Timescale uncertainty of abrupt events in the geologic record arising from unsteady sedimentation

Journal Item

Geology

Time-scale uncertainty of abrupt events in the geologic record arising from unsteady sedimentation

David B. Kemp and Philip F. Sexton

Geology 2014;42;891-894
doi: 10.1130/G35783.1

Notes

Time-scale uncertainty of abrupt events in the geologic record arising from unsteady sedimentation

David B. Kemp* and Philip F. Sexton
Environment, Earth and Ecosystems, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK

ABSTRACT

Defining the time scale of abrupt events in the stratigraphic record is a primary goal of high-resolution paleoclimate analysis. A significant hurdle in this endeavor is that abrupt, i.e., millennial and submillennial, events in deep time can rarely be temporally constrained accurately owing to the typical absence of high-precision age control at the scale of the events. Instead, the duration of abrupt events is commonly estimated via the linear partitioning of time between age control points (e.g., defined using astronomical cycles or radiometric dates) that bracket the event and span longer time intervals. The flaw with this approach is that sedimentation is an unsteady process and does not proceed linearly with time. Here a numerical model, parameterized by geologic data, is used to quantify theoretical time-scale uncertainties that result from unsteady sedimentation. This work demonstrates that the duration of assumed millennial events estimated via a linear partitioning approach may be significantly in error, even in complete, astronomically calibrated and unbioturbated successions best suited to the study of abrupt paleoclimate change. The uncertainties established in this study are largely a function of the precise statistical properties of the sedimentation process, properties that are difficult to constrain empirically, particularly over short time spans. Nevertheless, this study illustrates how unsteady sedimentation sets an important limit on the attainable temporal resolution of the stratigraphic record, with consequent implications for defining accurately the rates and durations of rapid events in Earth history.

INTRODUCTION

The stratigraphic record is an imperfect archive of the history of Earth, due in particular to its inherent incompleteness (Ager, 1973; Miall, 2014). A complete record (sensu Sadler, 1981) is one with no gaps that are longer than the time span at which the record is studied. Consequently, the minimum scale at which a succession is complete sets a logical upper limit on the attainable temporal resolution of the succession. In stratigraphic successions deposited in quiescent environments, the assumed absence of long (>1 k.y.) hiatuses underpins their use for high-resolution sampling and for identifying and temporally constraining geologically abrupt millennial- and submillennial-scale events. Nevertheless, accurately quantifying the duration of abrupt events is complicated by the common absence of high-precision age control at these short time scales. In the absence of unambiguous varves or radiocarbon dates, calibration of events spanning short stratigraphic intervals relies instead on the linear partitioning of time between age control points defined at longer time scales, such as those provided by astronomical cycle boundaries, radiometric dates, or magnetozone boundaries (e.g., Raymo et al., 1998; Kemp et al., 2005; Quillévéré et al., 2008; Sexton et al., 2011). Thus, if two dates delineating a given time interval occur *x* meters apart, a thinner package of sediment within this interval of 1/10th the thickness of *x* would be estimated to span 1/10th the duration of *x*. Typically, the most pressing problems with this approach are that successions are usually mixed through bioturbation, and the residence time of certain climate proxies (e.g., seawater dissolved inorganic carbon, with respect to sediment $\delta^{13}C$ analyses) often means that proxies do not respond on the same time scales as the forcing mechanisms (e.g., Anderson, 2001; Sluijs et al., 2012). Moreover, short-lived events pertaining to large-scale climate shifts can cause changes in sedimentation (e.g., through carbonate dissolution; Sluijs et al., 2012). These issues have the potential to attenuate, smear, or even condense abrupt events. Unbioturbated successions such as those deposited in suboxic environments and with astronomical age control offer the best opportunity for recognizing and temporally constraining short-lived events. Work on some of the most pronounced paleoclimate events of the Phanerozoic has emphasized the critical role unmixed successions play in determining rates of climate change on millennial and submillennial time scales (e.g., Kemp et al., 2005; Wright and Schaller, 2013). Despite this utility, the accuracy with which time can be constrained over geologically short intervals is poorly understood and has not received widespread attention. Notably, an underappreciated concern is that sedimentation rates are temporally variable, leading to nonlinear time-depth relationships that render linear interpolation of time error prone (Odell, 1975; Badgley et al., 1986; McMillan et al., 2002; Guyodo and Channell, 2002; Huybers and Wunsch, 2004). The significance of unsteady sedimentation is readily apparent in astronomically calibrated successions, where astronomical cycles with constant durations are preserved with variable thicknesses, even in unmixed, quiescent environments. This observation reminds us that the process of sedimentation is discrete, involving the instantaneous deposition of individual particles (either biogenic or clastic), and that stratigraphic completeness cannot prevail across all time scales. Ultimately, hiatuses, however short, lead to variations in sedimentation rate and compound to distort the sedimentation history into a nonlinear function of time across all time spans, regardless of the completeness of a succession.

Here a numerical model is used to simulate unsteady sedimentation in sedimentary successions best suited to the study of abrupt events, i.e., unbioturbated and age calibrated at astronomical time scales. These synthetic records are used to quantify theoretical uncertainties in the duration of assumed millennial events estimated via linear partitioning between astronomical cycle boundaries. We thus assess the utility of ostensibly ideal stratigraphic successions for quantifying the rates and duration of abrupt events.

SYNTHETIC SEDIMENTATION RATE RECORDS

Huybers and Wunsch (2004) demonstrated empirically that decompacted Pleistocene sedimentation rate records behave as autocorrelated processes with a frequency domain behavior consistent with a stochastic first-order autoregressive process with the generalized power spectrum:

$$\Phi(f) = \frac{1}{f^2 + f_0^2}, \tag{1}$$

where *f* is frequency and $1/f_0$ is the characteristic "memory" or decorrelation period of the record, typically ~100 k.y. in the records they studied (see the GSA Data Repository[1]). Spectral analysis of varve-thickness time series suggests that this red noise–like unsteadiness in the sedimentation process persists through to the annual scale (see Crowley et al., 1986), but

*E-mail: david.kemp@open.ac.uk.

[1]GSA Data Repository item 2014315, Figure DR1 (power spectra of empirical and modeled sedimentation rate data), Figure DR2 (probability distributions of empirical and modeled sedimentation rate data), and Table DR1 (Sedimentation rate statistics of marine records), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, October 2014; v. 42; no. 10; p. 891–894; Data Repository item 2014315 | doi:10.1130/G35783.1 | Published online 28 August 2014

that spectra tend to whiten at the highest frequencies, with the crossover point occurring at decadal periods (e.g., Crowley et al., 1986; Fagel et al., 2008; Davies et al., 2011; see the Data Repository). A lack of age control between annual and astronomical time scales means that the precise scaling of sedimentation rate variance between these periods in real successions is unclear, but by assuming a persistent autoregressive character of sedimentation (see the Data Repository), we can model this second crossover, and thus the spectrum of a generalized sedimentation rate history, with the addition of a second term:

$$\Phi'(f) = \frac{1}{f^2 + f_0^2} + \frac{1}{f_1^2}, \tag{2}$$

where $1/f_1$ ~ 10 yr. Following Huybers and Wunsch (2004), for practical purposes, discrete synthetic records of unsteady sedimentation, $R(t)$ (where t is the time step in a record of length T), are constructed directly from the inverse Fourier transform ($\Im^{-1}$) of $\sqrt{\Phi'}$ (i.e., the amplitude spectrum rather than the power spectrum) after multiplication with the Fourier transform of a Gaussian white noise (ω) of length T:

$$R(t) = \Im^{-1}\left\{\hat{\omega} \cdot \sqrt{\Phi'}\right\}. \tag{3}$$

With normalization of $R(t)$, the mean ($\bar{R}$) and standard deviation (σ) can be set allowing definition of the coefficient of variation (CV), a measure of the unsteadiness of $R(t)$:

$$\mathrm{CV} = \frac{\sigma}{\bar{R}}. \tag{4}$$

To consider only stratigraphically preserved rates, any negative rates in the synthetic records generate implicit erosion and thus hiatuses (per similar modeling approaches by Sadler, 1981; Kemp, 2012).

In a finite, discrete record of sedimentation with long-term memory, the coefficient of variation is time-span dependent: rates calculated over long time spans are a moving average (i.e., smoothed) filter output of the rate variability operating at shorter time spans, and hence sedimentation rate variance decreases with increasing averaging span (Fig. 1A). At the span, T, of the entire record the variance is 0. In detail, the precise scaling of the coefficient of variation with time span in a synthetic record is a function of f_0 and f_1. In astronomically calibrated successions the coefficient of variation can be calculated at the scale of the cycles because the theoretical age error of successive cycle boundaries is 0. From analysis of published sedimentation rate histories from both Mesozoic epicontinental and Cenozoic oceanic environments, we note broadly consistent coefficients of variation within the range of 0.22–0.52 (mean of ~0.33) when measured at astronomical or similar time spans and over ~1 m.y. intervals (see the Data Repository).

QUANTIFYING TIME-SCALE UNCERTAINTIES

In Figure 1, we consider a 1 m.y. record of sedimentation rates, $R(t)$, constructed from Equations 2 and 3 with t = 1 yr and conservative unsteadiness (CV at 20 k.y. time span = 0.25, σ = 0.01 mm yr^{-1}, and $\bar{R}$ = 0.04 mm yr^{-1}). In line with empirically determined best estimates, f_0 and f_1 are 1/100 k.y. and 1/10 yr, respectively (see the Data Repository). The colored cluster density plot in Figure 1A shows the distribution of all theoretically calculable rates from the record over time spans from 1 yr to 1 m.y. Because the rates are approximately normally distributed about the mean, the 2σ limits of the rate distribution (red lines, Fig. 1A) at any given time span bound ~95% of the rates (Fig. 1A). The intersection of a contour line of constant sediment thickness (e.g., curved black lines labeled 4 cm and 80 cm, Fig. 1A) with these 2σ limits delineates the range of time scales over which a given thickness of sediment can be expected to be deposited ~95% of the time (Fig. 1A). Consequently, we can observe that the expected (modal) thickness of a hypothetical 20 k.y. event in the succession is 80 cm ± 40 cm (2σ) (Fig. 1A). Conversely, the expected duration of an 80-cm-thick package of sediment will be 20 k.y., but with an approximately lognormally distributed ~95% uncertainty range between ~13.3 k.y. and ~33.5 k.y., i.e., –34% to +67% of the expected duration (Figs. 1A, 1B). This time-scale uncertainty becomes more significant when a thinner sediment thickness is considered (Figs. 1A and 1B). Thus, the expected thickness of a 1000 yr event is 4 cm (±2.46 cm, 2σ), and the expected duration of a 4-cm-thick interval is 1000 yr, with the ~95% uncertainty interval between ~640 yr and ~2520 yr, or ~–36% to ~+152% (Figs. 1A and 1B).

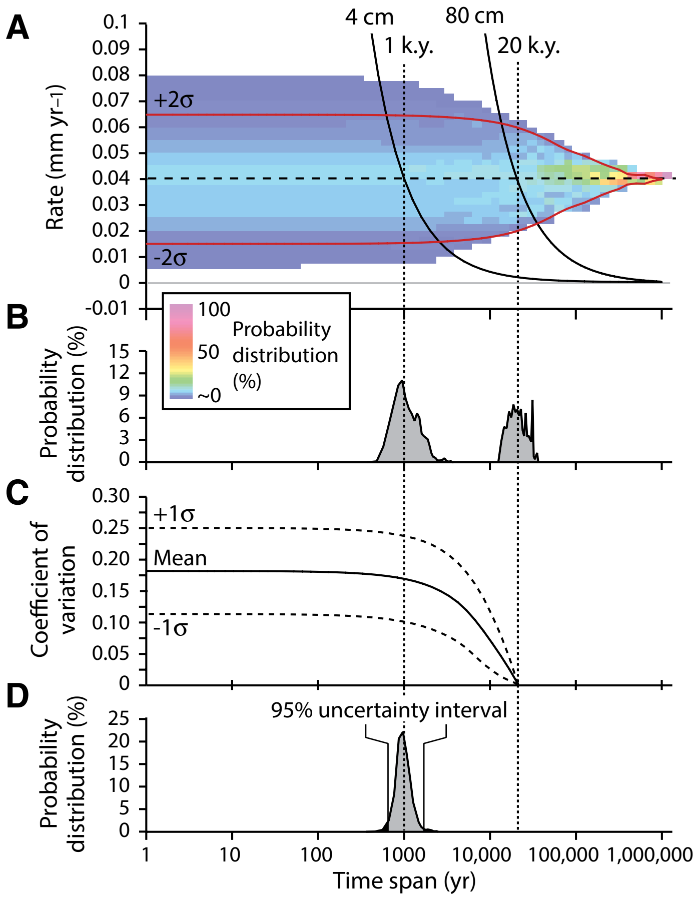

Figure 1. A: Cluster density plot showing distribution of all calculable rates from time spans of 1 yr to 1 m.y. in a 1 m.y. synthetic record of unsteady sedimentation (see text for model parameters used). Cluster density color relates to the probability density within 0.1 log yr by 0.0025 mm yr^{-1} bins. Red lines delineate the ±2σ limits at each time span. B: Histograms showing probability distributions of time scales over which sediment thicknesses of 4 cm and 80 cm are deposited. C: Plot showing mean coefficient of variation and ±1σ range of the 50 nonoverlapping 20-k.y.-long hypothetical cycles in the synthetic record. D: Histogram showing mean time-scale probability distribution of sediment thicknesses equal to 1/20th of the thickness of each 20 k.y. cycle. Time scales in the histogram are binned into 100 yr bins. This histogram indicates that the 95% uncertainty interval for the duration of an assumed millennial event in the synthetic record spans 740–1670 yr.

Figures 1A and 1B permit an assessment to be made regarding the accuracy with which time can be partitioned if accurate and precise dating at the top and bottom of the 1 m.y. succession was available. Theoretically, if the succession was astronomically calibrated at the 20 k.y. precession scale, age uncertainty exists only at scales <20 k.y. In this case, we can calculate the coefficients of variation and time-scale uncertainties at time spans within individual cycles (Fig. 1C). Figure 1C shows the wide range of coefficients calculable from the 50 nonoverlapping 20 k.y. cycles hypothetically present in the 1 m.y. synthetic record. Coefficients are generally lower compared to the scaling of coefficients over the entire 1 m.y. length of the record owing to the nonstationarity of our finite, discrete model (mean CV at 1 yr time span is ~0.18). Because the mean sedimentation rate varies for each 20 k.y. cycle, we calculate for each cycle the time-scale distribution of sediment thicknesses that are 1/20th the thickness of that cycle, i.e., assumed to be millennial (Fig. 1D). The histogram in Figure 1D shows the average time-scale probability distribution for these assumed millennial events calculated from analysis of all 50 individual cycles. Accordingly, while a stratigraphic event that is 1/20th the thickness of a precession cycle will have an expected duration of ~1000 yr, the results in Figure 1D indicate that this deduction will be accurate to within ±50 yr only in ~22% of cases, and 95% of the time the duration will be between 740 yr and 1670 yr (–26% to +67%; Fig. 1D).

Published sedimentation rate records exhibit a range of rate probability distributions, from normal (as in the synthetic record in Fig. 1) to lognormal with rates skewed markedly to higher values (e.g., Huybers and Wunsch, 2004) (see the Data Repository). Lognormal sedimentation rate distributions are also observed in varve records (e.g., Crowley et al., 1986). To investigate the effects of sedimentation rate distribution on the time-scale uncertainty of assumed millennial events, three separate models of sedimentation have been analyzed based on rate distributions observed in marine records (Fig. 2; see the Data Repository). Model 1 has a lognormal rate distribution with positive skew modeled on the relatively strongly skewed sedimentation rate record of Ocean Drilling Program Site 980 (Fig. 2A; see the Data Repository). Model 2 has a lognormal rate distribution that closely matches the average distribution of an ensemble of decompacted deep-sea sedimentation rate records from 14 separate Pleistocene cores (Fig. 2B; see the Data Repository). Model 3 has a normal rate distribution analogous to Jurassic epicontinental records (Fig. 2C; see the Data Repository). Skewed synthetic sedimentation rate records for each model were constructed by log transformation of $R(t)$ with prescribed base, a process that does not adversely affect the autoregressive properties or power spectra of the records. The 95% uncertainty intervals for the duration of assumed millennial events for these records were calculated following the methods outlined here at coefficients of variation ranging from 0.05 to 0.5, in 0.05 steps (with coefficient of variation determined at the 20 k.y. time span), and with hypothetical age calibration at the 20 k.y. precession and 100 k.y. eccentricity scales (Fig. 2). To provide statistically stable results, the synthetic records were 20 m.y. long (40 m.y. in the case of model 3). Time step (t) was 1 yr, $\bar{R}$ = 0.04 mm yr^{-1} and f_0 and f_1 were 1/100 k.y. and 1/10 yr, respectively. Two further models with rate probability distributions matching that of model 2 were analyzed to illustrate the sensitivity of results on f_0 and f_1, with these parameters set at 1/50 k.y. and 0 yr, and 1/200 k.y. and 1/100 yr, respectively (Fig. 2B).

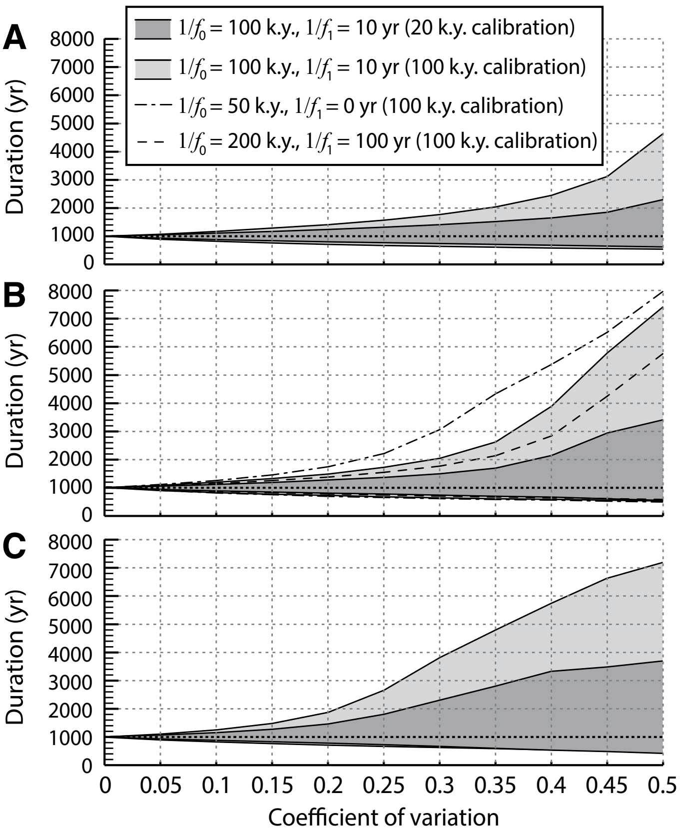

Figure 2. 95% uncertainty intervals associated with assumed 1000 yr events in 3 modeled successions at different coefficients of variation, and with age calibration at 20 k.y. precession and 100 k.y. eccentricity scales. See text and the Data Repository for details of model parameterization. A: Model 1 (positively skewed lognormal rate probability distribution). B: Model 2 (lognormal rate probability distribution with moderate skew that best matches average probability distribution of 14 separate records of decompacted Pleistocene sedimentation rate records). Uncertainty intervals are also shown for model 2 with different values of f_0 and f_1 (values in legend). C: Model 3 (normally distributed rates).

RESULTS AND DISCUSSION

Figures 1 and 2 demonstrate how the simple linear interpolation of time between discrete age control points in stratigraphic successions to estimate the time scale of narrow intervals is prone to potentially significant error due to unsteady sedimentation. Figure 2 emphasizes that the magnitude of these time-scale errors is a function of the precise statistical properties of the sedimentation rate history of a succession (notably the rate probability distribution and coefficient of variation), and the resolution of the age control. The uncertainty intervals for the analyzed synthetic records in Figure 2 widen with increasing unsteadiness, and the distributions of uncertainties in all three models skew markedly to longer durations (Fig. 2). The results of model 2 (Fig. 2B) indicate that calculated uncertainty intervals are also sensitive to values of f_0 and f_1 (Fig. 2B). With f_0 and f_1 at values best approximated by geologic data (1/100 k.y. and 1/10 yr, respectively), and with a geologically reasonable coefficient of variation of 0.35, the upper 95% uncertainty limit on the duration of an assumed millennial event for all three models is between ~+50% and ~+180% if time is calibrated at the precession scale (dark shaded areas in Fig. 2; ~+70% in model 2), and between ~+100% and ~+380% if time is calibrated at the eccentricity scale (light shaded areas in Fig. 2; ~+160% in model 2). Conversely, the duration of an assumed millennial event is unlikely to be more than 60% shorter than estimated in any of the models, regardless of the coefficient of variation.

The results in Figure 2 suggest that stratigraphic age control at time scales greater than that provided by short-term eccentricity cycles (i.e., >100 k.y.) likely precludes the accurate quantification of the duration of abrupt events in an unmixed succession. Our quantified uncertainties are conservative because the modeling assumes perfect astronomical age control. In reality, recognition of astronomical cycle boundaries in stratigraphic data can be ambiguous (and subjective), leading to additional duration uncertainties not explicitly quantified here. Our numerical simulations also demonstrate that the durations of abrupt events in the stratigraphic record are more likely to be significantly underestimated than significantly overestimated. Indeed, in positively skewed sedimentation rate records, the offset of the mean rate toward higher values relative to the mode means that the modal (i.e., expected) duration of an assumed millennial event will be >1000 yr. Importantly, the models also provide a theoretical assessment of the attainable temporal resolution in statistically similar real sedimentary successions. Sampling of such successions at presumed millennial resolution would generate data sets with the actual temporal spacing of samples varying within the modeled uncertainty bounds. While model 1 is complete at annual time scales, hiatuses >1000 yr duration occur in both models 2 and 3 at coefficients of variation above 0.45 and 0.4, respectively, thus further constraining the attainable resolution and likely influencing the morphology and apparent abruptness of preserved climate signals. Of course, our models represent only a parameterized simulation of sedimentation, and the geologic processes controlling sedimentation are distinct from those that govern winnowing and erosion, something the modeling does not consider. Intuitively, however, observed high coefficients of variation in real successions may arise specifically from the presence of relatively long hiatuses. The modeling also assumes strictly stochastic sedimentation. Sedimentation rates in astronomically calibrated successions can exhibit periodicities consistent with the dominant astronomical forcing parameters (e.g., Mix et al., 1995; Guyodo and Channell, 2002). Theoretically, at least, time-scale uncertainties for short-lived events could be reduced if a predictable association between expected rate and position within a given cycle could be demonstrated. Nevertheless, our calculated uncertainty estimates are predicated on the observation that unsteadiness in the sedimentation process persists at all time scales, from annual (e.g., Davies et al., 2011; Crowley et al., 1986) to astronomical (e.g., Huybers and Wunsch, 2004). The clear sensitivity of our modeled time-scale errors to the statistical properties of the numerical simulations (Fig. 2) reinforces the inherent difficulty of accurately quantifying the time scales of short-lived events in the geologic record.

CONCLUSIONS

Our numerical simulations of sedimentation have been used to extract quantitative estimates of how accurately time can be partitioned over short stratigraphic intervals, below the scale at which astronomical forcing provides relative age constraints. Our results indicate that the accuracy with which the duration of narrow intervals of strata can be determined decreases as thinner intervals are considered, and that time-scale uncertainties are skewed toward longer durations. Difficulties in resolving the precise time-scale errors of short-lived events in a given succession arise predominantly because in real stratigraphies the true nature of the sedimentation process, particularly over short time spans, is not cognizable. Our findings have particular implications for the accurate quantification of the rates and duration of abrupt paleoclimate events in unbioturbated, astronomically calibrated successions that are otherwise best suited to high-resolution sampling and study.

ACKNOWLEDGMENTS

Kemp acknowledges support from Natural Environment Research Council Fellowship Grant NE/I02089X/1. The comments of Andrew Miall and an anonymous reviewer greatly improved the manuscript.

REFERENCES CITED

Ager, D.V., 1973, The nature of the stratigraphic record: New York, Wiley, 114 p.

Anderson, D.M., 2001, Attenuation of millennial-scale events by bioturbation in marine sediments: Paleoceanography, v. 16, p. 352–357, doi:10.1029/2000PA000530.

Badgley, C., Tauxe, L., and Brookstein, F.L., 1986, Estimating the error of age interpolation in sedimentary rocks: Nature, v. 319, p. 139–141, doi:10.1038/319139a0.

Crowley, K.D., Duchon, C.E., and Rhi, J., 1986, Climate record in varved sediments of the Eocene Green River Formation: Journal of Geophysical Research, v. 91, p. 8637–8647, doi:10.1029/JD091iD08p08637.

Davies, A., Kemp, A.E.S., and Pälike, H., 2011, Tropical ocean-atmosphere controls on inter-annual climate variability in the Cretaceous Arctic: Geophysical Research Letters, v. 38, L03706, doi:10.1029/2010GL046151.

Fagel, N., Boës, X., and Loutre, M.F., 2008, Climate oscillations evidenced by spectral analysis of southern Chilean lacustrine sediments: The assessment of ENSO over the last 600 years: Journal of Paleolimnology, v. 39, p. 253–266, doi:10.1007/s10933-007-9116-z.

Guyodo, Y., and Channell, J.E.T., 2002, Effects of variable sedimentation rates and age errors on the resolution of sedimentary paleointensity records: Geochemistry Geophysics Geosystems, v. 3, p. 1–18, doi:10.1029/2001GC000211.

Huybers, P., and Wunsch, C., 2004, A depth-derived Pleistocene age model: Uncertainty estimates, sedimentation variability, and nonlinear climate change: Paleoceanography, v. 19, PA1028, doi:10.1029/2002PA000857.

Kemp, D.B., 2012, Stochastic and deterministic controls on stratigraphic completeness and fidelity: International Journal of Earth Sciences, v. 101, p. 2225–2238, doi:10.1007/s00531-012-0784-1.

Kemp, D.B., Coe, A.L., Cohen, A.S., and Schwark, L., 2005, Astronomical pacing of methane release in the Early Jurassic period: Nature, v. 437, p. 396–399, doi:10.1038/nature04037.

McMillan, D., Constable, C., and Parker, R., 2002, Limitations on stratigraphic analyses due to incomplete age control and their relevance to sedimentary paleomagnetism: Earth and Planetary Science Letters, v. 201, p. 509–523, doi:10.1016/S0012-821X(02)00747-1.

Miall, A.D., 2014, Updating uniformitarianism: Stratigraphy as just a set of "frozen accidents", *in* Smith, D.G., et al., eds., Strata and time: Probing the gaps in our understanding: Geological Society of London Special Publication 404, doi:10.1144/SP404.4 (in press).

Mix, A.C., Le, J., and Shackleton, N.J., 1995, Benthic foraminiferal stable isotope stratigraphy of Site 846: 0–1.8 Ma, *in* Pisias, N.G., et al., eds., Proceedings of the Ocean Drilling Program, Scientific results, Volume 138: College Station, Texas, Ocean Drilling Program, p. 839–854, doi:10.2973/odp.proc.sr.138.160.1995.

Odell, J., 1975, Error estimation in stratigraphic correlation: Mathematical Geology, v. 7, p. 167–182, doi:10.1007/BF02080491.

Quillévéré, F., Norris, R.D., Kroon, D., and Wilson, P.A., 2008, Transient ocean warming and shifts in carbon reservoirs during the early Danian: Earth and Planetary Science Letters, v. 265, p. 600–615, doi:10.1016/j.epsl.2007.10.040.

Raymo, M.E., Ganley, K., Carter, S., Oppo, D.W., and McManus, J., 1998, Millennial-scale climate instability during the early Pleistocene epoch: Nature, v. 392, p. 699–702, doi:10.1038/33658.

Sadler, P.M., 1981, Sediment accumulation rates and the completeness of stratigraphic sections: Journal of Geology, v. 89, p. 569–584, doi:10.1086/628623.

Sexton, P.F., Norris, R.D., Wilson, P.A., Palike, H., Westerhold, T., Röhl, U., Bolton, C.T., and Gibbs, S., 2011, Eocene global warming events driven by ventilation of oceanic dissolved organic carbon: Nature, v. 471, p. 349–352, doi:10.1038/nature09826.

Sluijs, A., Zachos, J.C., and Zeebe, R.E., 2012, Constraints on hyperthermals: Nature Geoscience, v. 5, p. 231, doi:10.1038/ngeo1423.

Wright, J.D., and Schaller, M.F., 2013, Evidence for a rapid release of carbon at the Paleocene-Eocene thermal maximum: National Academy of Sciences Proceedings, v. 110, p. 15,908–15,913, doi:10.1073/pnas.1309188110.

Manuscript received 16 April 2014
Revised manuscript received 25 July 2014
Manuscript accepted 27 July 2014

Printed in USA