the lock-in depth, as well as by sampling at discrete stratigraphic intervals. The PDRM process acts as a low-pass filter for high-frequency secular variation signals even at moderate sedimentation rates (>10 cm/kyr). We have also modelled the effects of modulation of sedimentation rate by a climatic forcing function (e.g., insolation). Even though the average sedimentation rate might be substantial, PDRM recording becomes much less reliable in intervals where sedimentation rates are lowest. In these cases, some excursions are reliably recorded in detail, while others may not be recorded at all. Our modelling suggests that in order to consistently detect the presence of geomagnetic excursions, it is ideal to work with sediments that maintain minimum sedimentation rates above 10 cm/kyr. If the normal spectrum of geomagnetic field behaviour contains abundant excursions, failure to document excursions in many apparently high-resolution analyses probably results from PDRM lock-in within relatively slowly deposited sediments, or to unrecognized intervals of slow sedimentation in environments with higher average sedimentation rates.

Keywords: post-depositional remanent magnetization; PDRM; geomagnetic; excursions; magnetization; lock-in; sediment

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1. Introduction

Sedimentary rocks provide the most continuous geological records of geomagnetic field behaviour and a great deal has been learnt about vector field behaviour from high-resolution studies of rapidly deposited sediments (e.g., [1]). Nevertheless, difficulties remain. For example, some detailed studies have suggested that a large number (10 or more) of geomagnetic excursions occurred during the Brunhes Chron (e.g., [2–5]). Based on the ages of geomagnetic excursions documented from around the world, it is often argued that excursions are global rather than local phenomena (e.g., [4,5]). Despite this evidence, high-resolution studies from a wide range of sedimentary environments routinely provide evidence of a far smaller number of excursions and some fail to document any excursions. It is widely accepted that sediments become magnetized through a post-depositional remanent magnetization (PDRM) that is locked-in at some depth below the sediment/water interface (e.g., [6]) and that some filtering of the input geomagnetic signal will occur (e.g., [7–9]). The duration of geomagnetic excursions is relatively poorly constrained, with estimates ranging from 300 years [10] to 1–2 kyr [4,5] to 3 kyr [11] to several thousand years (e.g., [12]). The apparently short duration of excursions has important consequences for the fidelity of sedimentary paleomagnetic recording if the remanence is acquired via a PDRM mechanism. Even though the mechanism of PDRM lock-in probably varies in different locations, conceptual modelling of the effects of PDRM lock-in on a high-frequency geomagnetic input signal can provide useful practical constraints on the problem of why geomagnetic excursions are not always recorded in sediments.

In this paper, we suggest limits for reliable recording of a high-frequency geomagnetic signal containing excursions with durations of up to a few thousand years. Relatively few studies have attempted to quantitatively model the effects of PDRM lock-in (e.g., [7–10,13–16]). Lund and Keigwin [8] modelled the recording of paleosecular variation and demonstrated that PDRM lock-in could cause significant smoothing of geomagnetic features with duration <2 k.y. Bleil and von Dobeneck [15] showed, among other things, that a polarity feature will only be recorded if it lasted longer than the median lock-in depth divided by the sedimentation rate. We build on these efforts here in order to further our understanding of the effects of PDRM lock-in on high-frequency geomagnetic signals, including geomagnetic excursions, to provide quantitative constraints on why geomagnetic excursions are often not documented in high-resolution studies.

2. Background constraints on PDRM modelling

2.1. Bioturbation and PDRM acquisition

Marine and lacustrine sediments are usually extensively bioturbated to depths ranging from a few centimetres to tens of centimetres. Occasional reports of mixing to depths of 1–3 m below the sediment surface [17,18] appear to be an exception rather than a rule. Burrowers are deposit feeders that live on or within the sediment and their activity is focussed near the sediment surface where their diet can maximize access to nutrients [19]. Bioturbation provides organisms with access to shallowly buried high-grade organic matter, and activity within the sediment provides an additional benefit of protection from predation [19]. Shallow activity is probably also favoured by the energetic costs of deep burrowing [20].

The thickness of the surface mixed layer is usually estimated by determining the vertical dispersion of a buried instantaneous deposit, such as a microtektite layer, or by analysing the stratigraphic distribution of relatively short-lived natural or artificial radioisotopic tracers in surficial sediments (e.g., ^{14}C, ^{210}Pb, ^{137}Cs, ^{241}Am; Fig. 1a). Boudreau [20,21] compiled published tracer-identified estimates of the depth of the surface mixed layer in marine sediments and calculated a worldwide environmentally invariant mean of 9.8 cm for the thickness of the surface mixed layer (standard deviation of 4.5 cm; minimum and maximum values of 2 and 30 cm, respectively). This estimate indicates that the depth of bioturbation is expected to be, on average, the same for abyssal and shallower water marine environments. It should be noted that this estimated mixing depth does not represent the maximum depth of bioturbation: it refers to the thickness of the surface zone that is most

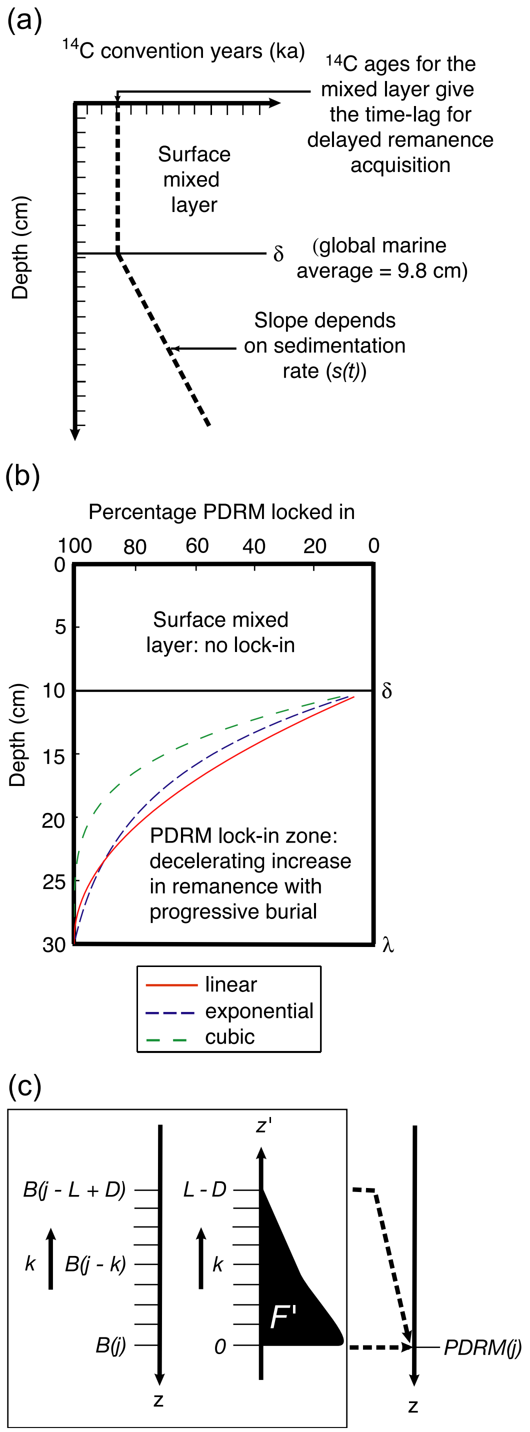


Fig. 1. Illustration of general aspects considered in PDRMz modelling. (a) ^{14}C dates from the surface mixed layer down to depth δ are constant and typically give ages of 3 ka for the Feni Drift, North Atlantic Ocean [25]. Ages below δ increase with depth at a rate depending on sedimentation rate. The global marine average of δ=9.8 cm is from Boudreau [21]. (b) The cumulative percentage PDRM locked-in with depth for linear, exponential, and cubic lock-in functions. No lock-in occurs above δ. PDRM acquisition is high immediately below δ and progressively decreases with depth. The modelled PDRM is completely locked-in at the base of this zone (20 cm in this example; i.e., at a depth of 30 cm below the sediment/water interface). (c) Numerical PDRM calculations are made by dividing the lock-in zone into discrete depth slices k, convolving the geomagnetic input signal ($B(z)$) with the lock-in function ($F'(z')$), and summing, as shown in Eq. (3) and as explained in the text. $PDRM(j)$ is the weighted sum of the magnetizations acquired at each depth slice during progressive burial, as shown on the right-hand side. The primed coordinates refer to the depth below δ during progressive burial during PDRM lock-in, while the unprimed coordinates refer to depths below the surface at the time of sampling.

frequently mixed and does not preclude the occasional deeper mixing event [20].

Sediments can provide excellent records of geomagnetic vector fluctuations that can be serially correlated on a global scale. This observation, despite documentation of extensive and rapid bioturbation, has brought about the widespread acceptance that sediments acquire a stable magnetization via a post-depositional remanent magnetization (PDRM) mechanism (e.g., [6,22–24]). We assume that a PDRM can only start locking-in when substantial bioturbation ceases. ^{14}C dates are observed to be uniform across the surface mixed layer, with ages typically of the order of a few thousand years (e.g., [25]) (Fig. 1a). Bioturbation will therefore simply cause a delay in PDRM acquisition (Fig. 1b), the duration of which can be estimated by ^{14}C dating of the surface mixed layer. The delay will depend on the thickness of the surface mixed layer and on the sedimentation rate. However, different radioisotopic tracers often produce different estimates of the thickness of the surface mixed layer because radioisotopes with longer half-lives are more likely to detect less frequent deeper burrowing episodes [25]. The likelihood that such deeper burrowing events are less common suggests that it is possible for some of the remanence to lock-in before the sediment has completely passed through the surface mixed layer. We do not account for this possibility in our modelling, but the fact that we do not offset our modelled records to account for delays in remanence acquisition (to maintain visual comparability between model input and output; see below) means that we effectively treat the PDRM acquisition process as starting at the sediment–water interface.

2.2. Lock-in functions

One of the biggest uncertainties in modelling PDRM lock-in concerns the nature of the lock-in function. Different lock-in functions have been suggested in the literature. The most commonly used is an exponential function (e.g., [13,14,26–29]). The rationale for using an exponential function is as follows. A PDRM is assumed to lock-in as a result of progressive sediment consolidation and dewatering [22,23]. Expulsion of interstitial water causes the sediment particles to crowd together and increased friction overcomes the geomagnetic force that might otherwise impart a realigning torque on a magnetic particle. Use of an exponential lock-in function seems reasonable since consolidation of continuously deposited sediments often proceeds in an exponential manner during initial stages [30]. Nevertheless, it is possible that different sediments could acquire a PDRM in variable ways since sediments can have highly variable physical, chemical and biological characteristics. Bleil and von Dobeneck [15] therefore used a linear lock-in function for some of their PDRM modelling. We have performed calculations using a range of lock-in functions (linear, cubic and exponential; Fig. 1b) and lock-in depths in order to accommodate a range of possible lock-in processes and to place conceptual constraints on the expected fidelity of PDRM recording. Lock-in is most rapid for a cubic function (Fig. 1b). We consistently used this function, so that our results provide a "best-case" scenario with the least amount of PDRM smoothing compared to other frequently used lock-in functions. We use lock-in depths of 10 and 20 cm, respectively, in our model. As shown in Fig. 1b, this means that 95% of the PDRM is locked in at half of the total lock-in depth for a cubic function (i.e., at 5 and 10 cm, respectively). In contrast, many studies have modelled the effects of deeper lock-in depths (e.g., [14,15,31]). Our modelling is aimed at conservatively constraining "best-case" recording where PDRM lock-in is virtually complete 5–10 cm below the surface mixed layer.

In modelling the effects of PDRM lock-in, we recognise that some workers have strongly argued that remanence can lock in within a few centimetres of the sediment surface [32]. It has also been argued that PDRM is an unlikely mechanism because flocculation of sediment is important and that inter-granular forces, such as van der Waal's forces, are much stronger than the magnetic forces that could cause post-depositional realignment of magnetic particles [33]. Nevertheless, other studies (e.g., [8]) provide strong evidence for post-depositional smoothing of the paleomagnetic signal in some settings. Our modelling is therefore aimed at constraining our understanding of the lock-in process in settings where a PDRM is the most likely mechanism for paleomagnetic recording.

3. Details of the PDRM lock-in model

We used the following steps to develop our conceptual model of PDRM lock-in within sediments. First, we produced a time series of geomagnetic field variations $B(t)$ for the last 900,000 years. We avoided using a "representative" paleomagnetic directional record as an input signal because any high-frequency paleomagnetic record will be a filtered representation of reality. We have used, however, the high-resolution paleomagnetic relative paleointensity record from Ocean Drilling Program (ODP) Site 983 [11,34] to approximate variations in field intensity because, even though this record is apparently affected by PDRM smoothing, it provides important constraints on the timing of geomagnetic excursions, which should coincide with major paleointensity minima. Sedimentation rates for this core varied between 2 and 36 cm/kyr [11,34], with an average of 12–15 cm/kyr, which is higher than the rates used in most of our PDRM simulations. The Site 983 paleointensity record therefore represents a suitable input signal for this study.

To develop an input signal for geomagnetic directional variations (at an arbitrary latitude of 30°N), we constructed a square-wave time series that includes geomagnetic excursions. Excursions were allowed to occur whenever the relative paleointensity signal fell below values of 0.15 (where the maximum value of the time series was set to 1). In cases where such a paleointensity feature had more than one minimum, we only allowed one excursion. Overall, this procedure produced nine excursions within the Brunhes Chron (e.g., Fig. 2a,d), which is consistent with the numbers suggested by literature compilations (e.g., [2–5]). To account for the stochastic nature of the geomagnetic field, and to simulate high-frequency variations such as secular variation, we added red noise to this square-wave polarity/excursion signal. We used AR-1 and AR-2 (AR=autoregressive) models to produce the record of noise as a function of time, since white noise does not adequately approximate the geomagnetic energy spectrum [8,35]. The dispersion of the virtual geomagnetic poles (VGPs) calculated from the synthetic input signal was set to 12° in order to reasonably approximate secular variation as recorded by lava flows at 30°N from time-averaged field models for the last 5 million years [36]. We define an excursion as occurring when the departure of VGPs from the geographic pole is larger than the secular variation (cf. [37]). In such cases, which coincide with paleointensity minima that fall below the 0.15 threshold, excursions are allowed to proceed to fully reversed polarity directions for durations of 1–4 kyr. The square-wave and red-noise signals were combined along with the Site 983 paleointensity record to produce a geomagnetic time series $B(t)$ that was used as the input signal for PDRM modelling (e.g., Fig. 2a,d,g).

Second, to simulate PDRM acquisition in sediments, the input geomagnetic time series must be converted into a depth (z) series. The sedimentation rate $s(t)$ controls the rate of burial and therefore the speed at which a given horizon passes through the lock-in zone (where $s(t)=(z(t+dt)-z(t))/dt$). The geomagnetic record as a function of depth is given by: $B(z(t+dt))=B(z(t)+s(t)dt)$. We have modelled cases where sedimentation rate is both uniform and variable over time. We simulated variable sedimentation by assuming that variations in the sedimentation rate are orbitally modulated, following the insolation record of Laskar et al. [38].

Third, we used a cubic function because lock-in is more rapid than with exponential or linear functions (Fig. 1b). The lock-in function $F(z')$ (F means filter and is a probability density function rather than a cumulative function) describes the relative contribution of each layer z' to the total PDRM (Fig. 1c) acquired at $z(t)$, down to a depth λ below the sediment/water interface such that:

$$\mathrm{PDRM}(z) = \int_0^{\lambda} B(z - z')F(z')\,dz' . \quad (1)$$

The primed coordinates refer to depth during deposition, while unprimed coordinates represent the depth of sediment layers before a core is taken (for simplicity, compaction is not taken into account). Upward values of z' in Fig. 1c represent progressive burial. While we assume that remanence lock-in does not begin until a horizon is buried below the base of the mixed layer, which is represented by δ (Fig. 1a,b), for the sake of simplicity and for clarity of comparison between the model input and output, we make no assumptions about this time lag and we do not offset our model results to illustrate such delays. It is adequate to simply state that the values of δ and $s(t)$ determine the time lag between deposition and the beginning of PDRM lock-in.

Fourth, for numerical modelling, it is suitable to transform the depth domain onto a regular grid, $B(z)$=>$B(j)$. We calculate the output PDRM by convolving the geomagnetic input signal with the lock-in filter function:

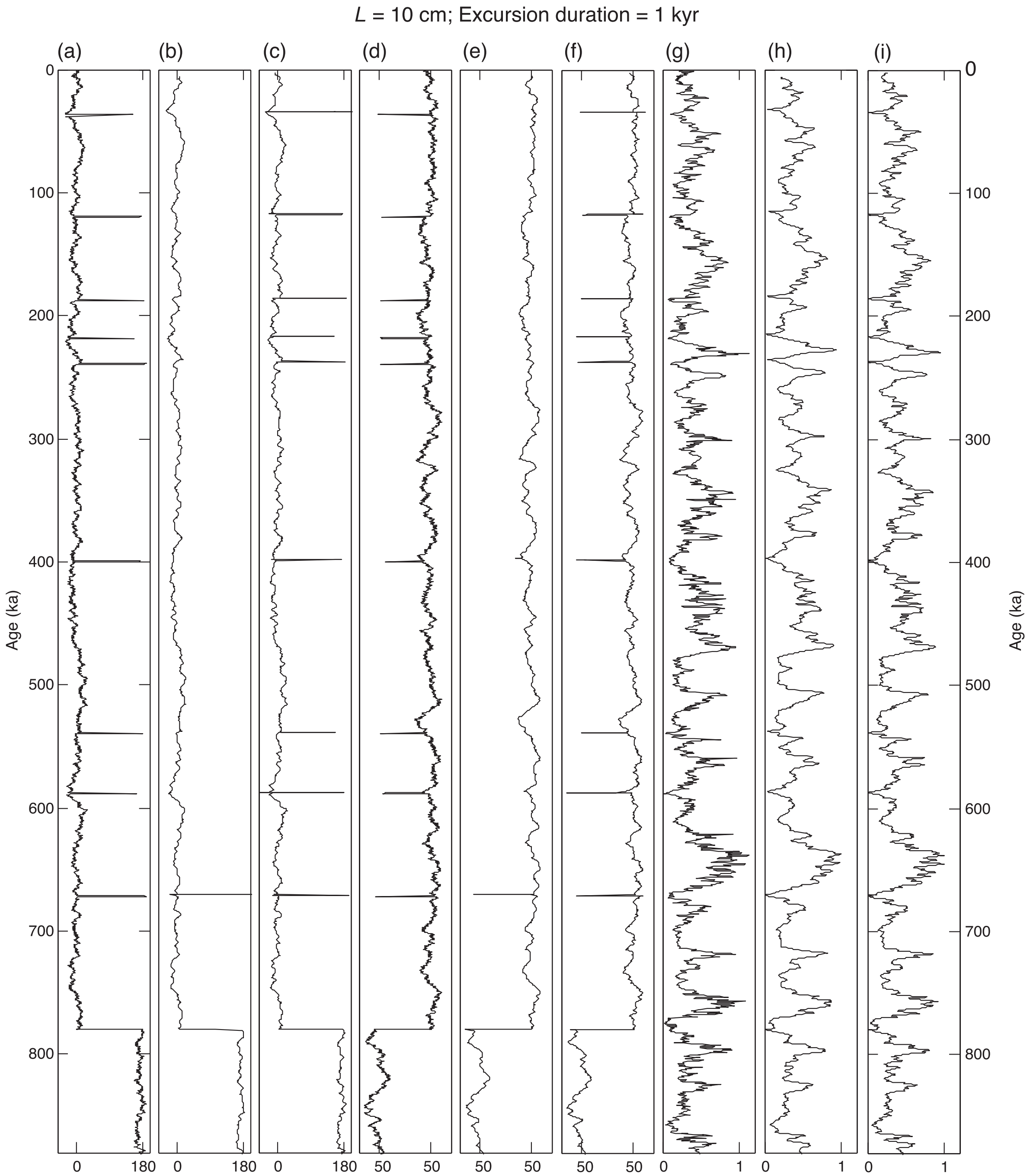
$$\mathrm{PDRM}(j) = \sum_{k=0}^{L} B(j-k)F(k), \quad (2)$$

where L is the lock-in depth in the discrete domain, which depends on the resolution of the model. Bioturbation produces a constant offset δ, which can be separated by introducing a constant D in the discrete description so that the PDRM can be written as:

$$\mathrm{PDRM}(j) = \sum_{k=0}^{L-D} B(j-k)F'(k). \quad (3)$$

As stated above, we maintain simplicity by neglecting this offset in our model outputs.

Fifth, different variables were progressively adjusted to ascertain their effects on the fidelity of the recorded PDRM. The variables included sedimentation rate, lock-in depth, the amount by which the sedimentation rate was modulated, and the length of the geomagnetic excursions. The model was run for this set of variables using a cubic lock-in function; use


L = 10 cm; Excursion duration = 1 kyr
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
Age (ka)
0
100
200
300
400
500
600
700
800
Dec_B (°)
Dec_PDRM (°) (2 cm/kyr)
Dec_PDRM (°) (4 cm/kyr)
Inc_B (°)
Inc_PDRM (°) (2 cm/kyr)
Inc_PDRM (°) (4 cm/kyr)
Int_B
Int_PDRM (2 cm/kyr)
Int_PDRM (4 cm/kyr)
0 180
50 50
0 1

of an exponential or linear lock-in function will cause even greater PDRM smoothing.

The model results represent the paleomagnetically recorded signal after PDRM filtering of the high-frequency geomagnetic input signal. We calculated this PDRM signal at 0.5-cm stratigraphic intervals, which represents an ideal output signal. Sediment compaction resulting from burial or coring, which is not considered in our model, discrete sampling at any spacing greater than 0.5 cm, and smoothing by the response functions in a u-channel magnetometer (e.g., [39]), will act to add noise or further smooth the idealized output signal. Non-continuous sampling could also cause aliasing of the recorded signal (e.g., [40,41]). Our results therefore represent a best-case scenario for PDRM recording at shallow lock-in depths. Diagenetic chemical change, which is known to have a major effect in many settings, will add further complexity to the remanence acquisition mechanism in sediments.

4. Results

For a lock-in depth (L) of 10 cm, excursion durations of 1 kyr, and low sedimentation rates of 1–3 cm/kyr, the fidelity of PDRM recording is poor, with the majority of excursions not being recorded (Fig. 2b,e). All of the excursions are recorded at sedimentation rates above 4 cm/kyr (Fig. 2c,f). Even at rates of 4 cm/kyr, however, the PDRM process acts as a low-pass filter that smoothes all three components of the high-frequency secular variation signal. As would be expected, doubling the lock-in depth to L=20 cm substantially increases the effect of PDRM smoothing (Fig. 3). No geomagnetic excursions are recorded even at sedimentation rates of 3 cm/kyr (Fig. 3b,e) and recording is still imperfect at sedimentation rates of 8 cm/kyr (Fig. 3c,f). The fidelity of PDRM recording of excursions is significantly improved, even with deep lock-in (L=20 cm), by doubling the duration of the excursions to 2 kyr (Fig. 4). With longer excursions, low sedimentation rates of 1 cm/kyr still completely lack evidence of excursions (Fig. 4b,e); however, all of the excursions are recorded at modest sedimentation rates of 3 cm/kyr (Fig. 4c,f).

The outcome of many model simulations is presented in nomograms of PDRM success rate (Fig. 5), where the excursion length is plotted versus sedimentation rate. We define the PDRM recording success rate as the percentage of the total number of excursions recorded after PDRM filtering. For shallow lock-in depth (L=10 cm), PDRM recording of excursions is inadequate for low sedimentation rates of 1 cm/kyr for excursions with duration exceeding 4 kyr even if the PDRM output is an idealized record sampled at 0.5-cm stratigraphic intervals (Fig. 5a). With more realistic sampling using discrete samples of 2-cm length, and a reasonable criterion that three consecutive samples are required to identify an excursion, sedimentation rates in excess of 2 cm/kyr are needed to provide evidence for excursions with 4-kyr durations and for 1-kyr durations, sedimentation rates in excess of 7 cm/kyr are required (Fig. 5b). For excursions with 500-year duration, sedimentation rates in excess of 15 cm/kyr are required for adequate recording. This pessimistic scenario is improved by u-channel sampling (Fig. 5c) because, even though the u-channel response function smoothes over a spatial half-width of 4.5 cm [39], measurements are usually made at 1-cm stratigraphic intervals, so a shorter interval can be measured to adequately document an excursion compared to that required for conventional discrete samples of 2-cm length. The result is that the chance of documenting an excursion is greater for u-channel measurements compared to 2-cm discrete samples (Fig. 5b,c). Increasing the lock-in depth to L=20 cm substantially worsens the chances of adequately documenting the presence of geomagnetic excursions (Fig. 5d,e,f).

In most studies of marine sediments, age control is provided by oxygen isotope stratigraphy. It is often only possible to identify the major glacial/interglacial

Fig. 2. Effect of PDRM smoothing on a high-frequency geomagnetic signal (this input signal is indicated by “B” subscripts): (a) declination, (d) inclination, and (g) paleointensity (normalized to a maximum value of 1). The VGP dispersion of the input geomagnetic signal is 12°, which is typical for the simulated site latitude of 30°N. The input paleointensity record is the high-resolution record of Channell [11] from ODP Site 983. Excursions are allowed at paleointensity minima below an arbitrary threshold value of 0.15 (which results in nine excursions in the Brunhes Chron). Excursion length is set at 1 kyr and the Matuyama–Brunhes boundary is set at 780 ka. PDRM recording is shown for a cubic lock-in function with lock-in depth of L=10 cm and constant sedimentation rate of (b), (e), and (h) 2 cm/kyr, and (c), (f), and (i) 4 cm/kyr. Recording of excursions is poor at 2 cm/kyr and good at 4 cm/kyr (see text).

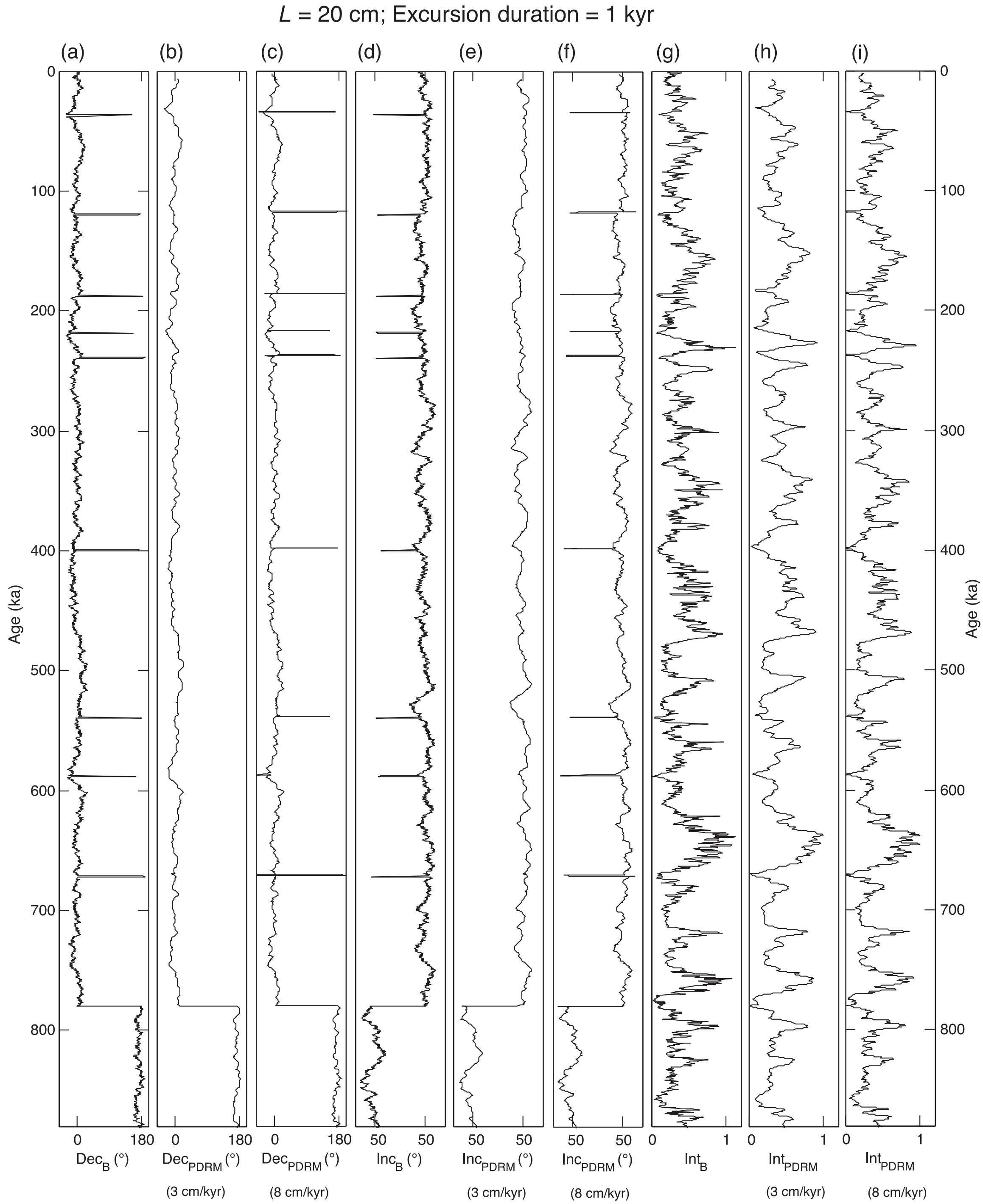


Fig. 3. Effect of PDRM smoothing on a high-frequency geomagnetic signal, following Fig. 2, except with a lock-in depth of L=20 cm. PDRM recording is worse compared to shallower lock-in depths and is imperfect even at sedimentation rates of 8 cm/kyr.

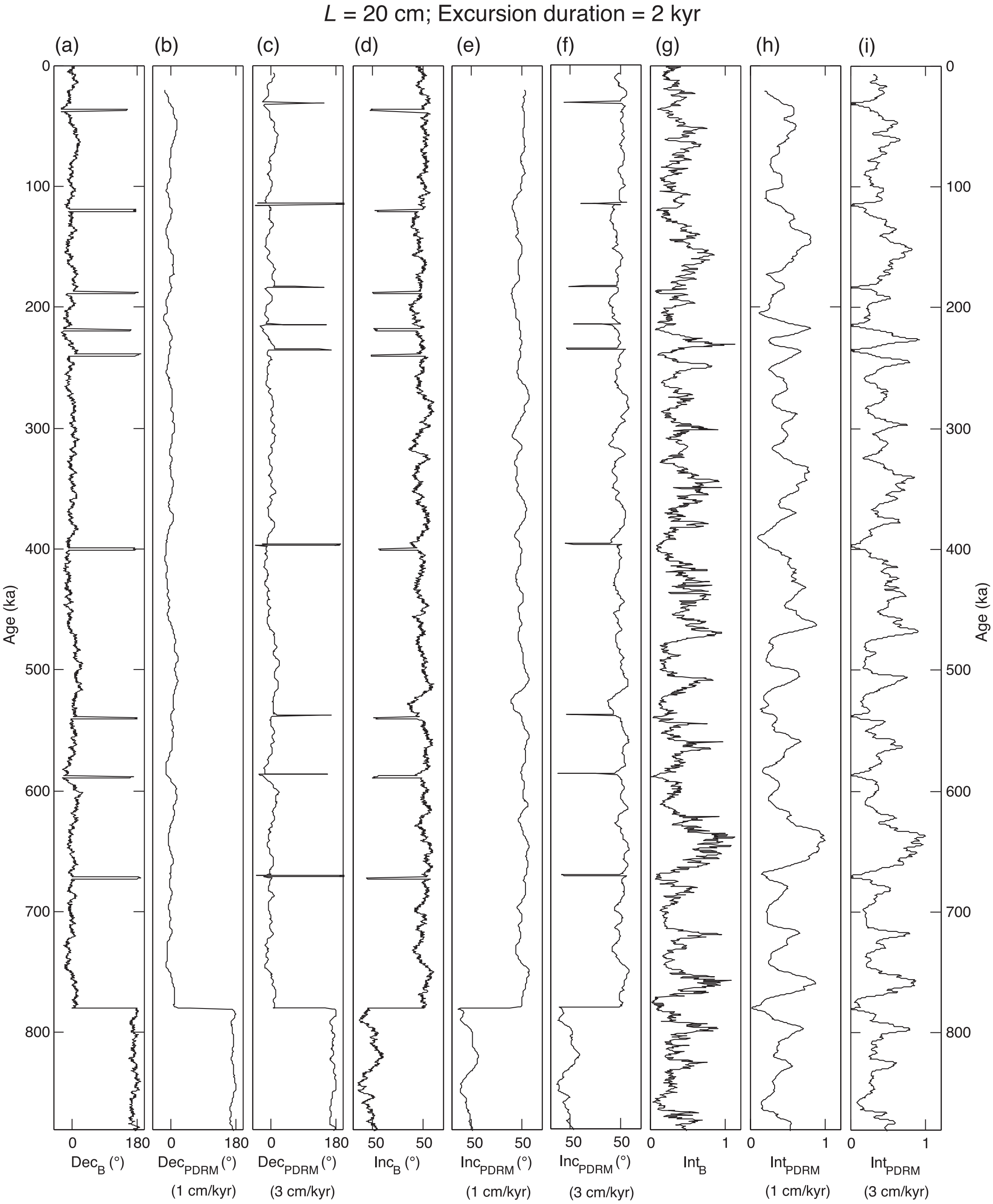


Fig. 4. Effect of PDRM smoothing on a high-frequency geomagnetic signal, following Figs. 2 and 3, with lock-in depth of L=20 cm, and a longer excursion length of 2 kyr. PDRM recording of excursions is much improved even at sedimentation rates as low as 3 cm/kyr and with relatively deep lock-in depth.

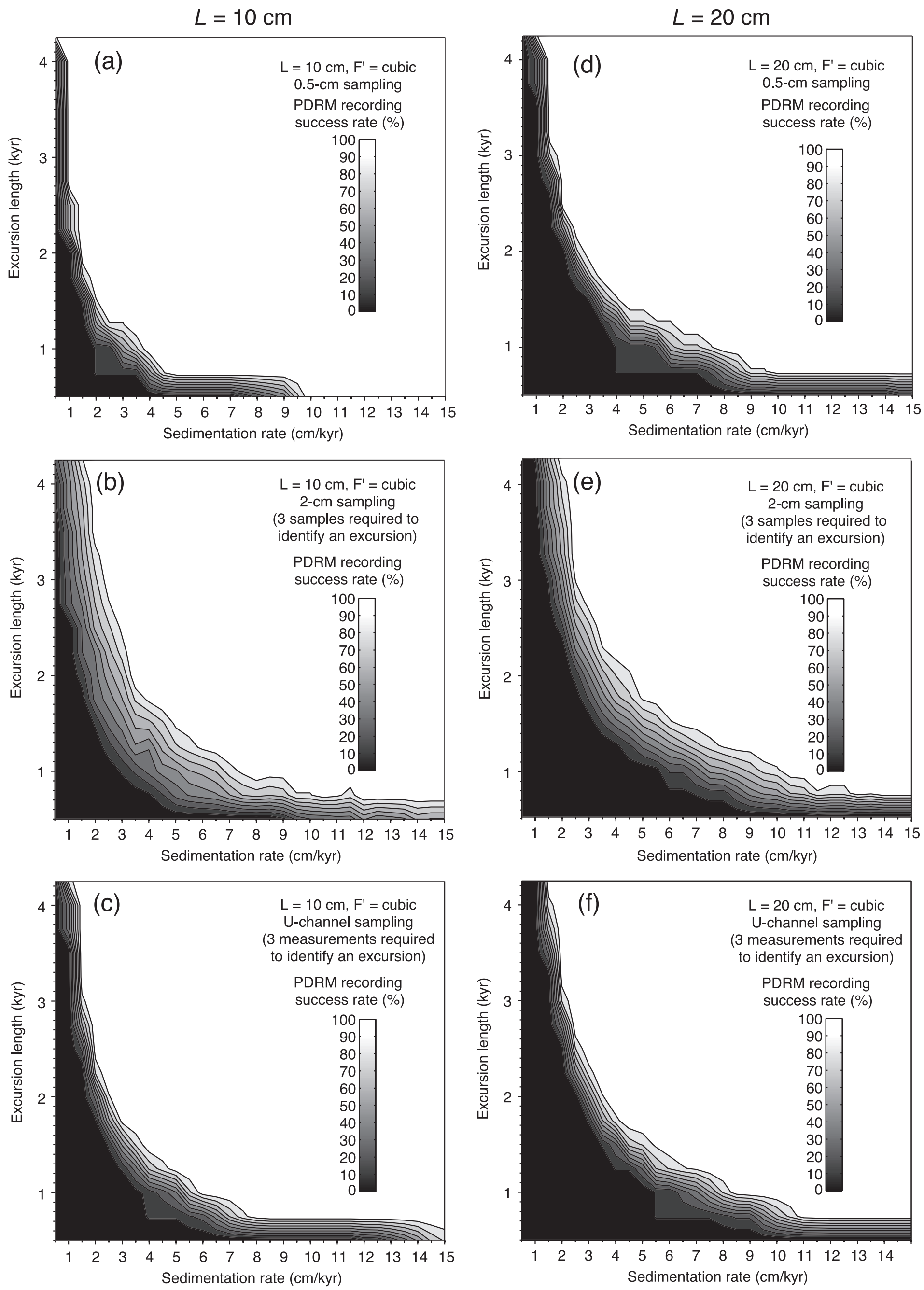


Fig. 5. Nomograms of PDRM recording success for variable sedimentation rate and excursion length. Nomograms are shown for shallow lock-in (L=10 cm, using a cubic lock-in function) for: (a) an idealized signal sampled at a 0.5-cm stratigraphic spacing, (b) the same PDRM sampled using conventional 2-cm samples where 3 adjacent samples must indicate the presence of an excursion, (c) the PDRM measured with a u-channel magnetometer (4.5-cm half-width for the response function; see Weeks et al. [39]), where an excursion must be identified in 3 adjacent measurements (spaced at 1-cm intervals). (d), (e) and (f) represent the same data except for L=20 cm. The PDRM recording success rate represents the percentage of the total number of excursions recorded.

transitions in δ^{18}O records and sedimentation rates between age control points are usually assumed to be linear. However, in reality, sedimentation rate is often climatically modulated and highly variable (e.g., [11,34,41]), and it can even undergo substantial variations on short timescales when climate was apparently stable [42]. Documentation of substantial variations in sedimentation rates (up to a factor of 40 in extreme cases) in deep-sea drift deposits [42], which are frequently used for high-resolution studies of geomagnetic field behaviour, suggests that consideration of variable sedimentation is important for understanding PDRM lock-in and its effects on the fidelity of high-resolution paleomagnetic records (variation by a factor of 10 is common on glacial/interglacial timescales). The quality of PDRM recording will therefore be limited by the minimum sedimentation rate rather than by the mean sedimentation rate, which is usually the parameter quoted for such records. We have explored the effect of variable sedimentation rate on PDRM recording by assuming that sedimentation rate is climatically controlled, for example, by insolation (Fig. 6). It should be noted that variations in sedimentation rate could be climatically forced on a range of timescales and with a relationship that is in-phase or out of phase with the climatic forcing parameter. For the purposes of illustration, we

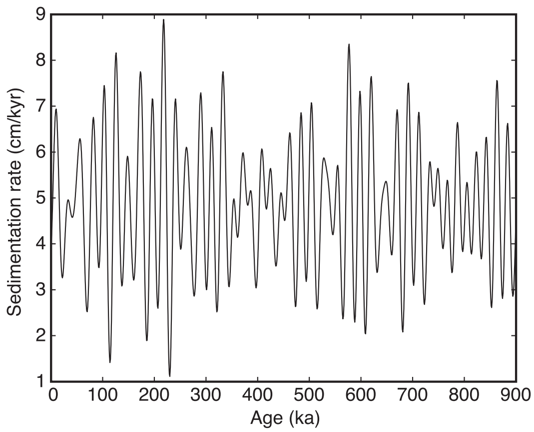


Fig. 6. Climatically modulated sedimentation rate (following the insolation solution of Laskar et al. [38]) used for calculation of the fidelity of PDRM recording in Fig. 7. The mean sedimentation rate shown is 5 cm/kyr, with modulation by a factor of 8 (modfac=8; i.e., sedimentation rate varies from 1.1 to 8.8 cm/kyr). The key variables for different calculations are the mean sedimentation rate and the modulation factor (modfac).

have used an in-phase relationship with insolation. Any relationship between sedimentation rate and paleoclimate will vary from environment to environment. The important point, as shown in Fig. 5, is that we would expect recording fidelity to be impaired every time the sedimentation rate drops into the shaded region of the nomograms. Model results (L=10 cm; excursion length=1 kyr) for relatively modest modulations of sedimentation rate by a factor of 5 (modfac=5) are shown for sedimentation rates of 5 cm/kyr (Fig. 7b,e,h) and 8 cm/kyr (Fig. 7c,f,i), respectively. In both cases, the mean sedimentation rate falls in the area of the nomogram where ideal recording would be expected (Fig. 5a), yet the idealized model results shown in Fig. 7 fail to document the complete sequence of excursions, even for mean sedimentation rates of 8 cm/kyr. This demonstrates that paleomagnetic results from environments with high mean sedimentation rates can be misleading if the sedimentation rate has undergone substantial modulation. The chance of recording is not simply a function of excursion duration; it is also strongly affected by variations in sedimentation rate, which can explain why an excursion is often recorded at some localities and not at others. When combined with the loss of resolution due to discrete sampling or to u-channel measurements (Fig. 5b,c), it is clear that for excursion lengths of 1-kyr or less, sedimentation rates need to consistently lie above minimum values of 8 cm/kyr to ensure adequate PDRM recording. Our modelling is aimed at constraining whether an excursion will be evident in a paleomagnetic record at all rather than at constraining the details of field behaviour during the excursion. High-resolution studies of geomagnetic excursions often reveal detailed waveforms and associated secular variation (e.g., [43–45]), much of which would not be preserved even at the low levels of PDRM smoothing discussed in this paper. It is likely that higher sedimentation rates beyond the range considered here (i.e., tens of cm/kyr) would be needed to record such waveforms in detail.

5. Discussion and conclusions

Our results verify the three basic conclusions of Bleil and von Dobeneck [15]: (1) the boundary of a

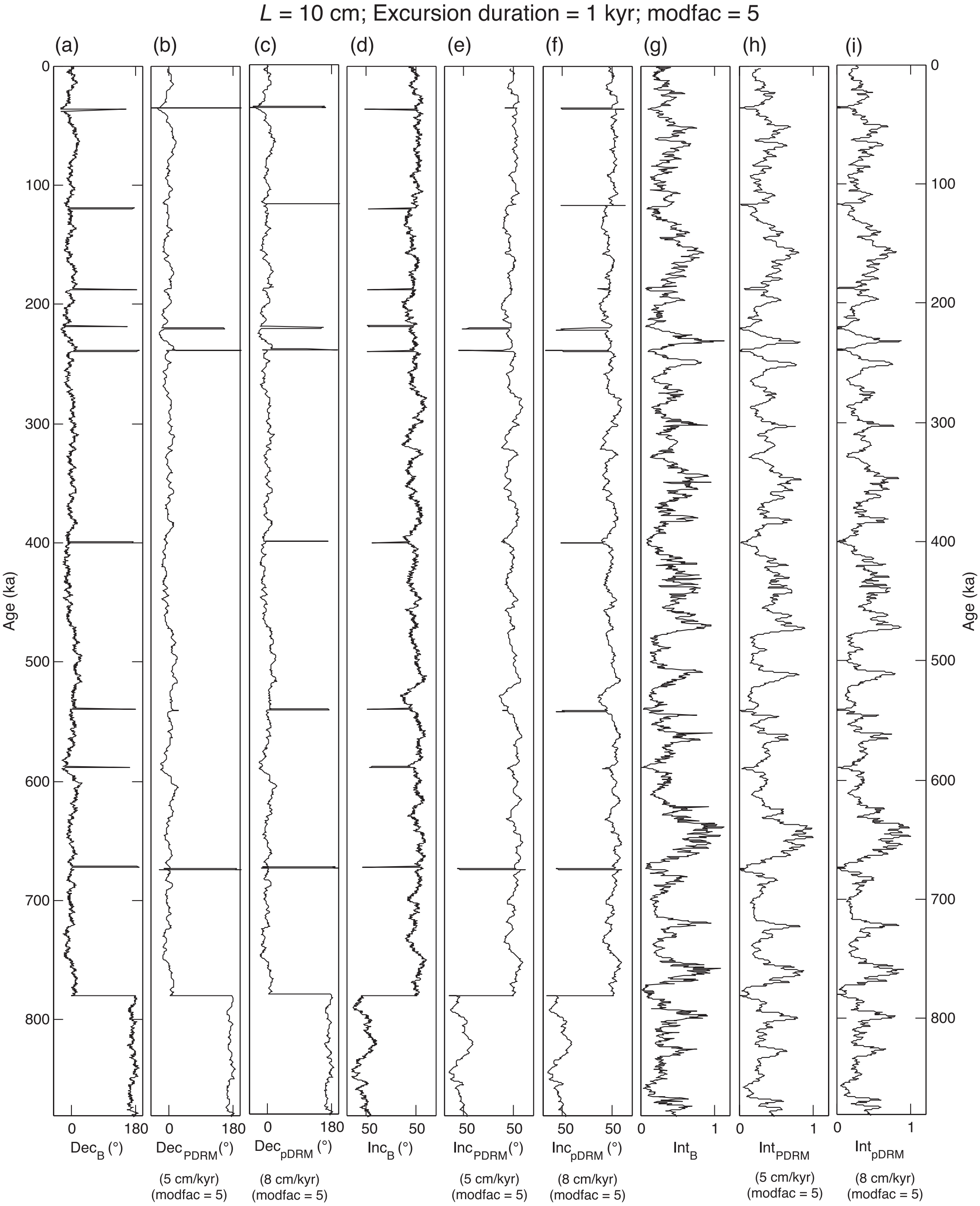


Fig. 7. Effect of PDRM smoothing on a high-frequency geomagnetic signal, following Figs. 2, 3, and 4, with lock-in depth of L=10 cm, excursion length of 1 kyr, and modulation of sedimentation rate by a factor of 5 (modfac=5). In (b), (e) and (h), where the average sedimentation rate is 5 cm/kyr (minimum=1.65 cm/kyr; maximum=8.25 cm/kyr), PDRM recording is poor. It is much improved for a mean sedimentation rate of (c), (f), and (i) 8 cm/kyr (minimum=2.65 cm/kyr; maximum=13.25 cm/kyr), but it is still not perfect.

geomagnetic feature will be shifted below its actual position by the depth to the base of the surface mixed layer plus the depth where half of the PDRM is locked in (median lock-in depth), (2) polarity features will only be recorded if they lasted longer than the median lock-in depth divided by the sedimentation rate, and (3) for geomagnetic features to be recorded as single features, they must be separated by a time span that exceeds the median lock-in depth divided by the sedimentation rate. These conclusions will be complicated if lithology varies, as shown by Bleil and von Dobeneck [15]. Spassov et al. [16] recently adapted this PDRM lock-in model to consider mixed detrital and chemical remanences in Chinese loess/paleosol horizons. Our treatment is restricted to lithologically homogeneous sediments with a distribution of grains that lock-in over a depth range following a cubic lock-in function (Fig. 1b). Our results represent "best-case" scenarios because the cubic lock-in function efficiently produces shallow lock-in (i.e., 95% of the PDRM is locked in 5 cm below the surface mixed layer for a lock-in depth of 10 cm). It is therefore likely that our model results will be relevant to studies of geomagnetic excursions and secular variation in sediments where a PDRM is the most likely recording mechanism. Our conclusions are summarized below.

First, even if it is possible to sample a sediment at high stratigraphic resolutions of 0.5-cm without disturbing the magnetic signal, sedimentation rates of ≥4 cm/kyr are needed to adequately record the presence of excursions with durations of 1 kyr for lock-in depths of 10 cm. Second, sedimentation rates of ≥8 cm/kyr are needed to adequately record the presence of 1-kyr excursions in three consecutive discrete samples of 2-cm length. Sedimentation rates of ≥6 cm/kyr are needed to adequately record the presence of 1-kyr excursions in 3 consecutive positions in a u-channel at 1-cm measurement intervals. Third, deeper lock-in depths will result in even greater smoothing of the PDRM record (Fig. 5). Fourth, large-scale modulation of sedimentation rate on relatively short time scales, which is common and which often goes unrecognized in sedimentary records, can significantly influence the fidelity of PDRM recording. In such cases, the minimum sedimentation rate is far more meaningful for considering paleomagnetic fidelity than the average sedimentation rate (which is usually quoted). Fifth, our results confirm the conclusions of Lund and Keigwin [8] that PDRM acquisition acts as a low-pass filter on geomagnetic secular variation records. Finally, our results can explain why many high-resolution paleomagnetic records do not contain evidence of geomagnetic excursions. This poor recording probably results from several factors, including PDRM smoothing, resolution limitations imposed by discrete sampling (even when continuous samples are taken) and the possible short duration (~1 kyr) of excursions. Overall, our results suggest that consistently high sedimentation rates are needed to obtain meaningful vector records of geomagnetic field behaviour, with minimum sedimentation rates preferably above 10 cm/kyr.

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