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# Stratigraphic completeness and resolution in an ancient mudrock succession

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## ABSTRACT

Mudrocks are the most common rock type at the Earth's surface, and they play a major role in informing current understanding of the palaeoenvironmental history of the planet. Their suitability for this purpose is at least partly underpinned by the assumed stratigraphic completeness of mudrock successions, and the ostensible fidelity with which they record temporal changes in palaeoenvironment. Mud does not necessarily accumulate, however, as a steady, near-continuous 'rain' under low energy conditions. Advective modes of mud transport and episodic, ephemeral accumulation have been shown to dominate in many ancient successions. This has implications for the completeness of these records and their suitability for high-resolution sampling and analysis. In this study, a numerical model of mud accumulation, parameterized with data from the Lower Jurassic of Yorkshire (UK) is presented to explore completeness and resolution constraints on ancient epicontinental mudrock successions. Using this model, stratigraphic completeness of the analysed Yorkshire succession is estimated to be *ca* 13% and *ca* 98% at centennial and millennial timescales, respectively. The findings indicate that sub-millennial scale processes and events are unlikely to be accurately resolved, despite the largely unbioturbated and well-laminated nature of the succession. Epicontinental mudrock successions are a crucial archive of ancient environmental changes, and the findings of this study help to define a plausible upper limit on the resolution achievable in these successions. Even with high-resolution sampling, sub-millennial scale records of palaeoenvironmental change may not be attainable in ancient epicontinental mudrocks.

**Keywords** Mudrock, palaeoenvironment, resolution, sampling, stratigraphic completeness.

## INTRODUCTION

Accurately linking strata and time is a core challenge of stratigraphy. This endeavour is complicated by the fact that sedimentation is an inherently discrete and unsteady process, and stratigraphic successions are replete with hiatuses at multiple temporal and spatial scales (Shaw, 1964; Ager, 1973; Sadler, 1981; Tipper, 1983). This incompleteness means that the stratigraphic record is an imperfect archive of Earth history. Sadler (1981) formalised the concept of a complete record: it is one that encompasses no hiatuses longer than the timespan at which the succession is sampled/studied (Sadler, 1981; see also Kemp, 2012). Intuitively, the minimum timespan at which a record is complete also sets an upper limit on the temporal resolution of the record (Kemp & Sexton, 2014).

In mud-dominated successions deposited under low energy conditions, ostensible steadiness and continuity of sedimentation limits both the frequency and duration of hiatuses (Sadler, 1981; see also Hilgen *et al.*, 2014, and references therein), underpinning their suitability for high-resolution sampling and analysis. Consequently, marine mudrocks play a major role in informing current understanding of the detailed palaeoenvironmental history of the Earth. Mudrock successions are often implicitly assumed to be capable of faithfully recording geologically abrupt (<$10^4$ years) events and processes, with minimal distortion of their true temporal pattern replicated stratigraphically in a succession (e.g. Kemp *et al.*, 2005; Méhay *et al.*, 2009; Wright & Schaller, 2013). However, this view is at odds with evidence from both the modern oceans and the geological record that has demonstrated instead the importance and prevalence of advective modes of mud transport and the likely episodic accumulation of mud under higher energy conditions than hitherto assumed (e.g. Schieber *et al.*, 2007; Schieber & Yawar, 2009; Macquaker *et al.*, 2010).

A key implication of these advances is that the stratigraphic record of mudrocks may not be as complete as sometimes assumed (a point made in particular by Macquaker & Bohacs, 2007; see also Schieber, 1998). The suitability of mudrocks for preserving or accurately resolving rapid events and processes may not be assured, yet the precise stratigraphic completeness of mud-dominated successions is largely untested. Indeed, the work of Sadler (1981) provides only generalized constraints on completeness for different sedimentary environments based on the compilation of sedimentation rate data from multiple sections. Assessing completeness in a single section is more problematic, but would ultimately be more useful. A key question related to this might be, given ideal conditions of little or no bioturbation, can mudrocks be sampled at such high-resolution that centennial or even decadal records can be generated? In this study, these issues are addressed using a numerical model of mud accumulation, parameterized by sedimentological observations, to explore the implications of episodic accumulation on the completeness and resolution of an ancient epicontinental mudrock succession.

## EPICONTINENTAL MUD DEPOSITION: THE LOWER JURASSIC OF YORKSHIRE, UK

Marine mudrocks (mean grain size <62·5 μm) are very common at the Earth's surface, and form perhaps the most important and readily examined archive of the palaeoenvironmental history of the Earth. Current understanding of the processes involved in the formation of mudrock successions is still incomplete, however. Notably, the widespread occurrence of mudrock accumulations across what were ancient, relatively shallow (<100 m) epicontinental seaways raises questions about the dispersal mechanisms of this material (Schieber, 2016). Recent advances have emphasized the importance of advective transport. It has been shown, for instance, how the cohesive nature of mud and its propensity to flocculate into aggregates means that muds can be deposited in current regimes that are powerful enough to move sand (Schieber *et al.*, 2007). Modern field observations, flume studies and microtextural analysis of ancient strata have all further revealed the importance of high-energy processes in both the dispersal and accumulation of mud (e.g. Schieber, 1994; Macquaker & Taylor, 1996; Macquaker & Howell, 1999; Traykovski *et al.*, 2007; Schieber & Southard, 2009; Macquaker *et al.*, 2010). Small-scale structures familiar in high energy environments such as scours, grading, and low amplitude-long wavelength ripples/inclined laminae are readily preserved in mudrocks, but can be easily missed (Schieber *et al.*, 2007; Schieber & Yawar, 2009; see also Macquaker & Bohacs, 2007).

Lower Jurassic mudrocks exposed along the coastline of Yorkshire, UK, have proven important for the development of some of these fairly recent ideas on mudrock accumulation, and have been the subject of a great deal of past sedimentological research (see for example Sorby, 1908; Pye & Krinsley, 1986; O'Brien, 1990; Macquaker & Taylor, 1996; Macquaker *et al.*, 2010; Ghadeer & Macquaker, 2011, 2012; Trabucho-Alexandre, 2014). Limited bioturbation in long intervals of the succession facilitates recognition and analysis of primary depositional features. Outcrop and thin section microtextural analysis of various intervals from the Pliensbachian and Toarcian has shown that the strata frequently comprise stacks of normally graded sub-parallel layers (typically <10 mm) with sharp erosional bases (Ghadeer & Macquaker, 2011, 2012). Each layer is readily interpreted as the product of a single, rapid depositional event with erosive power (Macquaker *et al.*, 2010; Ghadeer & Macquaker, 2011, 2012; Trabucho-Alexandre, 2014). Macquaker *et al.* (2010) recognised a tripartite internal structure in some of these layers (silt-rich base, intercalated silt/clay laminae and overlying clay drape) consistent with the texture predicted from sediments deposited from wave enhanced sediment gravity flows of fluidized mud (Macquaker *et al.*, 2010). As the name suggests, the energy required to keep sediment in suspension (and thus dispersed further than gravity alone could achieve) is from surface waves. Accordingly, storms have been suggested as the ultimate driver of mud dispersal by this mechanism (Ghadeer & Macquaker, 2011). Evidence for storm-influenced deposition also comes from normally graded layers with silt lags interpreted as tempestites, as well as ripples, gutter casts and putative hummocky cross-stratification (Wignall *et al.*, 2005; Ghadeer & Macquaker, 2011, 2012). Suspension settling of marine snow aggregates is also likely to have occurred (Ghadeer & Macquaker, 2012), but preservation of these aggregates and other authigenic components such as framboids was nevertheless probably via entrainment in layers. Indeed, in the Mulgrave Shale Member of the Yorkshire succession there is a link between basal silt lags and the occurrence of marine snow aggregates (Ghadeer & Macquaker, 2012), suggestive of similarly episodic delivery linked by an association between storm events and increased nutrient delivery from either storm-related fluvial discharge increases, and/or storm-induced nutrient recycling from bottom waters layers back to surface layer (Ghadeer & Macquaker, 2012).

## A NUMERICAL MODEL OF MUDROCK ACCUMULATION

### Rationale

Taken together, the observations above emphasise how mud accumulation can be episodic and erosive. The time needed to deposit sediment is geologically negligible, and most time, even in mudrock successions, is at bed/layer boundaries (Campbell, 1967; Dott, 1983; Macquaker & Howell, 1999; Trabucho-Alexandre, 2014). In this context, the accumulation of mud-dominated successions like those of the Lower Jurassic of Yorkshire can be modelled as a simple renewal process (Schwarzacher, 1975), fundamentally similar to the probabilistic models investigated by many workers (e.g. Kolmogorov, 1951; Mizutani & Hattori, 1972; Dacey, 1979; Tipper, 1983, 2016; Strauss & Sadler, 1989).

In the simplest form of such a model, the deposition of individual layers of mud is episodic and instantaneous, and these layers are separated by time gaps (hiatuses) with some unknown but random distribution. Of key importance for assessing stratigraphic completeness is knowledge of the duration and distribution of these hiatuses, since this provides a measure of how time is partitioned within an interval of strata of known duration. The Grey Shales Member (lower Toarcian, *ca* 182 Ma) of the Yorkshire succession is suitable for assessing stratigraphic completeness in this way via a model because: (i) discrete mud layers can be observed that are the likely instantaneously deposited product of storm events; and (ii) there is relative age control in the section in the form of astronomical cycles (Fig. 1). Furthermore, using a model to assess stratigraphic completeness in the Grey Shales Member is also a pertinent exercise because these strata preserve ostensibly very rapid (millennial-scale) shifts in organic carbon isotopes ($\delta^{13}C_{org}$) that have been interpreted to represent either: (i) sudden increases in biospheric $^{12}C$ from methane hydrate melting (Hesselbo *et al.*, 2000; Kemp *et al.*, 2005; Fig. 1); or (ii) stratigraphic hiatuses (Trabucho-Alexandre, 2014).

### Model parameterization

To parameterize a model of mud accumulation in the Grey Shales Member, the thicknesses of discrete layers from a *ca* 1 m interval of the succession (Fig. 1) were measured from high-resolution (12 megapixel) photographs of a vertical exposure taken using a Canon 100D DSLR with 50 mm macro lens (Canon, Tokyo, Japan; for example, Fig. 2). The Fe-rich weathered surface of the outcrop was removed using a steel wool grinding wheel fitted to an electric drill. The interval comprises a stack of 275 thin (0·4 to 17·0 mm, mean 3·4 mm) normally graded silt bearing clay-rich and organic-rich muddy layers (Fig. 3). Within this interval a well-expressed 75 cm cycle in $\delta^{13}C_{org}$ occurs that contains *ca* 220 of these layers (210 to 230, depending on the precise position of the cycle boundaries; Fig. 1). Kemp *et al.* (2011) interpreted these

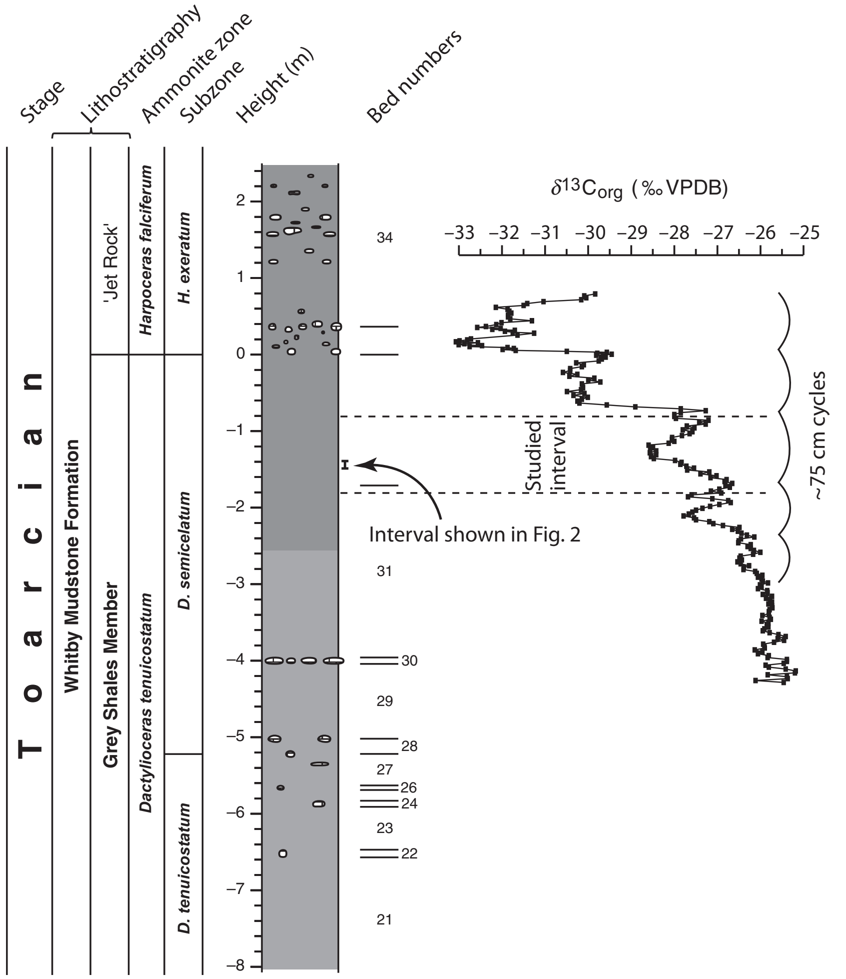


**Fig. 1.** Log and organic carbon-isotope ($\delta^{13}C_{org}$) stratigraphy of the studied Grey Shales Member interval and surrounding strata. $\delta^{13}C_{org}$ data below 0 m is from Kemp *et al.* (2005). The $\delta^{13}C_{org}$ shows cyclicity with a period of *ca* 75 cm. Bed numbers and ammonite stratigraphy is from Howarth (1992). The interval shown in Fig. 2 is indicated.

*ca* 75 cm cycles, which extend through the Grey Shales and overlying Jet Rock members, as *ca* 36 000 year obliquity cycles (see also Boulila *et al.*, 2014 and Boulila & Hinnov, 2017; who have recognised coeval cycles in strata in France; Fig. 1). The cycles have also been recognised through the succession in total organic carbon content, S and $CaCO_3$ (Kemp *et al.*, 2011).

The bases of individual muddy layers in the prepared outcrop interval are sharp, and normally silt-rich, with this silt typically lacking internal structure (Fig. 2). At least some of the layers appear to have the tripartite internal structure described in Macquaker *et al.* (2010) and above. In some cases a silt base is indistinct or absent (Fig. 2). Because >96% of the layers are <10 mm thick (Fig. 3), and because of the internal lamination that can sometimes be distinguished in these layers, the layers broadly fit a definition of 'laminaset' (e.g. Campbell, 1967). For simplicity, the term 'layer' is used throughout this work (Fig. 2). Layers are typically sub-parallel, and sometimes wavy (Fig. 2). Across the cleaned rock face analysed, layers are typically continuous, but the erosive nature of the layers is readily apparent in some instances by the down cutting of layers into underlying layers (Fig. 2). As noted in Ghadeer & Macquaker (2012), the tops of these layers are sometimes bioturbated, and some intervals of bioturbation exist that mask layer boundaries and internal structure (Fig. 2). The thickness distribution of the measured layers is close to exponential (Fig. 3). At the outcrop scale of investigation, layer boundaries may be misidentified, and very thin layers may be missed. To ascertain the effects of this kind of error, 1000 versions of the layer data were generated with 20% of the individual layers in each version randomly split or randomly summed with the preceding layers. Thickness distribution analysis of these error-prone datasets indicates a slightly closer match to an exponential distribution (Fig. 3).

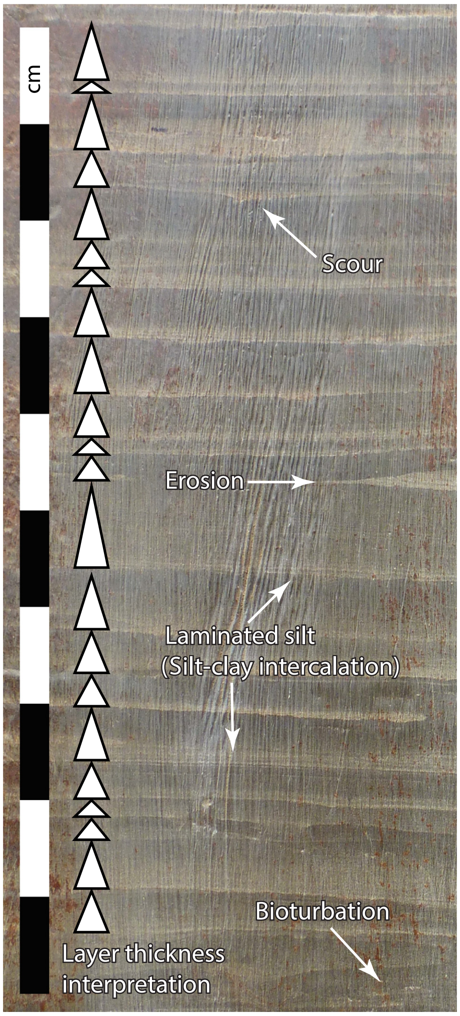


**Fig. 2.** Photograph of a section of prepared cliff face showing layer thickness interpretation and key sedimentary features. Location of this interval is shown in Fig. 1. Image captured using a Canon 100D DSLR camera with 50 mm macro lens. See main text for details.

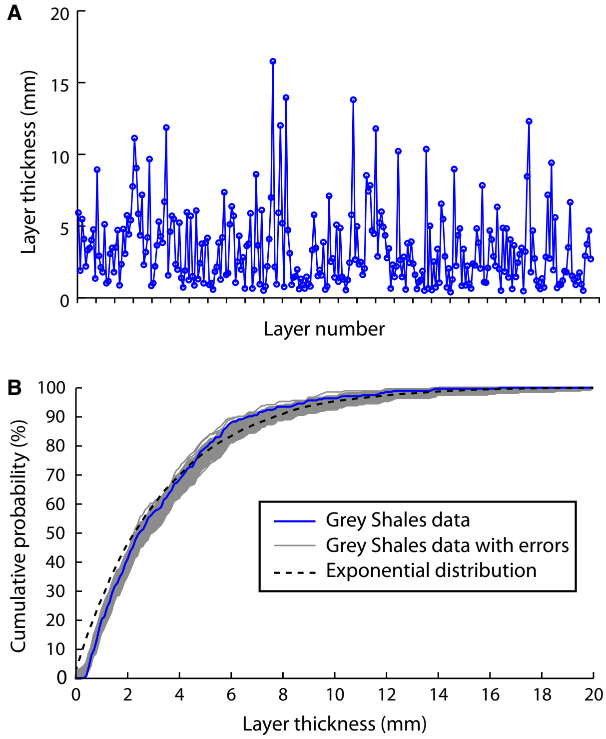


**Fig. 3.** (A) Layer thickness data through the studied Grey Shales Member interval. (B) Cumulative probability distribution of layer thicknesses (blue line). Note the reasonably close match to an exponential distribution (dashed black line, $R^2 = 0{\cdot}995$). Grey lines show probability distributions of 1000 modified layer thickness datasets that have measurement errors factored in, see main text for details.

## Model design

To model the deposition of the Grey Shales Member, synthetic layers are created that have exponentially distributed random thicknesses, with a mean thickness of 3·4 mm (Fig. 4). Thus, these synthetic layers match the statistical characteristics of the layers recorded in the studied interval of the Grey Shales Member. The scouring evident from the studied interval of the Grey Shales Member indicates that layer deposition is intimately linked to erosion, and thus each synthetic layer is associated with an erosion event with negative thickness (in millimetres) drawn from a similarly exponential distribution (Fig. 4). Layers are stacked to build a synthetic succession with a total thickness and layer count that matches the studied interval (i.e. *ca* 75 cm and 220 ± 10 layers). Compaction does not need to be considered because this has no influence on the model results. Synthetic layers, assumed to be the product of storm events and deposited instantaneously, are separated by hiatuses that sum to 36 000 years – in line with the cyclostratigraphic constraints noted above. These hiatuses are, like the layers, modelled as having an exponential distribution. This ensures that the recurrence of depositional events behaves as a Poisson process (Schwarzacher, 1975). This reasoning has a physical foundation based on observations of modern storm recurrence (e.g. Eagleson, 1978; Wilkinson *et al.*, 1998; Lin *et al.*, 2016).

The model described above is able to reproduce a Grey Shales Member-like succession of *ca* 220 layers that is *ca* 75 cm thick, deposited over a 36 000 year interval. Code for the model (written in Matlab®, The MathWorks Inc.,

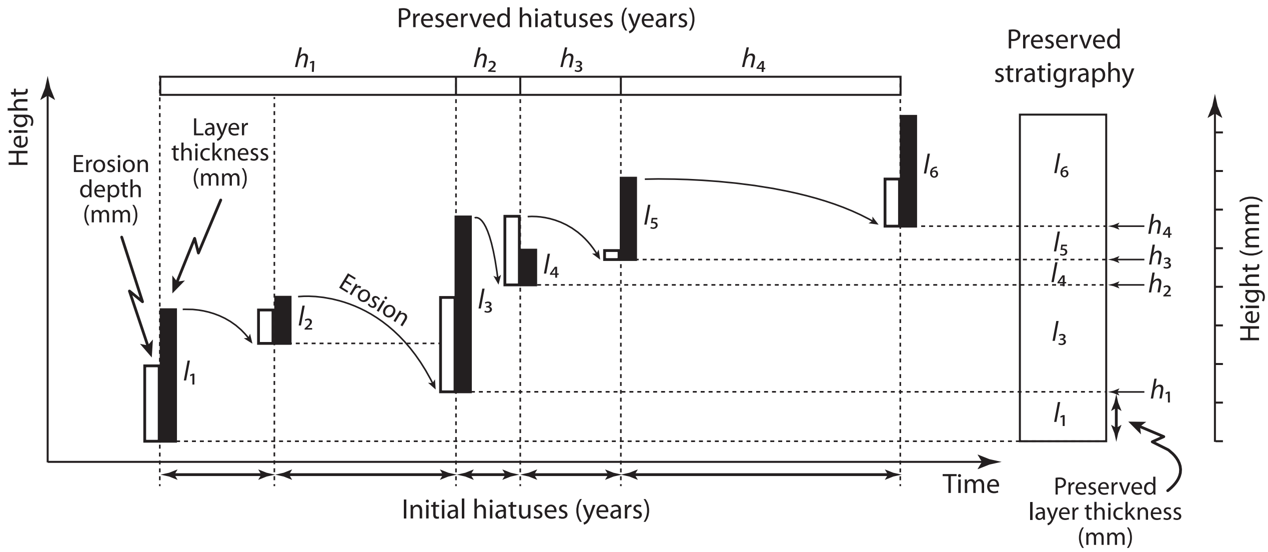


**Fig. 4.** Schematic representation of the sedimentation model. Instantaneous layer depositional events ($l$, black bars) have an exponential thickness distribution and are separated by hiatuses that also have an exponential distribution. Deposition is associated with erosion events (white bars, also with an exponential thickness distribution) that cut down into previously deposited layers (for example, note the total erosion of layer $l_2$). The key outputs of the model are a set of preserved layers, and a set of preserved hiatus durations. See main text for further details.

Natick, MA, USA) is available on request from the lead author. The key outputs from the model are a set of preserved layer thicknesses (measured in millimetres) and a corresponding set of preserved hiatuses (measured in years) (Fig. 4).

The key variable in the model is erosion depth. Erosion has the potential to completely remove a deposited layer (Fig. 4). Thus, a high erosion depth means that the number of layers that were initially deposited and then subsequently eroded in the model could be far higher than the *ca* 220 layers ultimately preserved. Zero erosion would mean that all layers initially deposited are preserved. The optimal erosion depth to use in the model is not easily ascertained from analysis of the Grey Shales Member sedimentology. Notably, it is difficult to unambiguously distinguish small-scale erosion from non-erosive ripples, sediment draping and bioturbation from the outcrop photographs. Larger scours that display erosive down cutting into underlying layers are more readily and unambiguously identified, however (example shown in Fig. 2). The maximum scouring depth observable at outcrop is 3·55 mm, with scours rarely cutting down into more than one preceding layer. Macquaker *et al.* (2010) observed similar scour depths of up to *ca* 3 mm in their own analysis of the Grey Shales Member. Based on the statistical properties of exponential distributions, a maximum erosion depth of 3·55 mm implies a mean erosion depth of 0·59 mm. This may be a conservative estimate of average erosion depth, since erosion of multiple layers is obviously not cognizable from the preserved strata. Equally, the limited width of the prepared outcrop surface (*ca* 10 cm) means that scouring is observed over only a finite lateral extent.

## RESULTS

Figure 5 shows the key results from analysis of three model scenarios. The first scenario uses the 'best estimate' mean erosion depth of 0·59 mm. The second scenario is an end-member scenario that considers minimal erosion ('low erosion', mean erosion depth of 0·1 mm). The third scenario is a 'high erosion' end-member scenario where the mean erosion depth is only slightly lower than the mean layer thickness (3 mm). To obtain meaningful statistics, each model scenario was run 1000 times (i.e. 1000 synthetic successions were generated) and the results averaged/compiled (Fig. 5).

All three model scenarios produce successions of 220 ± 10 preserved layers that have a

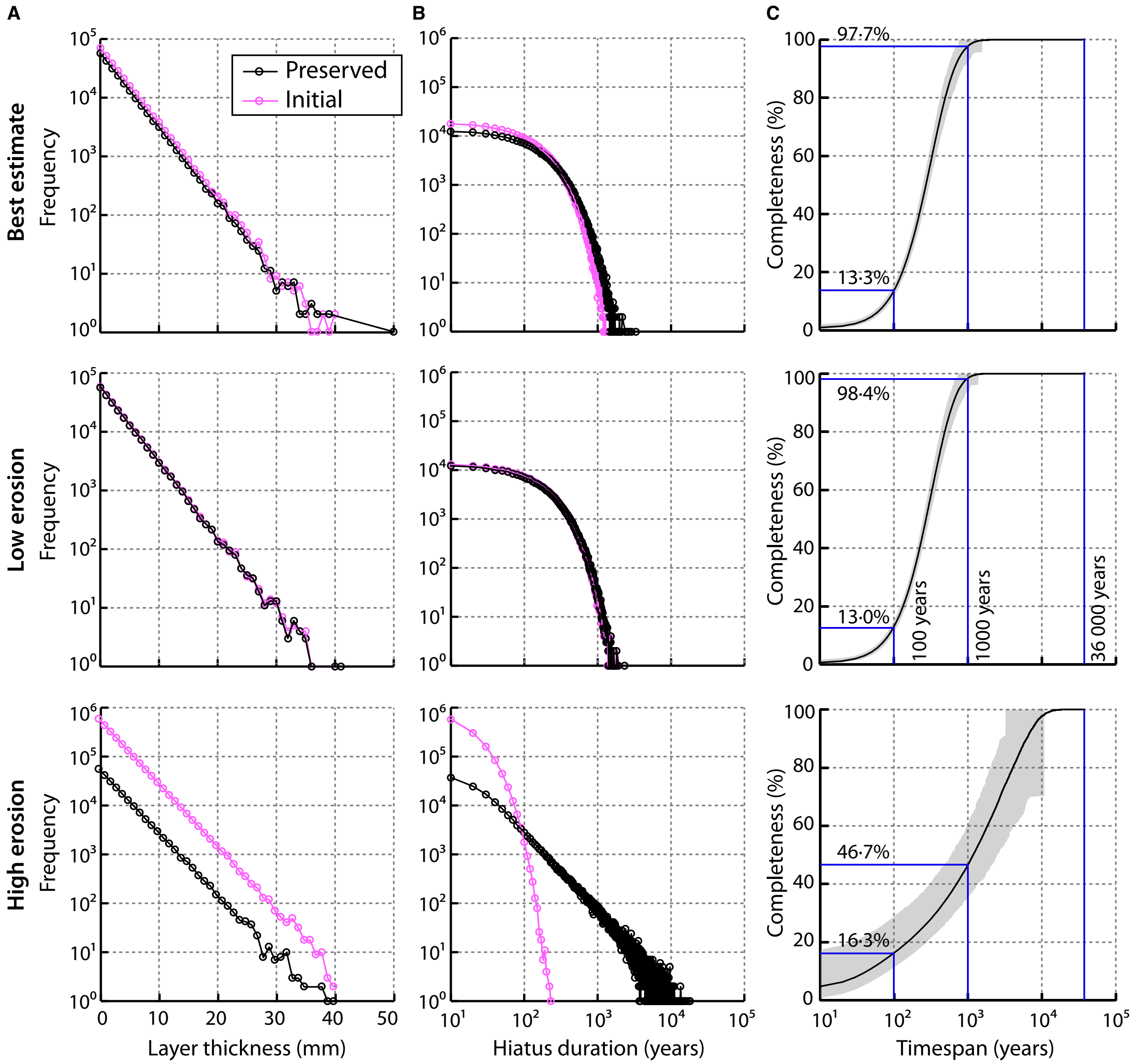


**Fig. 5.** Key results of three different model scenarios designed to reproduce a *ca* 75 cm Grey Shales Member-like succession of 220 ± 10 layers deposited in 36 000 years (see main text for details of scenarios). (A) Thickness distributions of layers from the three model scenarios. Initially deposited layer thicknesses (purple data) are exponentially distributed. The plot helps to show how, after erosion, the preserved layer thickness distributions (black data) in the model scenarios remains exponential. The mean thicknesses of the initially deposited and preserved layers are also the same. (B) Hiatus duration distributions from the three model scenarios. Note how in the high erosion scenario the distribution of preserved hiatuses tends towards a power law distribution (straight line on log–log plot). (C) Completeness curves for each of the model scenarios, along with 90% uncertainty envelope (grey shading). Note how completeness at 100 year and 1000 year scales is much lower in the 'high erosion' scenario. All plots are based on analysis of 1000 simulations of each model scenario. All models use exponentially distributed erosion depths and hiatuses. See main text for details.

mean thickness of 3·4 mm and exponential thickness probability distributions, deposited in 36 000 years (Fig. 5). Thus, each scenario produces synthetic successions that are consistent with the Grey Shales Member data. In the 'best estimate' scenario (mean erosion depth = 0·59 mm), *ca* 270 layers need to be initially deposited to leave a preserved *ca* 75 cm record of 220 ± 10 layers: 17·5% of deposited layers (*ca* 50) are completely eroded and not preserved. In other words, the average probability of preserving a deposited layer is 82·5%. Over the 36 000 year duration of the modelled succession, this equates to an average initial hiatus duration (i.e. mean recurrence time between the *ca* 270 initially deposited layers) of *ca* 133 years (36 000/270). In the 'low erosion' scenario, *ca* 227 layer deposition events need to occur to leave a preserved *ca* 75 cm record of *ca* 220 ± 10 layers. This equates to an average initial hiatus duration of *ca* 159 years. The probability of layer preservation is *ca* 97·0%. In the 'high erosion' scenario, *ca* 2300 layers need to be deposited to leave a *ca* 75 cm record of 220 ± 10 layers. The average initial hiatus duration is *ca* 16 years. The probability of layer preservation is just *ca* 9·7%.

In the 'low erosion' scenario, the distribution of preserved hiatuses is very close to the original exponential distribution of the initial hiatuses (Fig. 5B). In the 'high erosion' scenario, the distribution of preserved hiatuses is more complex. This is because the frequent total erosion of one or more layers causes hiatuses to compound together. This means that the distribution of preserved hiatuses is different to the distribution of the initial hiatuses (Fig. 5B). The number of hiatuses more than *ca* 100 years is increased, and the number of hiatuses less than *ca* 100 years is decreased (Fig. 5B). The distribution of preserved hiatus durations in the high erosion scenario is no longer exponential. Instead, the distribution is close to that of a power law (Fig. 5B). A power law distribution would be consistent with the fractal distribution of hiatuses posited by Plotnick (1986) (see also Kemp, 2012). The 'best estimate' hiatus distribution is similar to that of the 'low erosion' scenario (Fig. 5). Maximum preserved hiatus durations (i.e. timespans at which the records are 100% complete) are *ca* 3300 years in the 'best estimate' scenario, *ca* 2300 years in the 'low erosion' scenario, and *ca* 18 200 years in the 'high erosion' scenario (Fig. 5C). At centennial timespans (100 years), the mean completeness in the three model scenarios is similar: 13·0%, 13·3% and 16·3% in the 'low', 'best estimate' and 'high' erosion scenarios, respectively. At millennial timespans (1000 years), however, the mean completeness of the 'best estimate' and 'low erosion' models is 97·7% and 98·4% respectively, but only 46·7% in the 'high erosion' scenario (Fig. 5C).

To explore in further detail the sensitivity of the model results to erosion, the stratigraphic completeness for a range of layer preservation probabilities has been calculated, from 100% (no erosion) down to 5% (mean erosion depth 3·3 mm) (Fig. 6). For layer preservation probabilities

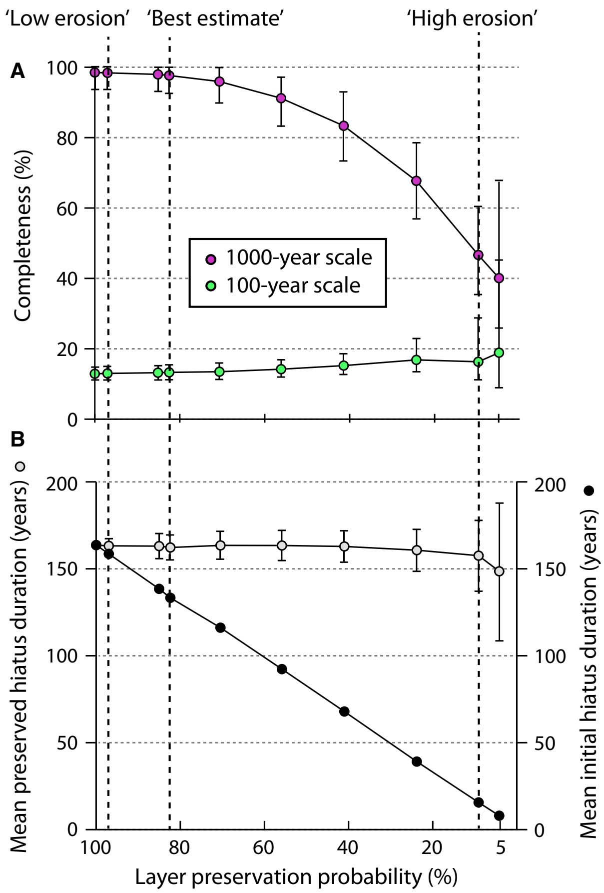


**Fig. 6.** (A) Summary of completeness statistics for model scenarios with varying layer preservation probability that reproduce a *ca* 75 cm Grey Shales Member-like succession of 220 ± 10 layers deposited in 36 000 years. Note how completeness at the 1000 year scale is sensitive to layer preservation probability, but that completeness at the 100 year scale is largely invariant to changing layer preservation probability. See main text for details. (B) Mean preserved hiatus durations and mean initial hiatus durations. Note how the mean preserved hiatus duration does not vary significantly with layer preservation probability. The mean initial hiatus duration (i.e. the mean recurrence time between layer depositional events) falls with decreasing layer preservation probability. This reflects the fact that with higher erosion (i.e. decreased preservation probability) more layers need to be initially deposited to ensure preservation of *ca* 220 layers. All models use exponentially distributed erosion depths and hiatuses, and all results are based on analysis of 1000 simulations for each layer preservation probability scenario. Error bars show the 95% uncertainty.

<50% (mean erosion depth >1·7 mm) more layers are eroded than preserved. Figure 6A shows how completeness at the 100 year scale is largely invariant to changes in layer preservation probability. At the 1000 year scale, however, completeness falls with decreasing layer preservation probability (Fig. 6A). The mean preserved hiatus duration remains broadly constant (*ca* 170 years) regardless of layer preservation probability (Fig. 6B). Conversely, the mean initial hiatus duration (i.e. mean recurrence time between initially deposited layers) falls with decreasing layer preservation probability (Fig. 6B). This reflects the fact that with higher erosion (i.e. decreased preservation probability) more layers need to be initially deposited within 36 000 years to ensure final preservation of *ca* 220 layers.

The assumption that the initial hiatus durations follow an exponential distribution is a key assumption that ostensibly influences the results shown in Figs 5 and 6. Although this is based on the expected Poisson distribution of modern storm recurrence, the authors lack any certainty that storms behaved in a similar way during the Jurassic. If storm events, and hence initial hiatuses, are instead uniformly distributed, the modelled completeness curves and preserved hiatus distributions are more complex (Fig. 7, cf. Fig. 5). Importantly, however, completeness results are largely unaffected by this difference in initial hiatus distribution, and are similar to the results presented in Figs 5C and 6 (Figs 7C and 8A). Equally, in the 'high erosion' scenario there is still the same tendency towards a power law distribution of preserved hiatuses (Fig. 7B). Similarly, completeness results from models that use uniformly distributed erosion depths rather than exponentially distributed erosion depths also do not differ significantly (Fig. 8B). Taken together, these results indicate that the precise statistical characteristics of erosion and hiatuses in the modelled successions have no significant impact on stratigraphic completeness.

A further potential uncertainty that could impact the modelled estimates of the completeness of the Grey Shales Member above is the overall duration of the succession. It has been suggested that the *ca* 75 cm cycles observed in the Yorkshire section represent *ca* 100 000 year eccentricity cycles, not *ca* 36 000 year obliquity cycles (Huang & Hesselbo, 2014). Using a 100 000 year timescale in the modelling increases overall hiatus durations, and thus alters the completeness statistics. In particular, for the 'best estimate' scenario in Fig. 5, the succession would be 2·7% and 64·2% complete at centennial and millennial timescales, respectively, if the studied interval spanned 100 000 years. Clearly, the millennial-scale completeness of the succession is lower compared to using a 36 000 year timescale (*ca* 34% lower), but this is still significantly higher than the completeness at centennial timescales (*ca* 80% lower).

## IMPLICATIONS FOR STRATIGRAPHIC RESOLUTION

The modelling shows how a range of very different layer preservation probabilities can all generate the same Grey Shales-like synthetic succession of *ca* 220 discrete layers spanning *ca* 75 cm. A key insight of the modelling is that it is possible to build a sedimentary succession like the Grey Shales Member under conditions where erosion dominates. It may not be possible from field observations alone to infer the amount of erosion that a succession has undergone, especially given the typical difficulty of identifying erosion and quantifying its extent. Importantly, however, none of the model scenarios yield completeness >20% at centennial scales. Thus, regardless of the amount of erosion, or indeed the distribution characteristics of erosion and hiatuses, the Grey Shales succession is a poor archive for centennial-scale geological processes and events.

In the absence of varves or unambiguous sub-millennial time markers (seasonal laminae, Schwabe cycles, etc.), a centennial-scale could be considered a reasonable bound on the attainable resolution of epicontinental mudrock successions. One hundred years is, in any case, close to or shorter than the timescale typically affected by thorough sediment mixing through bioturbation (e.g. Schiffelbein, 1984; Boudreau, 1998; Charbit *et al.*, 2002). It is also shorter than the likely residence time of many of the elements that are of use as palaeoclimatic proxies (Chester, 2003). In particular, 100 years is shorter than the time needed to transfer a global biospheric carbon-isotope signal (such as that recorded in the Grey Shales Member, Fig. 1) to the rock record (e.g. Sluijs *et al.*, 2012).

The completeness data calculated from the modelling have implications for the use of mudrock successions as high-resolution palaeoenvironmental archives. A standard procedure in high-resolution palaeoenvironmental studies is to sample a succession at regular, closely spaced

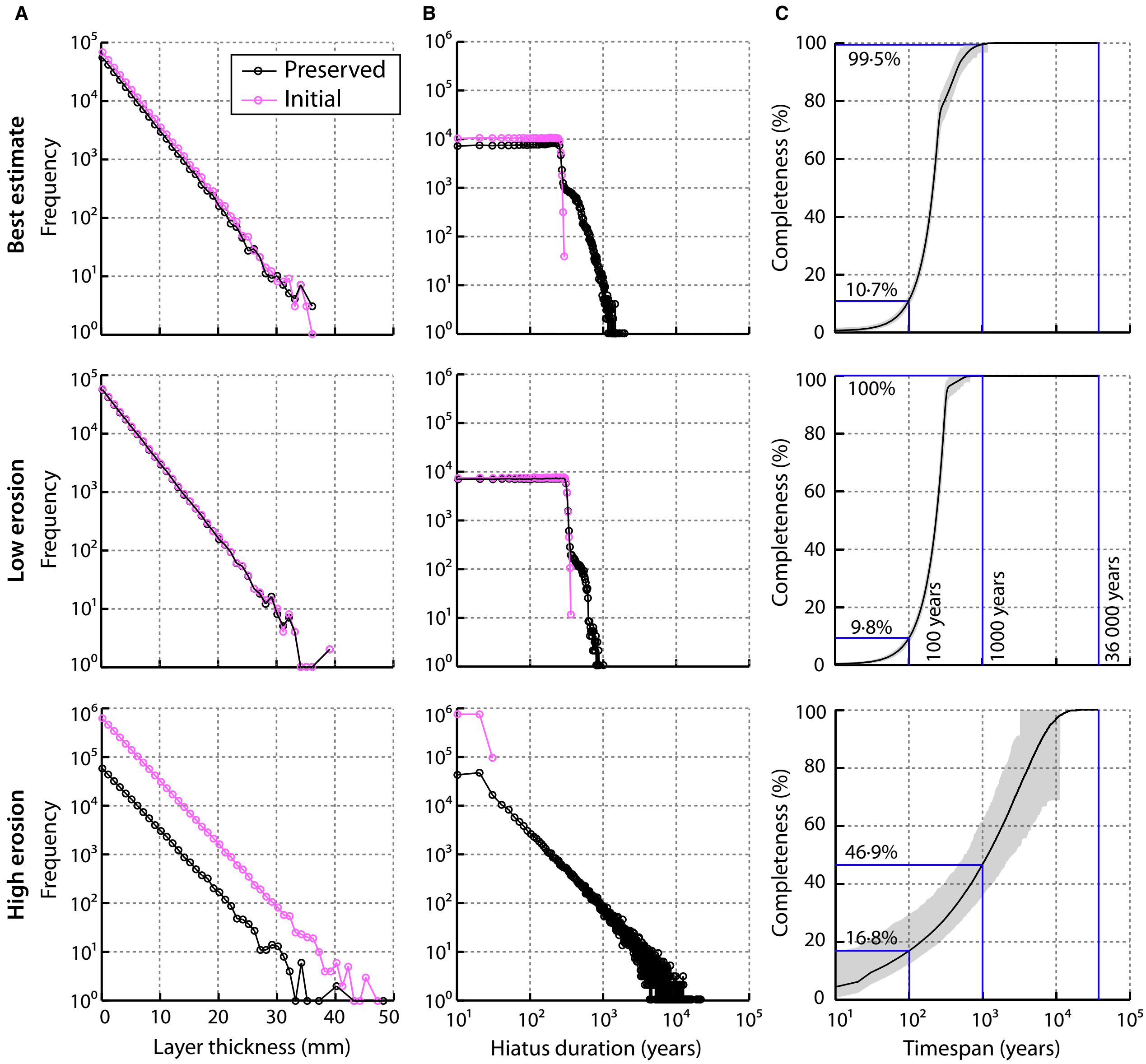


**Fig. 7.** (A) Thickness distributions; (B) hiatus distributions; and (C) completeness data for the three model scenarios shown in Fig. 5, but with uniformly distributed initial hiatuses used instead of exponentially distributed hiatuses. Note how the probability distributions of the initial hiatuses (purple data) are uniformly distributed (horizontal lines, except for a slight drop off at longer durations). Preserved hiatuses (black data) develop a more complex distribution. In the 'high erosion' scenario, this distribution tends towards a power law, just as in the 'high erosion' scenario shown in Fig. 5. Note how completeness at 100 year and 1000 year scales is broadly similar to Fig. 5 (grey shading is the 90% uncertainty envelope). All results are based on analysis of 1000 simulations for each model scenario.

intervals. The effective temporal resolution of the modelled successions can be explored by assessing variability in the ages of these samples. If sedimentation behaved as a perfect, continuous rain of material to the sea floor, thickness would be linearly related to time, and the ages of successive samples would increase evenly with no uncertainty. In the case of the modelled successions, and indeed real strata, however, the relationship is not linear (Huybers & Wunsch, 2004; Kemp & Sexton, 2014). Such distortions have important implications for accurately resolving climatic processes and events (e.g. Huybers & Wunsch, 2004).

Figure 9 shows the temporal resolution of hypothetical samples taken at sampling

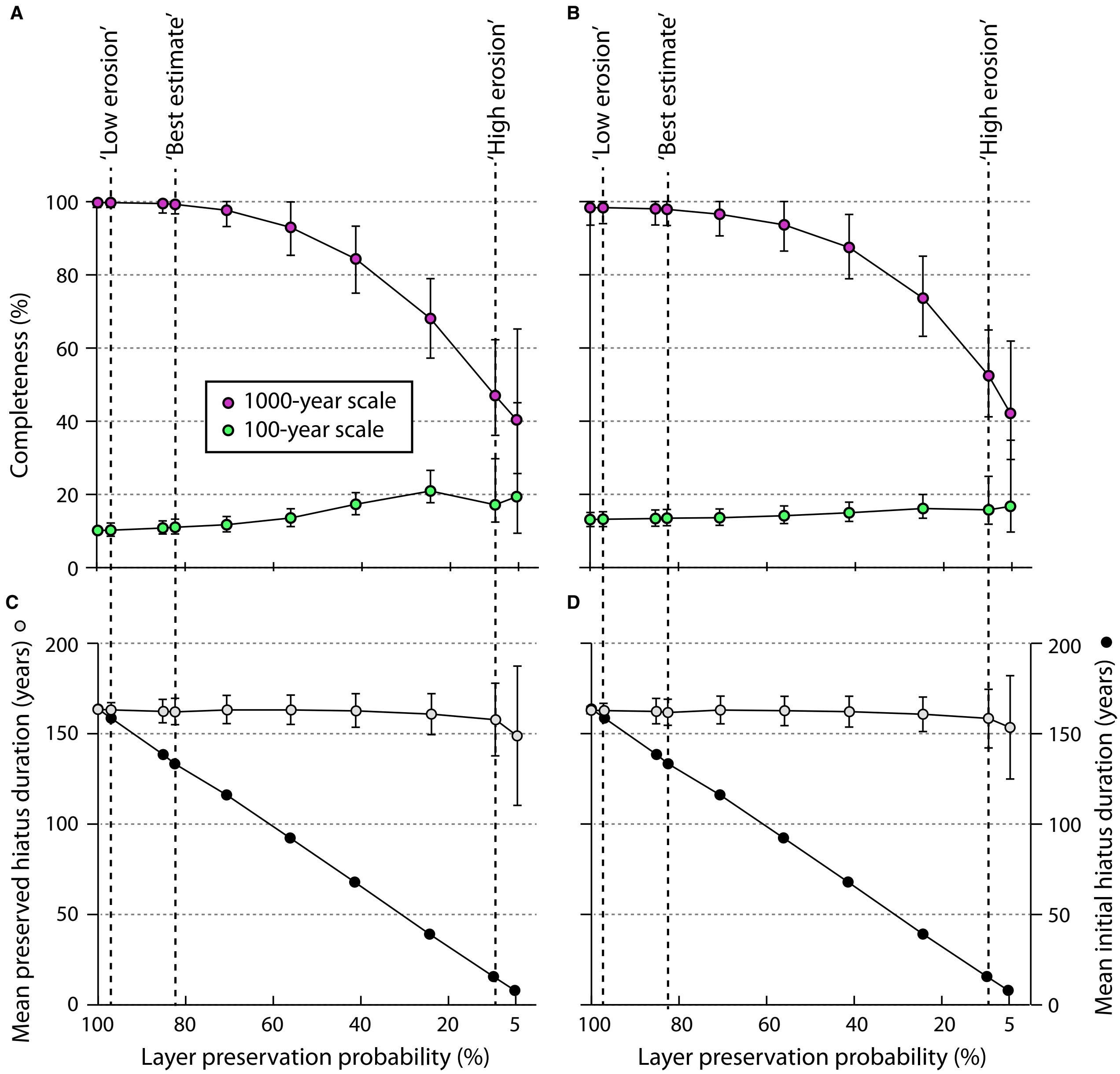


**Fig. 8.** Summary of completeness statistics for model scenarios with varying layer preservation probability: (A) shows results for model simulations that have uniformly distributed initial hiatuses and exponentially distributed erosion; (B) shows results for model simulations that have exponentially distributed initial hiatuses and uniformly distributed erosion. Note how the results are very similar, and also very similar to results in Fig. 6 (which used exponentially distributed initial hiatuses and erosion); (C) and (D) show corresponding hiatus statistics that also do not differ to the results in Fig. 6. All results are based on analysis of 1000 simulations for each layer preservation probability scenario. Error bars show the 95% uncertainty.

resolutions ranging from 1 to 25 cm from the model scenarios presented in Fig. 5. Temporal resolution is defined here as the mean age difference between successive samples taken from a succession. Thus, at a sampling resolution of 1 cm, the expected temporal resolution is 480 years because the long-term sedimentation rate of the succession is 75 cm in 36 000 years. Figure 9 also shows the 95% uncertainty envelopes on the mean sample age differences. For a succession built using the 'best estimate' erosion scenario (Fig. 9A), and using a sampling resolution of 1 cm, the mean temporal spacing of samples is *ca* 480 years as expected, but with a 95%

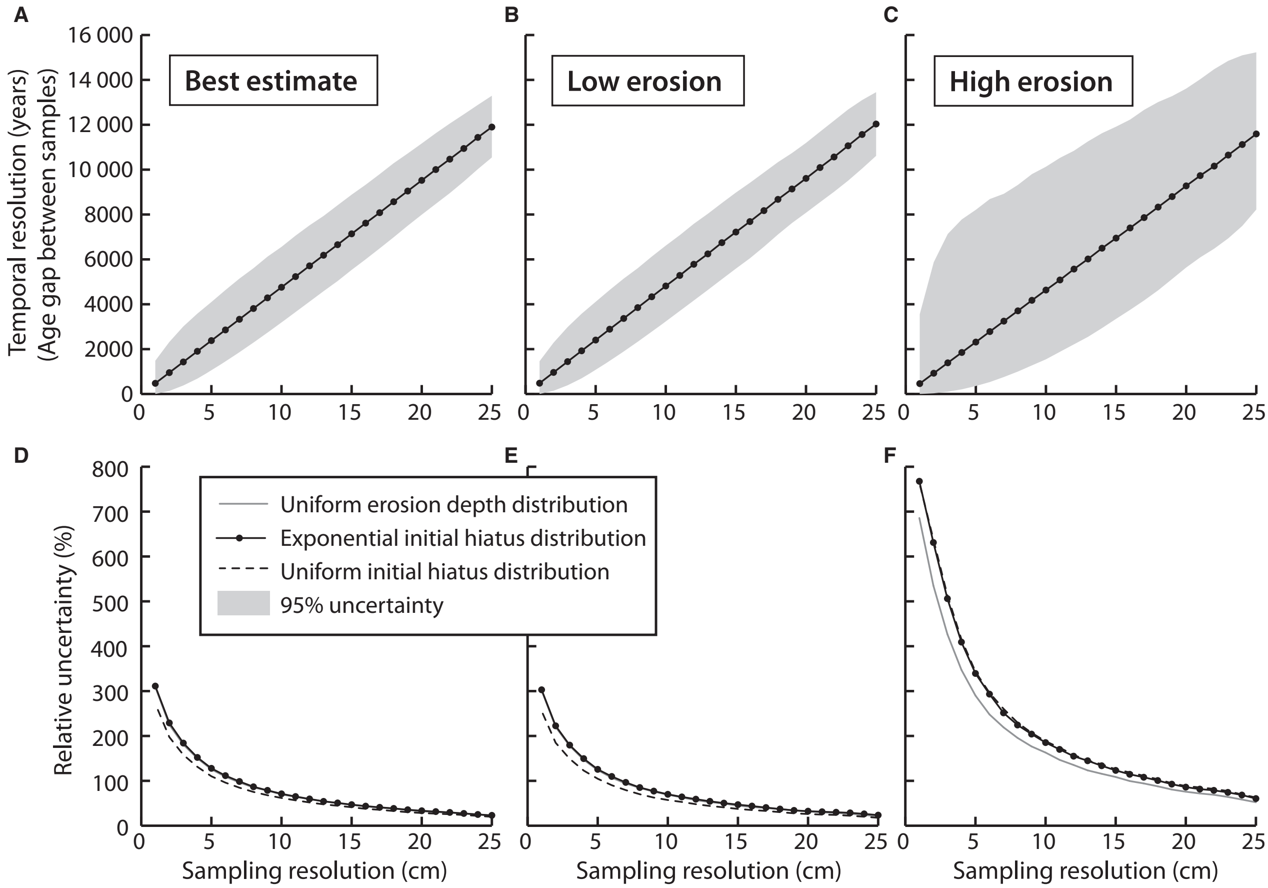


**Fig. 9.** Resolution data for the three model scenarios: (A) to (C) show the relationship between sampling resolution (the spatial gap between samples, in centimetres) and temporal resolution (i.e. the time gap between samples, in years). The grey shading shows the 95% uncertainty. Hence, sampling a succession modelled using the 'best estimate' scenario at a resolution of 1 cm means that the expected time gap between samples is 480 years, but with a 95% probability that the time gap is between two years and 1484 years (see also main text). (D) to (F) show the relative uncertainty, i.e. the 95% error envelope divided by the mean age gap (expressed as a percentage). Note how the relative uncertainty decreases with decreasing sampling resolution (increasing sample spacing). Also shown in (D) to (F) is the relative uncertainty for models that use uniformly distributed initial hiatuses, and uniformly distributed erosion (as in Fig. 8). All models use exponentially distributed layer thicknesses. Note how the choice of distribution for initial hiatuses and erosion has little impact on results, and indeed results using uniform erosion distribution and exponential initial hiatus distribution are so similar that these cannot easily be distinguished. See main text for details. All results are based on analysis of 1000 simulations for each scenario.

uncertainty spanning two to 1484 years (i.e. there is a 95% probability that the actual age gap between successive samples is between two years and 1484 years; Fig. 9A). The relative uncertainty (total uncertainty divided by mean temporal spacing) is *ca* 309% (Fig. 9D). At a sampling resolution of 20 cm, the temporal spacing of samples is 9600 years on average, with 95% of the data between 7993 years and 11 167 years (33% relative uncertainty, Fig. 9D). The results show how sampling a succession at higher resolution should yield more information, but the relative uncertainty in sample ages increases. In the case of the 'high erosion' scenario (Fig. 9C and F), uncertainty is very high. This is a consequence of the greater unsteadiness in sedimentation that results from higher erosion. The statistical distribution of erosion depths and hiatuses makes little difference to relative uncertainty (Fig. 9D to F).

For all of the scenarios shown in Fig. 9, the relative uncertainty versus sampling resolution plots demonstrate how relative uncertainty in temporal resolution broadly stabilizes at a sampling resolution of *ca* 5 to 10 cm (2400 to 4800 year mean temporal resolution, Fig. 9). In this regard, a sampling resolution of between 5 cm and 10 cm in the modelled Grey Shales succession does a reasonable job of balancing the benefits of getting more information with high-resolution sampling with the negative effects of reduced relative temporal precision. It can be interpreted as the approximate sample spacing that ensures a broadly linear relationship between stratigraphic height and time.

Importantly, these results are fairly robust even if the number of layers in the succession is underestimated. This could occur if very thin layers are missed by the outcrop scale analysis. If the actual number of layers in the 75 cm studied interval here was significantly underestimated, i.e. there were 420 layers, rather than 220, for example, then the mean layer thickness would be 0·18 cm. For the 'best estimate' scenario, completeness at the 100 year scale would be 32·6%, and at the 1000 year scale it would be 99·6%. Thus, the succession would still be a poor recorder of centennial-scale processes/events, and would remain a good recorder of millennial processes/events. Figure 10 shows that the relative uncertainty in temporal spacing of samples in a succession with 420 layers is lower than in the scenario with 220 layers, but only by *ca* 19%. Equally, the general trend to lower relative uncertainty with decreasing sampling resolution remains (Fig. 10B). This result helps to emphasise that completeness is not necessarily a measure useful for describing the 'resolution' of a succession. What matters most to someone interested in sampling and studying a succession is the relationship between the strata and time. A measure of percent completeness only partly, and indirectly, describes that relationship.

In light of the episodic nature of sedimentation in the Grey Shales Member, and the clear evidence for subaqueous erosion, Trabucho-Alexandre (2014) has considered the possibility that the abrupt negative carbon-isotope shifts in the Grey Shales and overlying Jet Rock members (Fig. 1, shifts at 0 m and −0·8 m) are artifacts caused by hiatuses (see also Them *et al.*, 2017). In reality, this interpretation is not tenable because: (i) the shifts are defined by multiple data points; (ii) the shifts do not interrupt trends of decreasing carbon-isotope values; and (iii) the shifts have been recognised across multiple basins (e.g. Hermoso *et al.*, 2012; Ruebsam *et al.*, 2014; Suan *et al.*, 2015; see also fig. 5 in Izumi *et al.*, 2018). Furthermore, the timing between these shifts in inorganic and organic carbon isotopes differ slightly in the same borehole record in the Paris Basin (Hermoso *et al.*, 2012), and this feature cannot result from a stratigraphic gap. Nevertheless, the modelling results presented here implicitly mean that the shifts (*ca* 8 cm each, Fig. 1 and Kemp *et al.*, 2005) are very likely to be interrupted by hiatuses that are ≥100 years in duration. The stratigraphic abruptness of the shifts is a poor guide to their actual temporal rapidity. An 8 cm interval of strata in

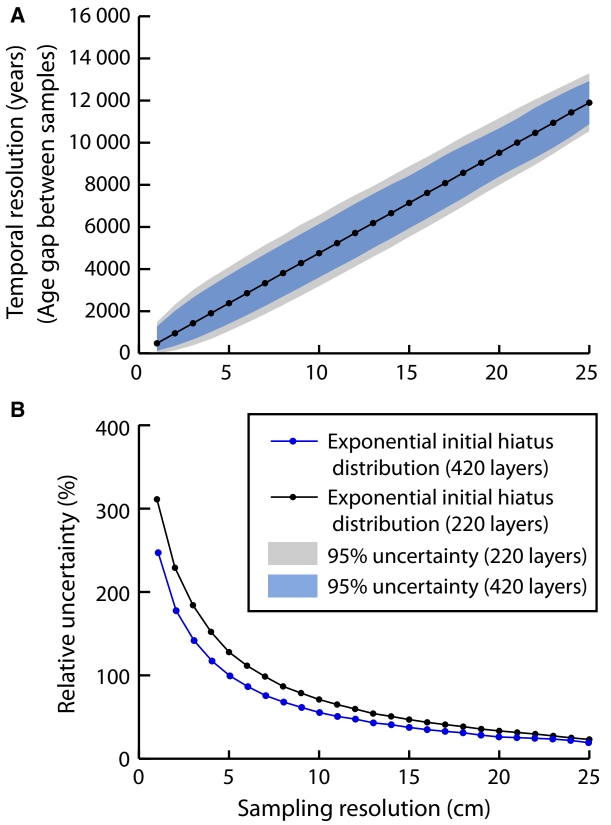


**Fig. 10.** Resolution data for the 'best estimate' scenario model using either 220 layers (black data, same result as in Fig. 9A and D) or 420 layers (blue data). These results highlight the effects of a possible miscounting (underestimation) of layers in the studied Grey Shales interval. (A) Shows the relationship between sampling resolution (the spatial gap between samples, in centimetres) and temporal resolution (i.e. the time gap between samples, in years). Note the slightly decreased uncertainty in the model using 420 layers (shading shows the 95% uncertainty). (B) Shows the relative uncertainty, i.e. the 95% error envelope divided by the mean age gap (expressed as a percentage). Relative uncertainty is slightly lower in the 420 layers data, but shows the same trend of falling relative uncertainty with increasing sample spacing. See main text for details. All results are based on analysis of 1000 simulations for each scenario.

the Grey Shales Member should represent *ca* 3800 years, but the 'best estimate' scenario data in Fig. 9A shows that an 8 cm interval of the Grey Shales Member could represent anywhere between 2300 years and 5600 years. In the 'high erosion' scenario, the duration is likely to be between 1000 years and 9300 years (Fig. 9C). This finding is similar to that of Kemp & Sexton (2014), who used a different model of sedimentation to make the case that abrupt events may last longer than estimated from stratigraphic thickness. Ultimately, this kind of uncertainty tempers the ability to deduce rates and durations of short-lived events in epicontinental mudrocks, even in largely unbioturbated successions.

## CONCLUSIONS

This study helps to demonstrate how advective mud transport and episodic accumulation impacts stratigraphic completeness in epicontinental mudrock successions. Sedimentation is certainly subject to more controls than the model accounts for, but this analysis makes it clear that it is possible to estimate completeness given accurate age constraints and knowledge of the depositional character of a succession. All of the models considered in this study are characterised by a sharp fall in completeness at sub-millennial timescales. This result is the same regardless of the precise statistical characteristics or amount of hiatuses, depositional events and erosion, or indeed the duration of the succession. Stratigraphic completeness is an indirect guide to the suitability of a succession for high-resolution sampling and palaeoenvironmental study, but the results suggest that epicontinental mudrock successions like the Grey Shales Member may be inherently unsuitable for resolving centennial-scale events and processes. This is despite the fact that deposition of the Grey Shales Member occurred under the somewhat idealized conditions of minimal bioturbation.

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