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Micrometeorites: A possible bias on the sedimentary magnetic record

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[1] Micrometeorites are strongly magnetic and continuously accumulate at the Earth's surface. On the basis of previously acquired magnetic data, we investigated at which conditions micrometeorites can bias the sedimentary palaeomagnetic and rock magnetic record. We calculated the probabilities for a sediment sample (discrete samples or U-channel samples) to have its detrital remanent magnetization deviated by the presence of a micrometeorite. Our model shows that direction anomalies $>5^\circ$ caused by micrometeorites may be rather frequent (more than 1% of measured samples), even for sediments with typical values of sedimentation rate (up to 10 cm/kyr) and remanent magnetization (up to 5×10^{-3} A/m). Excursions $>30^\circ$ caused by micrometeorites have probabilities $>1\%$ in sediments with remanent magnetization $<10^{-3}$ A/m and sedimentation rate <10 cm/ka. Reversals caused by micrometeorites have probabilities $>1\%$ for sediments with remanent magnetization $<2 \times 10^{-4}$ A/m and sedimentation rate <1 cm/ka. On the other hand, only sediments with magnetic susceptibilities $<10^{-5}$ SI and sedimentation rates <1 cm/ka can be significantly affected by the presence of micrometeorites.

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1. Introduction

[2] Micrometeorites are terrestrially collected extraterrestrial particles smaller than about 1 mm. They constitute the main part of the mass flux of extraterrestrial matter accreted on Earth [Love and Brownlee, 1993; Taylor et al., 1998]. No significant variability of this flux with time is detectable from marine osmium isotope records [Peucker-

Ehrenbrink, 1996]. Micrometeorites have been found in deep-sea sediments, in Greenland seasonal lakes, in Antarctic aeolian sedimentary traps, ice and snow, and in continental sands (see Taylor and Lever [2001] for a review). The majority of micrometeorites are strongly magnetic due to a high magnetite content. On the basis of the measurement of the magnetization and magnetic susceptibility of Antarctic micrometeorites (C. Suavet et al., Magnetic properties of micrometeorites, sub-

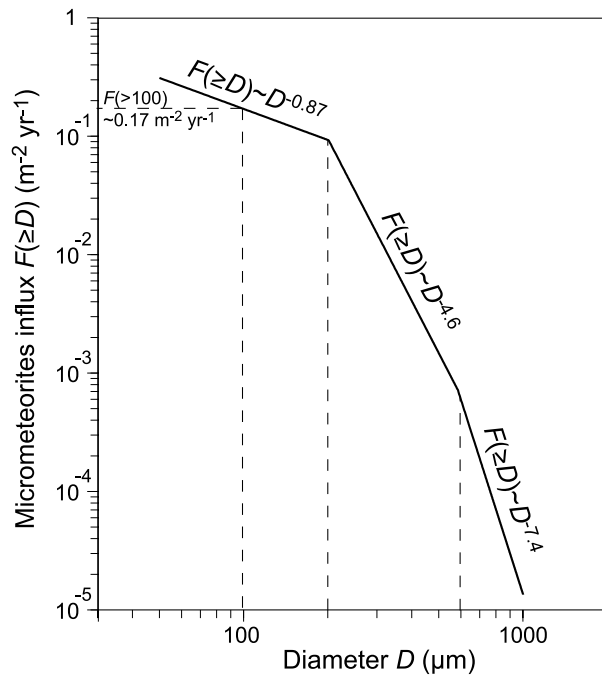


Figure 1. Cumulative size flux distribution of micrometeorites used in the calculations.

mitted to *Journal of Geophysical Research*, 2008), we investigate the possibility that under certain conditions the influx of micrometeorites may contribute significantly to the magnetization and/or the magnetic properties of sediments and bias their palaeomagnetic record.

2. Potential Effect on the Natural Remanent Magnetization

[3] In order to estimate the contribution of micrometeorites to the natural remanent magnetization (NRM) of sediments, we calculate the probability P_d for a standard sediment sample used in palaeomagnetic studies to have its detrital remanent magnetization (DRM) deviated of an angle $\delta \geq d$ by a micrometeorite. Small-diameter micrometeorites may be present in large numbers but they contribute to the background noise only: they do not induce anomalies. In the following, we study the cases $d = 5^\circ$ (small disturbance of the palaeomagnetic signal), $d = 30^\circ$ (critical value defining geomagnetic excursions), and $d = 90^\circ$ (reversed polarity) and their associated probabilities P_5 , P_{30} and P_{90} . In the case of standard U-channels (with a square section of $2 \times 2 \text{ cm}^2$), the volume measured by magnetometers is about 16 cm^3 . For discrete standard palaeomagnetic cores, the volume is 10.8 cm^3 . In

the following calculation, a sediment volume $V_{sed} = 10 \text{ cm}^3$ is used. We have checked that using any V_{sed} value in the range $8\text{--}16 \text{ cm}^3$ induces only slight differences in P_d values, so that the results are valid for all types of sediment samples used in paleomagnetic studies.

[4] The parameters controlling the value of P_d for a given sediment are as follows:

[5] 1. The sedimentation rate S_r (m/a). We consider sedimentation rates in the range of $10^{-6}\text{--}10^{-4}$ m/a ($0.1\text{--}10$ cm/ka).

[6] 2. The background DRM of the sediment J_{sed} (A/m). We consider sediment DRM in the range of $10^{-6}\text{--}10^{-2}$ A/m.

[7] 3. The flux and size frequency distribution of micrometeorites. The cumulative size frequency distribution we use (Figure 1) is based on Antarctic micrometeorites collections: the 2000 South Pole collection [Taylor et al., 2005], Frontier Mountain, and Miller Butte collections [Rochette et al., 2008]. The size frequency distribution follows a power law with exponent slopes of -0.87 for diameters $D \leq 200 \mu\text{m}$, -4.6 for $200 < D \leq 600 \mu\text{m}$ and -7.4 for $D > 600 \mu\text{m}$. The micrometeorites influx (number of micrometeorites with mean diameter $\geq D$ (m) falling per year per square meter) deduced from these parameters is

$$F(\geq D) = \begin{cases} a_1 D^{b_1} = 6 \times 10^{-5} D^{-0.87} & \text{if } D \leq 2 \times 10^{-4} \text{ m} \\ a_2 D^{b_2} = 10^{-18} D^{-4.6} & \text{if } 2 \times 10^{-4} < D \leq 6 \times 10^{-4} \text{ m} \\ a_3 D^{b_3} = 9 \times 10^{-28} D^{-7.4} & \text{if } D > 6 \times 10^{-4} \text{ m} \end{cases} \quad (1)$$

In the following, we write $F(\geq D) = a D^b$; (a_i, b_i) , $i = \{1, 2, 3\}$ must be substituted to (a, b) according to the diameter range. If we note t the sediment sample collection duration (the time it takes to deposit a height h (m) of sediment, in years) and A the collection surface area (in square meters), we have $t = h/S_r$ and $V_{sed} = h A$. The average number of micrometeorites of diameter $\geq D$ in the sediment sample is $N(\geq D) = AtF(\geq D) = (V_{sed}/S_r)aD^b$.

[8] 4. The NRM of micrometeorites J_m (A/m). We use the NRM distribution of Miller Butte micrometeorites collection [Rochette et al., 2008; Suavet et al., submitted manuscript, 2008]. There is no correlation between the NRM and the diameter of micrometeorites. The NRM of micrometeorites (180 measured) ranges from 10^{-1} to more than 100 A/m, with a mode value of 10 A/m. The

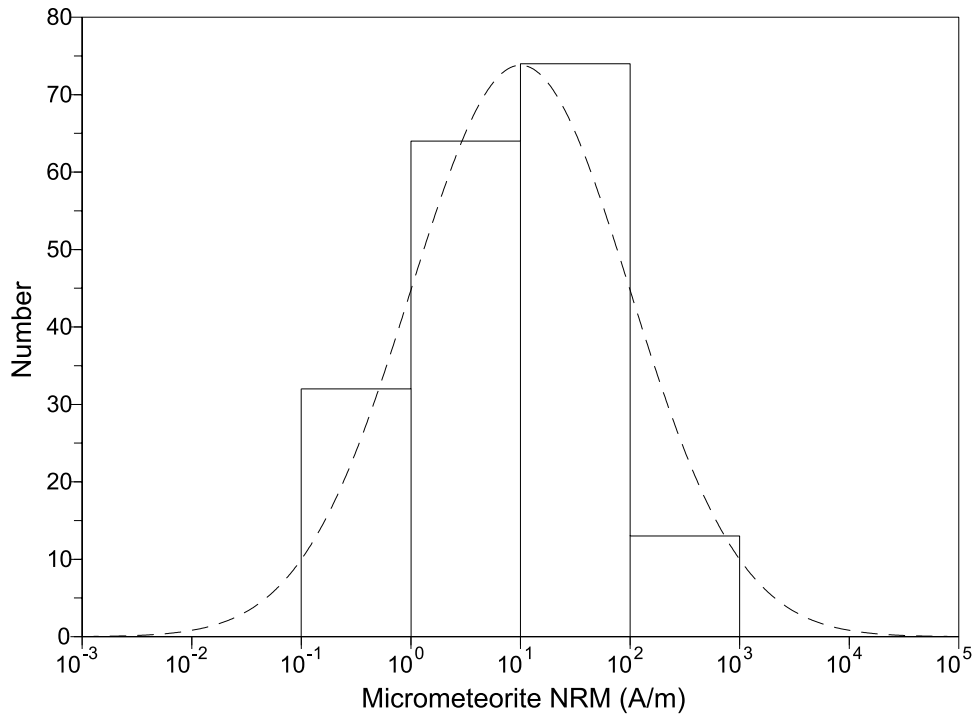


Figure 2. Natural remanent magnetization distribution for Miller Butte micrometeorite collection [Rochette et al., 2008] and approximation by a log-normal distribution (mode is 10 A/m; standard deviation is 1).

distribution is approximated by a log-normal distribution $n(J_m)$ (Figure 2).

[9] The angular deviation due to the addition of the magnetization vector of one micrometeorite \mathbf{M} to the coherent vector of the bulk sediment \mathbf{S} is

$$\delta = \arccos \left(\frac{\mathbf{S} \cdot (\mathbf{S} + \mathbf{M})}{\|\mathbf{S}\| \|\mathbf{S} + \mathbf{M}\|} \right) \quad (2)$$

if we note $\alpha = \|\mathbf{M}\|/\|\mathbf{S}\|$ and θ the angle between the two vectors, equation (2) becomes

$$\begin{aligned} \delta &= \arccos \left(\frac{\|\mathbf{S}\|^2 + \|\mathbf{S}\| \|\mathbf{M}\| \cos \theta}{\|\mathbf{S}\| \sqrt{\|\mathbf{S}\|^2 + \|\mathbf{M}\|^2 + 2\|\mathbf{M}\| \|\mathbf{S}\| \cos \theta}} \right) \\ \delta &= \arccos \left(\frac{\|\mathbf{S}\|^2 + \alpha \|\mathbf{S}\|^2 \cos \theta}{\|\mathbf{S}\| \sqrt{\|\mathbf{S}\|^2 + \alpha^2 \|\mathbf{S}\|^2 + 2\alpha \|\mathbf{S}\|^2 \cos \theta}} \right) \\ \delta &= \arccos \left(\frac{1 + \alpha \cos \theta}{\sqrt{1 + \alpha^2 + 2\alpha \cos \theta}} \right) \end{aligned} \quad (3)$$

The maximum deviation $\delta_{\max}(\alpha)$ is

$$\delta_{\max}(\alpha) = \begin{cases} \arcsin(\alpha) & \text{if } \alpha \leq 1 \\ \pi & \text{if } \alpha > 1 \end{cases} \quad (4)$$

[10] Assuming that micrometeorites are randomly oriented when they get trapped in the sediment, which is realistic considering the size of the particles as surface forces dominate the magnetic

couple, we calculate the average deviation $\bar{\delta}(\alpha)$ by integration on a spherical uniform distribution.

$$\bar{\delta}(\alpha) = \frac{\int_0^\pi \delta(\alpha, \theta) \sin \theta d\theta}{\int_0^\pi \sin \theta d\theta} = \frac{1}{2} \int_0^\pi \delta(\alpha, \theta) \sin \theta d\theta \quad (5)$$

[11] The intensity anomaly induced by the presence of a micrometeorite is estimated with the ratio I_a of the resulting and background intensities.

$$\begin{aligned} I_a &= \frac{\|\mathbf{S} + \mathbf{M}\|}{\|\mathbf{S}\|} = \frac{\sqrt{\|\mathbf{S}\|^2 + \alpha^2 \|\mathbf{S}\|^2 + 2\alpha \|\mathbf{S}\|^2 \cos \theta}}{\|\mathbf{S}\|} \\ I_a &= \sqrt{1 + \alpha^2 + 2\alpha \cos \theta} \end{aligned} \quad (6)$$

Figure 3 shows the value of I_a as a function of α and θ : for a given α , the anomaly is positive for low values of θ and becomes negative for increasingly high values of θ as α becomes higher. Hence positive intensity anomalies induced by micrometeorites are more frequent than negative anomalies. This last comment is important as geomagnetic excursions are generally associated with a lower magnetization intensity.[12] The volume of the micrometeorite is V_m (m^3).

$$\|\mathbf{M}\| = \alpha \|\mathbf{S}\| \Leftrightarrow J_m V_m = \alpha J_{sed} V_{sed} \Leftrightarrow D = \sqrt[3]{\frac{6 \alpha J_{sed} V_{sed}}{\pi J_m}} \quad (7)$$

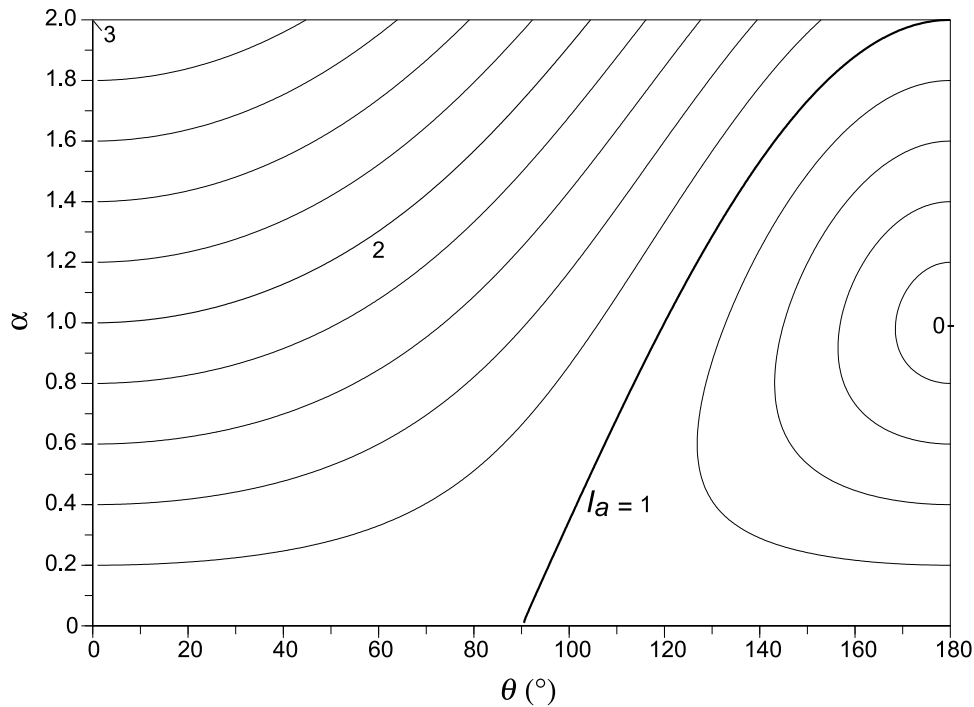


Figure 3. Contour lines of the ratio of resulting and background intensities I_a as a function of the ratio of the micrometeorite and sediment magnetizations α and the angle between the magnetizations θ .

[13] The average number of micrometeorites with a diameter in the range $D_1 - D_2$ ($D_1 < D_2$) in the sediment sample is $[N(\geq D_1) - N(\geq D_2)]$, so the probability of presence of a micrometeorite with $\alpha \|\mathbf{S}\| \leq \|\mathbf{M}\| < (\alpha + d\alpha) \|\mathbf{S}\|$ is $Q(\alpha)d\alpha = -dN$. $Q(\alpha)$ is the density function for the probability of presence of a micrometeorite with $\|\mathbf{M}\| = \alpha \|\mathbf{S}\|$

$$Q(\alpha) = -\frac{dN}{d\alpha} \quad (8)$$

[14] The probability R_d for a randomly oriented micrometeorite with a magnetization $\|\mathbf{M}\| = \alpha \|\mathbf{S}\|$ to induce an angular deviation $\delta \geq d$ in a sediment sample is

$$R_d(\alpha) = \frac{\int_0^\pi f(\alpha, \theta) \sin(\theta) d\theta}{\int_0^\pi \sin(\theta) d\theta}$$

$$R_d(\alpha) = \frac{1}{2} \int_0^\pi f(\alpha, \theta) \sin(\theta) d\theta \quad (9)$$

with

$$f(\alpha, \theta) = \begin{cases} 0 & \text{if } d(a, q) < d \\ 1 & \text{if } d(a, q) \geq d \end{cases}$$

P_d is obtained by a double integration on α and J_m .

$$P_d(J_{sed}, S_r) = \iint Q(\alpha, J_m) R_d(\alpha) n(J_m) d\alpha dJ_m \quad (10)$$

[15] We compute P_5 , P_{30} , and P_{90} numerically. Figures 4, 5, and 6 show contour lines of P_5 , P_{30} , and P_{90} for sedimentation rates in the range of 0.1–10 cm/ka and sediment DRM intensities in the range of 10^{-6} – 10^{-2} A/m.

3. Potential Effect on the Magnetic Susceptibility

[16] The magnetic susceptibility of sediments is a commonly measured property. We tried to estimate if the presence of a micrometeorite in a sediment sample can induce a significant susceptibility anomaly. The case of diamagnetic sediments, with negative susceptibility, has not been studied specifically, but the occurrence of susceptibility anomalies in these sediments can be estimated by using the absolute value of susceptibility.

[17] Although micrometeorites with diameter $< 100 \mu\text{m}$ (most of them unmelted) that are present in much larger number than large micrometeorites contribute to the magnetic susceptibility of the sediment, their contribution is continuous: they do not induce anomalies. It is not necessary to include them in the calculation as they only change the background susceptibility signal. Only micrometeorites that fall less frequently are likely to

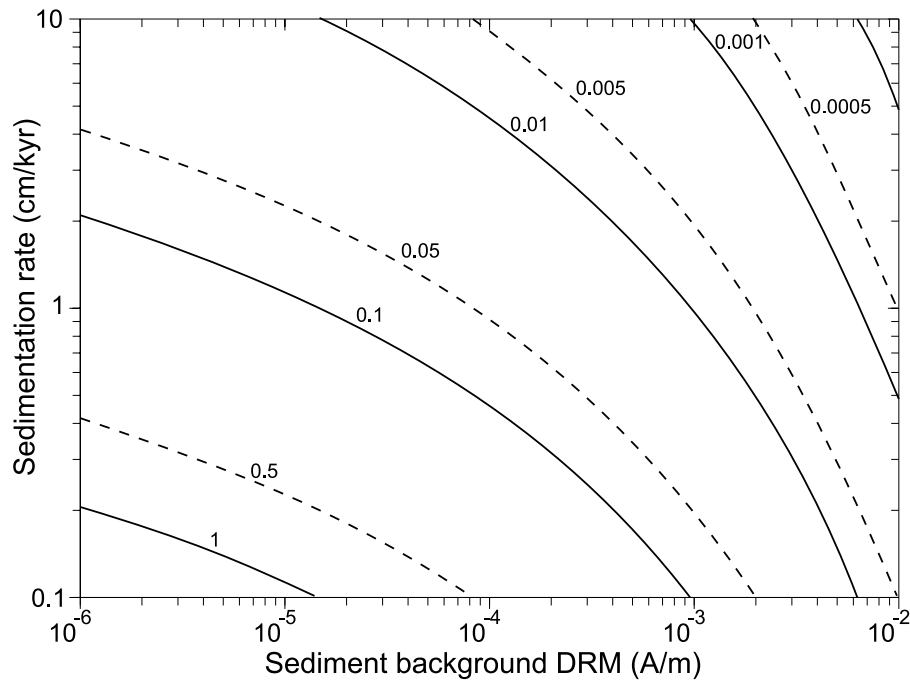


Figure 4. Probability for a 10 cm^3 sediment sample to have its detrital remanent magnetization deviated of an angle $\delta \geq 5^\circ$ by a micrometeorite.

induce a detectable anomaly in the magnetic susceptibility record.

$X_{sed}(\text{m}^3)$ (volume susceptibility $\kappa_{sed}(\text{SI})$) induces a significant susceptibility anomaly if

[18] We consider that a micrometeorite of total susceptibility $X_m(\text{m}^3)$ (volume susceptibility $\kappa_m(\text{SI})$) in a sediment sample of total susceptibility

$$\frac{X_m}{X_{sed}} \geq \beta_{\min} \Leftrightarrow \kappa_m V_m \geq \beta_{\min} \kappa_{sed} V_{sed} \quad (11)$$

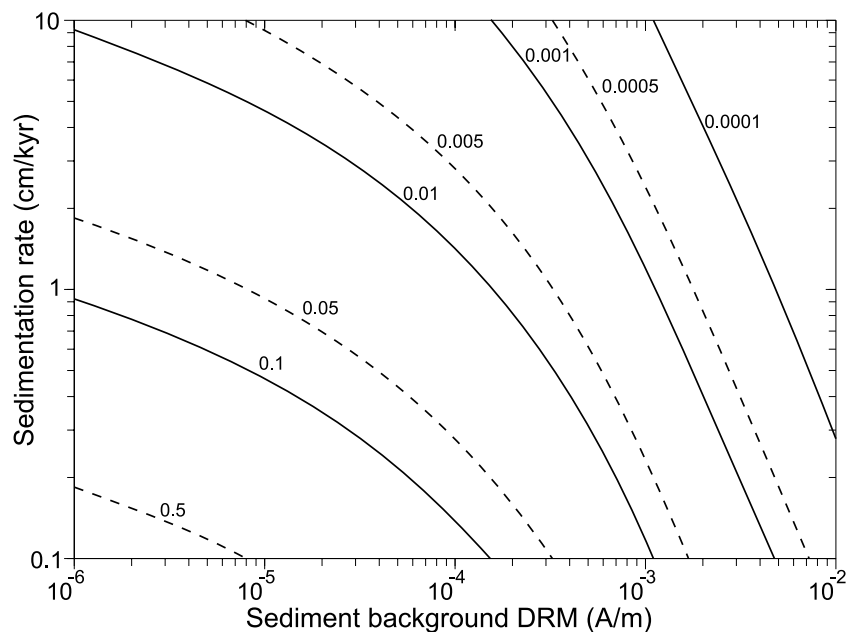


Figure 5. Probability for a 10 cm^3 sediment sample to have its detrital remanent magnetization deviated of an angle $\delta \geq 30^\circ$ by a micrometeorite.

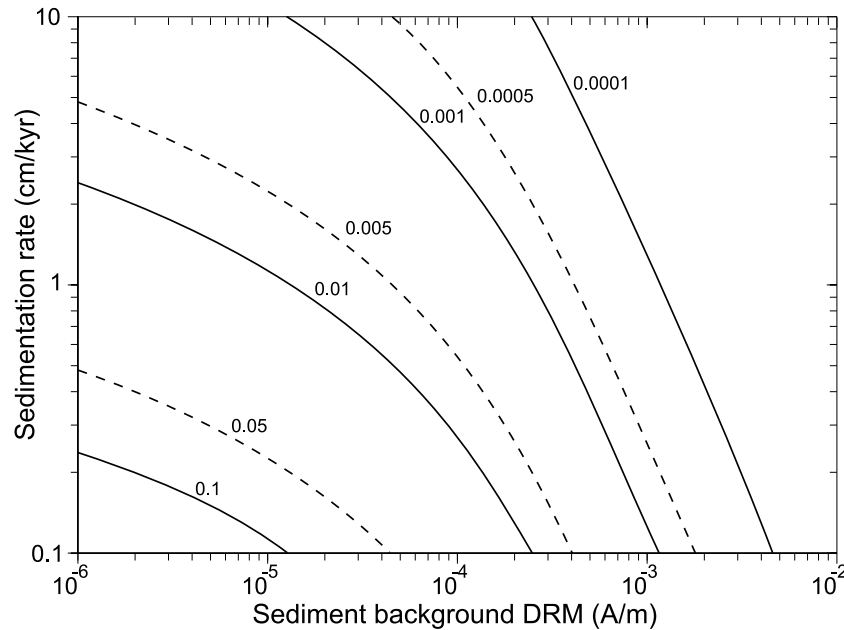


Figure 6. Probability for a 10 cm³ sediment sample to have its detrital remanent magnetization deviated of an angle $\delta \geq 90^\circ$ by a micrometeorite.

This is true for

$$D \geq D_{\min} = \sqrt{[3] \frac{6 \beta_{\min} \kappa_{\text{sed}} V_{\text{sed}}}{\pi \kappa_m}} \quad (12)$$

[19] We selected two critical values for β_{\min} in the calculation: $\beta_{\min 1} = 1$ (anomaly of 100% of the background susceptibility) and $\beta_{\min 2} = 1/10$ (anomaly of 10% of the background susceptibility).

[20] The average number (equivalent to the probability of presence) of micrometeorites with a sufficient size to induce a magnetic susceptibility anomaly in a sediment sample is

$$P_{\beta}(\geq D_{\min}) = AtF(\geq D_{\min}) = \frac{V_{\text{sed}}}{S_r} a(D_{\min})^b$$

$$P_{\beta}(\geq D_{\min}) \frac{a V_{\text{sed}}}{S_r} \left(\frac{6 \beta_{\min} \kappa_{\text{sed}} V_{\text{sed}}}{\pi \kappa_m} \right)^{\frac{b}{3}} \quad (13)$$

[21] According to magnetic susceptibility measurements of micrometeorites collected at Miller Butte (Antarctica) [Rochette et al., 2008; Suavet et al., submitted manuscript, 2008], there is no correlation between the volume susceptibility and the diameter of micrometeorites. The measurement of 185 micrometeorites yields values ranging from 10^{-3} to 10 SI. We combine equation (13) with the volume susceptibility distribution of Miller Butte collection approximated by a log-normal distribution (Figure 7) to obtain the probability of presence of a micrometeorite of a sufficient size to induce a

susceptibility anomaly in a sediment sample (Figure 8).

4. Discussion

[22] The validity of this model can be tested with micrometeorites recovered from deep-sea sediments. According to equation (5), micrometeorites recovered from zeolitic clays cored in the Pacific Ocean: 5–38–1 and 5–38–2 (diameters: 210 and 140 μm), with NRM $>10^{-10}$ Am² (Suavet et al., submitted manuscript, 2008), would induce an average deviation of 30° on a sediment sample with a DRM of $\sim 2 \times 10^{-5}$ A/m and an average deviation of 5° on a sediment sample with a DRM of $\sim 10^{-4}$ A/m. These DRM values are common for most sediments (siliceous/calcareous chalk or ooze usually have DRM in the range of 10^{-5} – 10^{-3} A/m, as can be seen in ODP/IODP Initial Reports). However, these micrometeorites would not induce significant direction anomalies in deep-sea clays, as their DRM is usually above 10^{-3} A/m.

[23] Figures 4 and 5 show that even for sediments with a DRM of $\sim 10^{-3}$ A/m and a sedimentation rate of ~ 1 cm/ka, the probability to have a deviation of the DRM $\geq 30^\circ$ ($\geq 5^\circ$) is $\sim 0.5\%$ (1%). This means that the measurement of 4 m of U-channel samples taken from such a sediment (covering a time span of 400 ka) with a typical step of 2 cm would show approximately one $\geq 30^\circ$ excursion

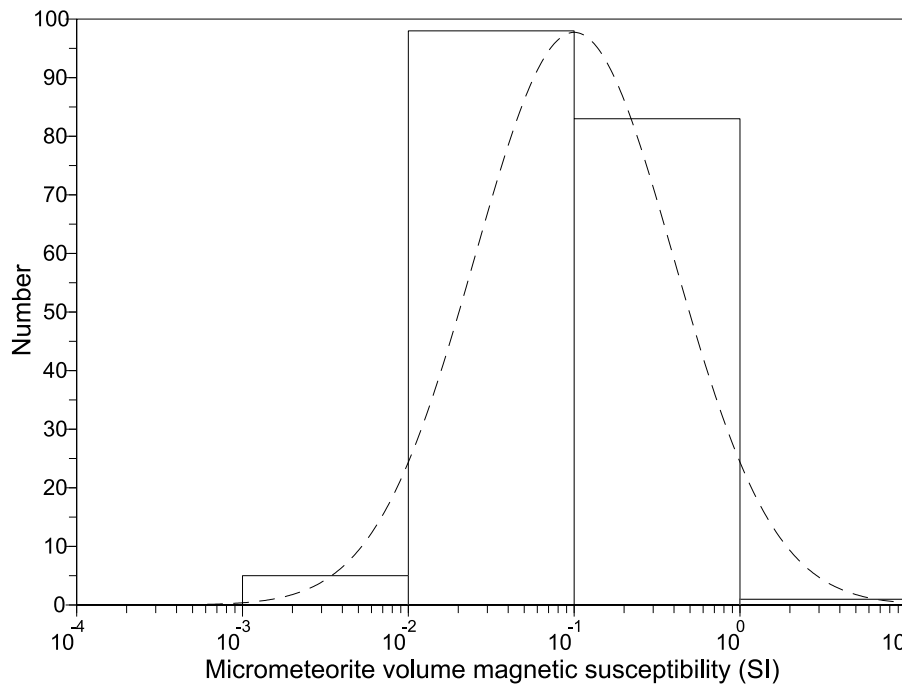


Figure 7. Volume magnetic susceptibility distribution for Miller Butte micrometeorite collection [Rochette et al., 2008] and approximation by a log-normal distribution (mode is 0.1 SI; standard deviation is 0.6).

and approximately two $\geq 5^\circ$ direction anomalies. Figure 6 shows that the probability for a sediment sample to show a magnetic reversal due to a micrometeorite is $\geq 1\%$ for sediments DRM $< 10^{-4}$ A/m and sedimentation rate < 1 cm/ka.

[24] Anomalies caused by micrometeorites in the magnetic susceptibility record are much less likely than DRM direction anomalies. The probability for sediment samples to contain a micrometeorite of a sufficient size to induce an anomaly of 100% (10%) of the background susceptibility in a sediment with

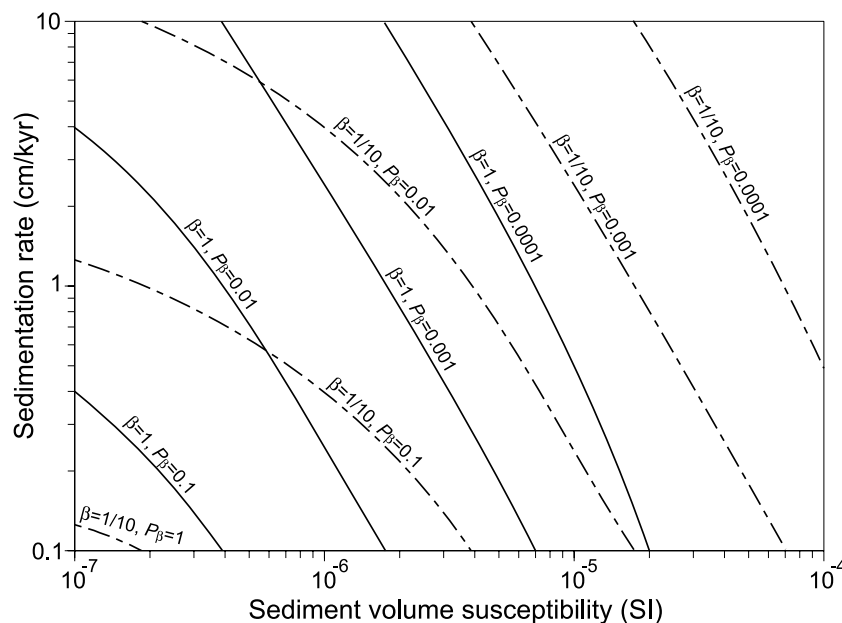


Figure 8. Probability P_β of presence of micrometeorites with a susceptibility at least equal to βX_{sed} in a 10 cm^3 sediment sample of total susceptibility X_{sed} for different sediment mass susceptibilities and sedimentation rates.



a volume susceptibility of $\sim 10^{-5}$ SI (low value for calcareous ooze or siliceous ooze) and a sedimentation rate of 1 cm/ka is only 0.0001 (0.001).

[25] Looking for micrometeorites in sediment samples with a direction and/or magnetic susceptibility anomaly should only be attempted if the probability P_d is high enough. For example, this is the case for the Cretaceous pelagic limestones studied by Cronin *et al.* [2001]. Interestingly, these authors reported single sample excursions (about 1.5% of the total number of samples) that could be accounted for by our model. The sedimentation rate of 0.8 cm/ka and sediment DRM in the range of $\sim 5 \times 10^{-5}$ – 2×10^{-3} A/m yield a probability of excursions $\geq 30^\circ$ induced by a micrometeorite of ~ 0.5 – 2% , well in agreement with the number of excursions observed by Cronin *et al.* [2001]. These authors proposed that their excursions are of rock magnetic rather than geomagnetic origin. Their interpretation, based on an anomalous magnetic fabric, was that these samples were affected by “cryptoslumping.” One way to prove our alternative explanation would be to recover the micrometeorite responsible for the directional excursion in a given sample. Recovery of the micrometeorite could be done by cutting the sediment sample in two parts and measuring the NRM (however this operation must be performed before demagnetization) or the magnetic susceptibility to identify in which half the micrometeorite is. This operation can be repeated until the volume is small enough to be searched by gentle crushing and magnetic separation.

[26] If thermal or alternating field demagnetization is performed, a blocking temperature outside the range 560–580°C or a median destructive field outside the range 10–60 mT, that are characteristic of micrometeorites (Suavet *et al.*, submitted manuscript, 2008), would discard micrometeorites as a possible cause for direction anomaly. Anisotropy of magnetic susceptibility is also expected to be strong when a micrometeorite is the cause for the anomaly (micrometeorites have anisotropy degrees in the range of 1.15–1.64 (Suavet *et al.*, submitted manuscript, 2008)).

5. Conclusion

[27] Our model shows that magnetization direction anomalies $>5^\circ$ caused by micrometeorites may be rather frequent (more than 1% of measured sam-

ples), even for sediments with typical values of sedimentation rate (up to 10 cm/ka) and remanent magnetization (up to 5×10^{-3} A/m). The calculation of the probability P_d for a 10 cm^3 sediment sample to have its detrital remanent magnetization deviated of an angle $\delta \geq d$ by a micrometeorite gives: $P_{30} > 1\%$ for sediments with magnetizations $< 10^{-3}$ A/m and sedimentation rates < 10 cm/ka, and $P_{90} > 1\%$ for sediments with magnetizations $< 2 \times 10^{-4}$ A/m and sedimentation rates < 2 cm/ka. Care should be taken when interpreting anomalous directions as possible geomagnetic excursions in such sediments. Conversely, the magnetic susceptibility record is less likely to exhibit anomalies caused by a single micrometeorite, but this possibility cannot be excluded for very low susceptibility sediments ($< 10^{-5}$ SI).

Acknowledgments

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