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A 56 million year rhythm in North American sedimentation during the Phanerozoic

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ABSTRACT

Long-term (>10 Myr) fluctuations in climate, sea-level and sedimentation have been documented in the stratigraphic record, but the lack of well-constrained data series has made it difficult to rigorously evaluate cyclic (periodic or quasi-periodic) changes at this scale. Here we utilize a new compilation of the coverage area of sedimentary rocks in North America to investigate the dominant modes ("orders") of stratigraphic variability, and to evaluate potential long-period cyclic changes in sedimentation on the continent during the Phanerozoic. Our analysis resolves two principal temporal modes of variability: (1) a strongly sinusoidal mode with a periodicity of 56 Myr +/− 3 Myr, and (2) a longer-term Phanerozoic mode (the "M-curve", linked to the Wilson cycle), which is indistinguishable from a stochastic autoregressive process. The newly identified 56 Myr cycle in sedimentation delineates most of the cratonic sequences that have previously been identified qualitatively in North America, but here we propose a quantitative redefinition that includes nine distinct units and two mega-sequences. The timing of the 56 Myr beat in sedimentation is consistent with an orogenic oscillator source or an oscillatory dynamic in mantle convection, and its tempo is statistically similar to a known rhythm in number of marine animal genera in the global fossil record. Thus, the identification of a significant periodic signal in the sedimentary record of North America provides new evidence for an important tectonic- and/or mantle-scale cyclic process that links both large-scale biological evolution and physical environmental change.

1. Introduction

Rhythmic changes in climate, sea-level and sedimentation are a prominent feature of the Neogene, fundamentally linked to interactions between orbital-insolation and cryosphere dynamics (Clark et al., 1999; Hays et al., 1976; Lisiecki, 2010; Zachos et al., 2001). Although longer-term (>10 Myr) fluctuations in climate, sea-level and sedimentation are known to occur (Haq et al., 1987; Kominz, 1995; Miller et al., 2005; Vail et al., 1977), the lack of well-constrained, high-resolution data on the character and extent of sedimentary rocks has prevented rigorous quantitative analysis of their cyclic temporal variability. In this study, we utilize the total coverage area of sedimentary strata, derived by macrostratigraphic analysis of the rock record of North America (Peters, 2006), to (1) extract the dominant modes ("orders") of stratigraphic variability, and (2) evaluate potential long-period cyclic changes in sedimentation during the Phanerozoic. This continent-scale record reflects both the production and preservation of sediments, factors that are governed by large-scale crustal deformation, mantle-controlled dynamic topography, global eustatic sea-level, and climate (Miall, 1997). Our novel approach to this research problem integrates emerging macrostratigraphic and cyclostratigraphic methods to provide a robust quantitative foundation for evaluation of the stratigraphic record.

2. Material and methods

A comprehensive macrostratigraphic database (Peters and Heim, 2010) consisting of 18,815 sedimentary rock units from 814 geographic locations in North America (Fig. 1) is used to estimate total sediment coverage area (A_{sed}), primarily based upon published correlation charts for the United States (Childs, 1985; Salvador, 1985) and Canada (Douglas, 1970). The database (accessible at http://macrostrat.geology.wisc.edu) includes most known rock units from both the surface and subsurface, and utilizes stage boundary ages from the most recent International Stratigraphic Chart (International Commission on Stratigraphy; http://www.stratigraphy.org/upload/ISChart2009.pdf). To determine the areal extents of sedimentary rock units, a Dirichlet tessellation (Fig. 1b) around each of the 814 stratigraphic column control points (Fig. 1a) is calculated using the Delaunay triangulation function in the 'deldir' package for R (R development core team, 2006). The spacing of columns and the resultant areas generally reflect the complexity of the geological record of that region, with continental margins having, on average, a closer packing of columns than the sediment-covered continental interior. In the absence of data to the contrary, we presume that the areal extent of rock units that occur in one column but not in an adjacent column extends half-way between the two.

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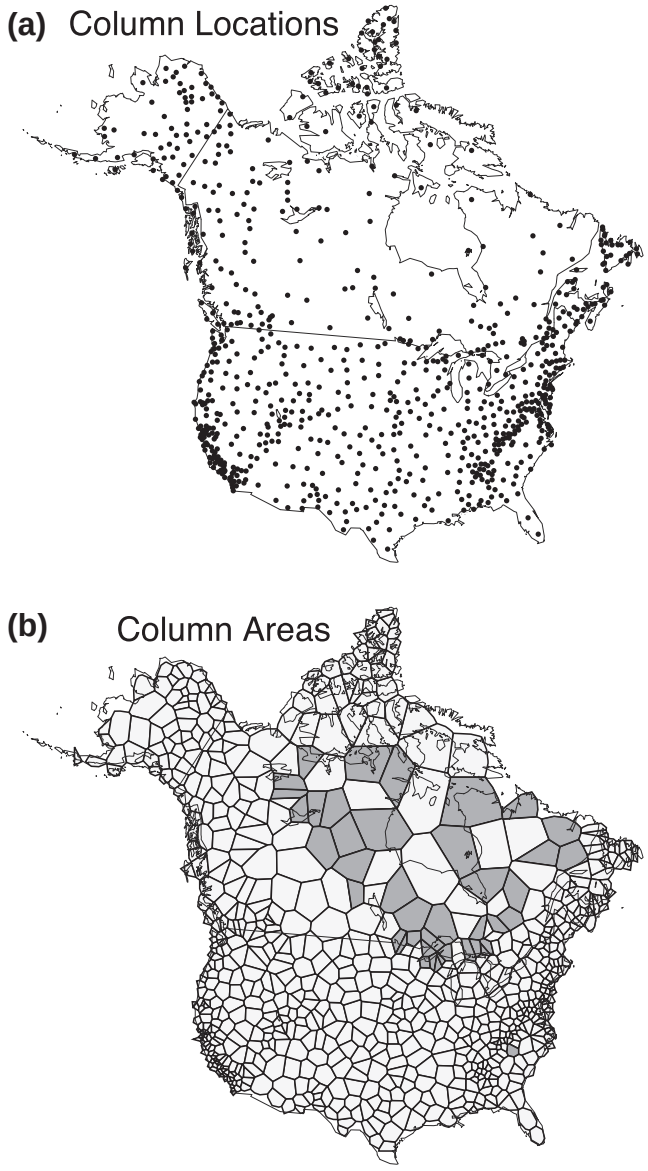

Fig. 1. Geographic distribution of sampling regions for macrostratigraphic analysis. a, Location of all 814 geologic column control points. b, Interpolated areas represented by each column. Dark polygons have no pre-Pleistocene sedimentary cover.

A_{sed} is estimated for each Phanerozoic time interval by summing the area of all polygons that preserve at least one sedimentary rock unit of that age. Our analysis of A_{sed}, which includes all terrestrial and marine sedimentary rocks that are present at both the Earth's surface and in the subsurface, is complimented by a preliminary assessment of the coverage area of marine strata (A_{mar}). We only tentatively interpret the A_{mar} data here, as its determination is complicated by uncertainties associated with the partitioning of marine and terrestrial deposits in the macrostratigraphy database (a subject of ongoing work). The A_{sed} and A_{mar} data series have an average sampling resolution of 6.6 Myr (+/−3.5 Myr, 1σ), and approximately 85% of the data are characterized by a sample spacing of ≤10 Myr. Neither A_{sed} nor A_{mar} indicates a significant correlation between area and temporal bin size (r^2 of 0.004 and 0.021, respectively), indicating that this is not a substantial source of bias. Both data sets are linearly interpolated to a resolution of 1 Myr prior to time series analysis, but to account for limitations of the original sampling resolution, all analyses are conservatively restricted to frequencies $<1/20\ Myr^{-1}$.

To evaluate the dominant modes of variability, and to test for cyclic changes in A_{sed} and A_{mar}, we apply three complimentary statistical approaches: multi-taper method (MTM) spectral analysis (Thomson, 1982), evolutive harmonic analysis (EHA; Meyers et al., 2001), and singular spectrum analysis (SSA; Ghil et al., 2002). MTM spectral analysis permits the identification and deconvolution of periodic, quasi-periodic and broadband stochastic noise variance (Mann and Lees, 1996; Meyers et al., 2008; Thomson, 1982). We evaluate the A_{sed} and A_{mar} power spectra against a stochastic red noise process, which is estimated by fitting an autoregressive [AR(1)] model to a log-transformed median smoothed version of the MTM power spectra (Mann and Lees, 1996). The red noise hypothesis test is supplemented with an independent MTM harmonic F-test for the identification of phase-coherent sinusoids (periodic components; Thomson, 1982). Frequency bands that exceed both the 99% red noise confidence level and 99% harmonic F-test confidence level provide strong confirmation of cyclic variability. To further investigate the persistence and temporal evolution of hypothesized cycles, time-frequency analysis (EHA) is applied to the A_{sed} and A_{mar} data series.

Singular spectrum analysis (SSA) is utilized to extract the dominant modes of variability within the "delay-coordinate" phase space for A_{sed} and A_{mar} (Ghil et al., 2002). This technique enables the identification of both oscillatory and non-oscillatory signals, and provides an objective approach by which to define multiple "orders" of stratigraphic variability. Of note, in contrast to Fourier and wavelet-based methods, SSA does not force decomposition of the data series to a prescribed basis set (e.g., sinusoids).

Our investigation of A_{sed} is paired with an assessment of macrostratigraphic truncation, initiation and turnover rates (Peters, 2006). These parameters are stratigraphic analogs of the commonly used paleobiologic metrics (Foote, 2000), where the fundamental unit is a "hiatus-bound" sedimentary package (see Peters, 2006). As in previous studies (Hannisdal and Peters, 2010), chronostratigraphic gaps are defined as time intervals that exceed the level of resolution employed by the compilation, which is approximately 1 to 3 Myr. Four classes of gap-bound packages can be recognized for any given stratigraphic interval: those confined to the interval (FL), those that only cross the bottom boundary (bL), those that only cross the top boundary (Ft) and those that cross both boundaries (bt) (Fig. 2; Hannisdal and Peters, 2010; Peters, 2006). Estimated macrostratigraphic rates assume a Poisson process for the probability of persistence across contiguous stratigraphic intervals, and thus are determined as (Foote, 2000; Peters, 2006):

$$\text{Truncation Rate} = -\ln(X_{bt} / (X_{bt} + X_{bL})) / \Delta t$$
$$\text{Initiation Rate} = -\ln(X_{bt} / (X_{bt} + X_{Ft})) / \Delta t$$
$$\text{Turnover Rate} = \text{Initiation Rate} - \text{Truncation Rate}$$

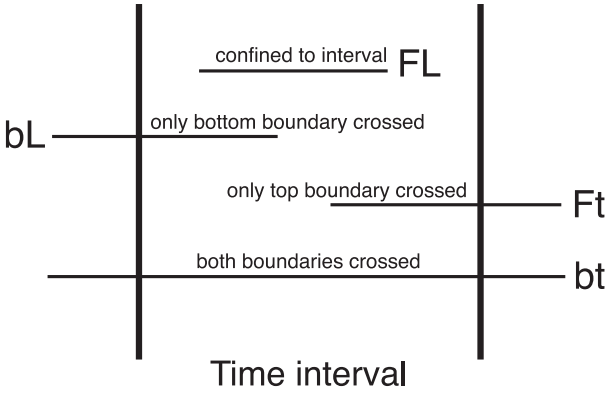

Fig. 2. Four classes of gap-bound packages can be recognized for any given stratigraphic interval: those confined to the interval (FL), those that only cross the bottom boundary (bL), those that only cross the top boundary (Ft) and those that cross both boundaries (bt). Figure adapted from Peters (2006).

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where Δt = time interval, X_{bt} = number of gap bound packages that cross both the lower and upper time interval boundaries, X_{bL} = number of gap bound packages that only cross the lower time interval boundary, X_{Ft} = number of gap bound packages that only cross the upper time interval boundary.

3. Results

MTM power spectral analysis indicates that most of the variance observed in the A_{sed} data series can be explained by a stochastic autoregressive model (at the 99% confidence level), with the exception of a region of power centered on a frequency of 1/56 Myr (Fig. 3c). MTM harmonic F-test results confirm the presence of a highly significant (>99.9% confidence level) phase-coherent sinusoid in A_{sed}, exhibiting a periodicity of 56 Myr (Fig. 3b). The variance attributable to this frequency component (gray area in Fig. 3c), once deconvolved from the A_{sed} power spectrum (Thomson, 1982), yields an estimate of the residual spectrum that is consistent with the autoregressive red noise model. The 56 Myr cycle accounts for 14% of the observed variance in the A_{sed} power spectrum (<1/20 Myr^{-1}), and uncertainty in its true periodicity is estimated to be 56 Myr +/− 3 Myr (+/−0.5 f_{ray}; f_{ray} = Rayleigh resolution). EHA of the A_{sed} record reveals the temporal evolution of this 56 Myr beat (Fig. 3d), which is persistent throughout most of the Phanerozoic, with the notable exception of a gap at approximately 325 Ma.

SSA extracts two dominant modes of variability in the A_{sed} data series: (1) a sinusoidal mode with variance concentrated at a frequency of ~1/56 Myr^{-1} (Fig. 3a and Fig. 4b), and (2) a longer-term Phanerozoic mode (Fig. 4a). Together, these modes of variability account for 95% of the variance in A_{sed} (Fig. 4c), with the 56 Myr oscillation (Fig. 4b) representing 19% of the total variance. Thus, the SSA results for the A_{sed} data series afford strong independent confirmation of the MTM and EHA results, and also corroborate a diminishment of the 56 Myr cyclic signal at ~325 Ma (Fig. 3). The SSA results further highlight a relatively diminished 56 Myr cyclic variability in A_{sed} during the Cenozoic.

Finally, comparison of the extracted 56 Myr rhythm (Fig. 4b) with the independently estimated macrostratigraphic rates (Fig. 4d) illustrates that most of the observed oscillations are associated with an increase in macrostratigraphic package initiation and/or truncation rate (asterisks in Fig. 4d). Based on these results, we conclude that the 56 Myr A_{sed} cycle is a consequence of changes in both package initiation and truncation rate, but the relative importance of these two distinct phenomena is variable. The highest magnitude package turnover rates (initiation-truncation; Fig. 4d) are observed at the Cretaceous–Paleogene boundary, the Permian–Triassic boundary, and the middle Ordovician (~465 Ma), all of which are preceded by pronounced negative turnover rates that reflect a reduction in the area of sedimentation. In total, these truncation, initiation, and turnover rate responses are diagnostic of geographic expansion of erosion/non-deposition (sea-level fall and "sequence boundary"

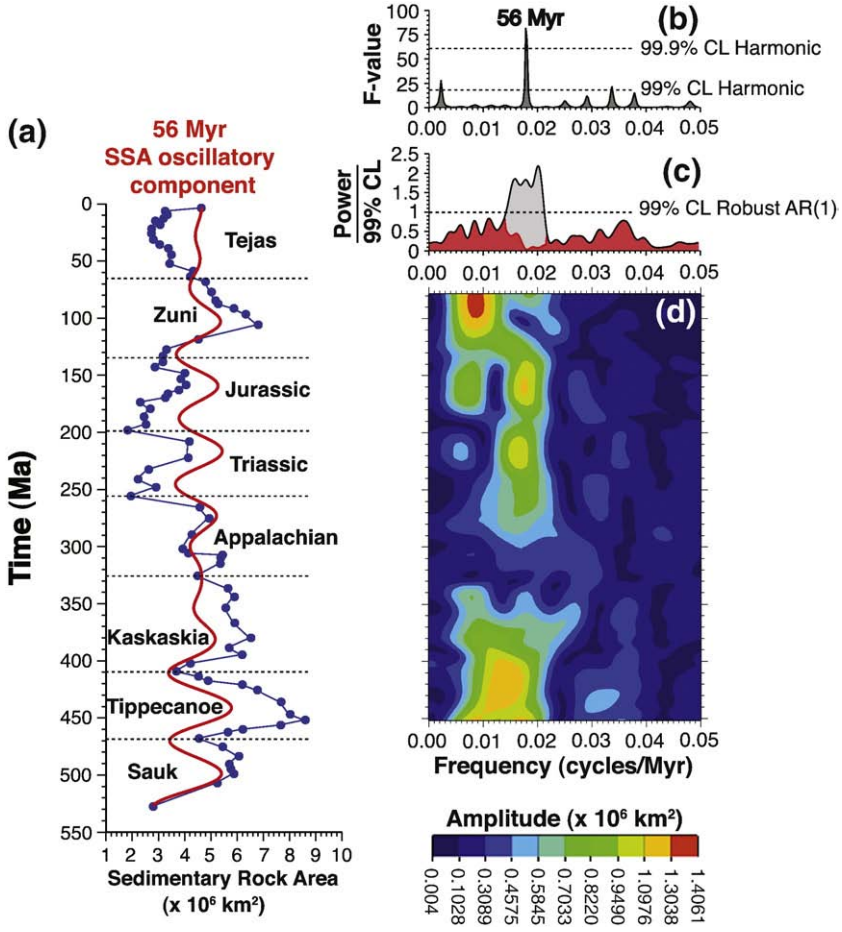

Fig. 3. Cyclic variation in North American sedimentation. a, Area of preserved sedimentary strata (A_{sed}) in North America during the Phanerozoic (blue), with North American sequences (Peters, 2008; Sloss, 1963) and a 56 Myr oscillatory component extracted using SSA (red). b, MTM harmonic F-test spectrum for A_{sed}, calculated using three 2π prolate tapers (Thomson, 1982). Dashed lines indicate the 99% and 99.9% confidence levels for F-values. c, MTM power spectrum for A_{sed}, calculated using adaptive weighting and three 2π prolate tapers (Thomson, 1982). Total power has been divided by the 99% confidence level for a robust AR(1) red noise model (Mann and Lees, 1996). Grey area indicates power attributable to the 56 Myr phase-coherent sinusoid identified in part b, following spectral reshaping (Thomson, 1982). d, EHA of A_{sed}, using three 2π prolate tapers and a 150 Myr moving window. A linear trend has been removed from each 150 Myr data window prior to harmonic analysis.

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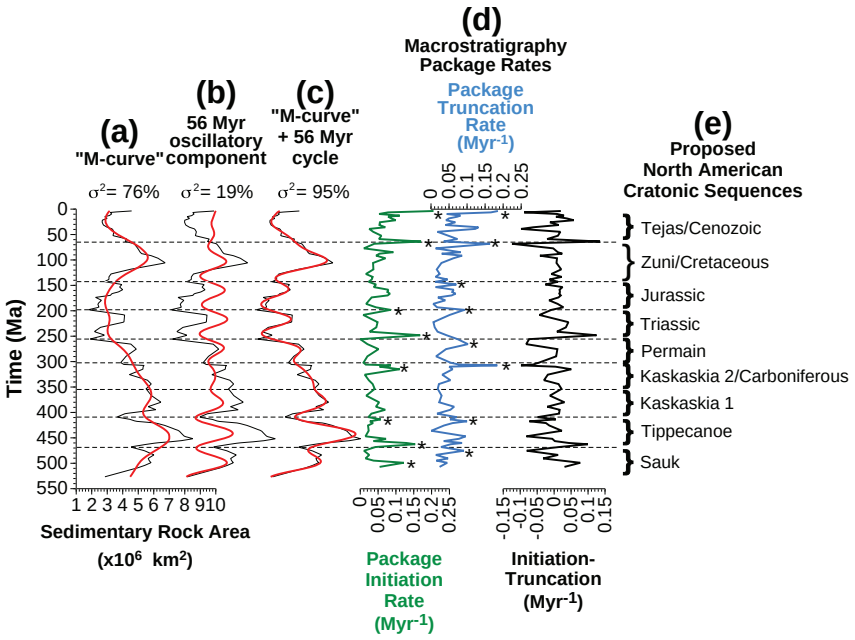

Fig. 4. Singular spectrum analysis (SSA) results for the A_{sed} data series, as compared to macrostratigraphy package rates. The A_{sed} data series is shown as a thin black line, and the SSA reconstructions are shown in red. SSA utilizes an embedding dimension of 80 with the Vautard and Ghil covariance estimator (Ghil et al., 2002), and extracts four dominant reconstructed components (RCs). a, RC 1 and RC 2 (combined), which comprise the long term Phanerozoic "M-curve". b, RC 3 and RC 4 (combined) constitute an oscillatory pair with variance concentrated at a frequency of ~1/56 Myr^{-1}. c, Total SSA reconstruction, which incorporates RC 1, RC 2, RC 3 and RC 4, and accounts for 95% of the variance in A_{sed}. d, Package initiation rate (green), package truncation rate (blue), and initiation rate-truncation rate (black), determined by macrostratigraphic analysis. Initiation and truncation rates are calculated according to the estimated per-package per million-year rate adapted from Foote (2000). e, Designation of major North American cratonic sequences based on macro-cyclostratigraphic analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

development) followed by sea-level rise and the restoration of sediment accumulation and preservation. This is in contrast to the Triassic/Jurassic boundary, for example, where truncation and initiation rate responses are characterized by a degree of covariation, indicating changing loci of deposition on the continent, but also a general reduction in the area of sedimentation (Fig. 4).

The Permian–Triassic and middle Ordovician turnover maxima noted above approximately coincide with minima in the 56 Myr A_{sed} cycle (Fig. 4). The lack of a strong 56 Myr A_{sed} minimum associated with the Cretaceous–Paleogene boundary is potentially due to the increased influence of terrestrial sediment during the Cenozoic (up to 72% of the area), in contrast to pre-Cenozoic sediments, which are dominated by marine strata (Peters, 2006; averaging 92% of the area). This hypothesis is supported by a separate analysis of the area of marine strata (A_{mar}), documented below, which indicates a ~55 Myr A_{mar} minimum associated with the Cretaceous/Paleogene boundary (Figs. 5 and 6).

Preliminary analysis of the coverage area of marine strata (A_{mar}), yields similar results, although generally of lower statistical significance (Fig. 5). The noisier nature of A_{mar} (relative to A_{sed}) may correctly characterize the nature of marine sedimentation on North America, or alternatively, it could be due to inaccuracies in the partitioning of marine and terrestrial deposits in the current version of the macrostratigraphic database. Given the present status of the A_{mar} data series, we tentatively identify a 55 Myr +/− 3 Myr (+/−0.5 f_{ray}) cycle that accounts for 8% of the variance observed in the A_{mar} power spectrum (<1/20 Myr^{-1}), a 55 Myr oscillatory signal extracted by SSA, constituting 13% of the A_{mar} variance (Figs. 5a and 6b), and a long-term Phanerozoic mode accounting for 83% of the A_{mar} variance (Fig. 6a). A notable distinction between A_{mar} and A_{sed} is the indication of a strong ~55 Myr SSA oscillation in marine sedimentation during the Cenozoic, and distortion (elongation) of the SSA oscillation during the "Zuni" cycle (compare Figs. 4b and 6b). Both A_{mar} and A_{sed} reveal a diminishment of the oscillatory signal centered on ~325 Ma. Minima in the ~55 Myr A_{mar} rhythm approximately coincide with maxima in package turnover rates observed at the Cretaceous–Paleogene boundary, the Permian–Triassic boundary, and in the middle Ordovician (Fig. 6).

4. Discussion

Building upon the previous work of Sloss (1963) and Peters (2008), our macro-cyclostratigraphic analysis of North America motivates a redefinition of the North American cratonic sequences. We propose nine individual ~56 Myr-long cratonic sequences (Figs. 4e and 6e), including four units previously defined qualitatively by Sloss (Sauk, Tippecanoe, Zuni/Cretaceous, Tejas/Cenozoic), two units previously defined by Peters (Triassic and Jurassic, which together comprise part of Sloss' Absaroka), and three new sequences (Kaskaskia 1, Kaskaskia 2/Carboniferous, Permian, which together comprise Sloss' Kaskaskia and part of the Absaroka). With the exception of Kaskaskia 1 and 2, each of these cratonic sequences is associated with an increase in macrostratigraphic package initiation and/or truncation rate (asterisks in Figs. 4d and 6d). Our proposed separation of Kaskaskia 1 and 2 is based on two criteria: (1) the observation of a strong ~56 Myr oscillation, extracted via singular spectrum analysis, which defines Kaskaskia 1 (Figs. 4b and 6b) and (2) the occurrence of a substantial change in the nature of sedimentation (from siliciclastic-dominated to carbonate-dominated) between Kaskaskia 1 and 2, which coincides with the Devonian/Carboniferous boundary (Peters, 2008).

Cycles in sedimentation of similar duration have also been identified in the European stratigraphic record spanning the upper Norian to middle Eocene (Smith and McGowan, 2005), supporting the hypothesis that the ~56 Myr oscillation in sedimentation may be global, and at least partially influenced by eustatic sea-level change. Additional evidence for a eustatic origin of sedimentation cycles comes from a complimentary analysis of the coverage area of marine strata in North America (A_{mar}), which exhibits a ~55 Myr oscillation (Fig. 5).

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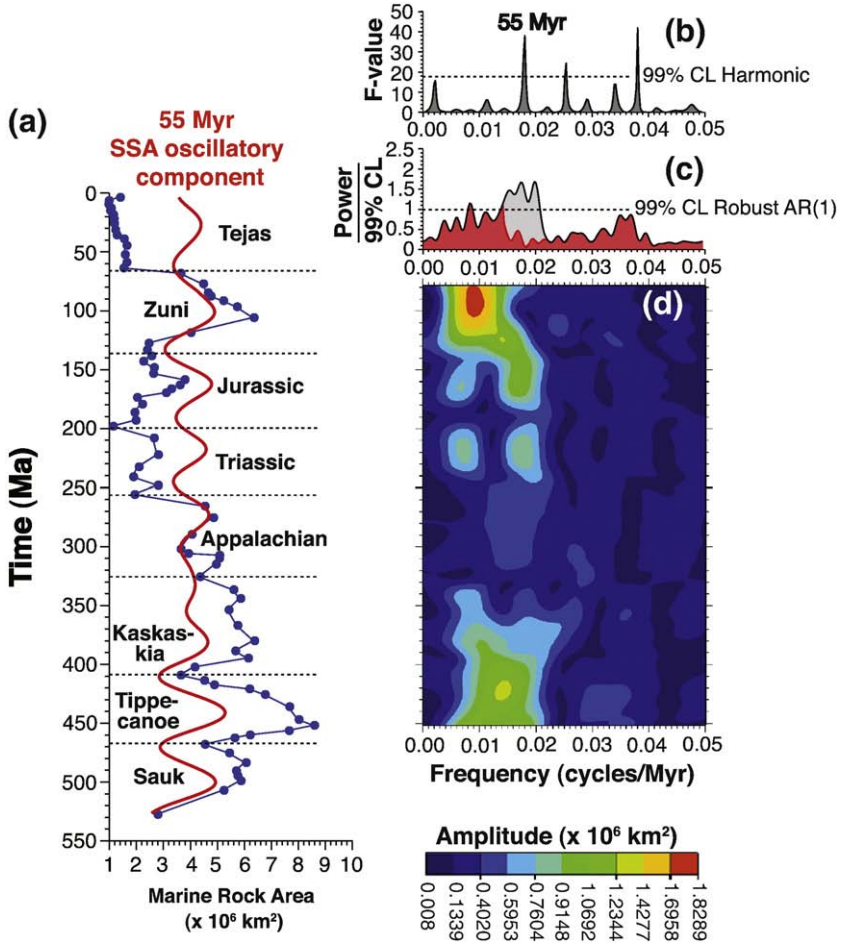

Fig. 5. Cyclic variation in North American marine sedimentation. a, Area of preserved marine strata (A_{mar}) in North America during the Phanerozoic (blue), with North American sequences (Peters, 2008; Sloss, 1963) and a 55 Myr oscillatory component extracted using SSA (red). b, MTM harmonic F-test spectrum for A_{mar}, calculated using three 2π prolate tapers (Thomson, 1982). Dashed line indicates the 99% the confidence levels for F-values. c, MTM power spectrum for A_{mar}, calculated using adaptive weighting and three 2π prolate tapers (Thomson, 1982). Total power has been divided by the 99% confidence level for a robust AR(1) red noise model (Mann and Lees, 1996). Grey area indicates power attributable to the 55 Myr phase-coherent sinusoid identified in part b, following spectral reshaping (Thomson, 1982). d, EHA of A_{mar}, using three 2π prolate tapers and a 150 Myr moving window. A linear trend has been removed from each 150 Myr data window prior to harmonic analysis.

The identification of a significant, long-period rhythm in the extent of sedimentation on the North American continent is a novel result that demands the presence of a large-scale oscillatory forcing mechanism. DeCelles et al. (2009) recently proposed such a mechanism for generating long-term cycles in orogenic activity, and this hypothesis may help to explain the origin of cratonic sequences (Sloss, 1963) and the quantitative periodic signal documented here. The orogenic oscillator hypothesis (DeCelles et al., 2009) invokes upper plate processes operating at ocean–continent convergent margins, and a ~50 Myr cycle in magmatic activity in the Sierra Nevada batholith is comparable to the ~56 Myr cycle we observe in the extent of sedimentation. A link between orogenesis and sedimentation is expected because crustal uplift and subsidence are one determinant of the extent to which sediments are delivered to and accumulate on continental crust. Importantly, the history of ocean–continent convergence in North America is dominated by east coast orogenesis during the Palaeozoic, and west coast orogenesis during the Mesozoic and Cenozoic, potentially yielding two geographically distinct oscillators. Diminishment of the ~56 Myr A_{sed} cycle during the Carboniferous could be the consequence of interference between an eastern (Acadian orogeny) and western (Antler orogeny) oscillatory forcing during this time.

Quasi-periodic mantle plume formation (Mjelde and Faleide, 2009; Prokoph et al., 2004; Ribe et al., 2007), hypothesized to occur based on experimental laboratory simulations (Schaeffer and Manga, 2001), represents an alternative mechanism for generating the observed ~56 Myr beat in North American sedimentation. Mantle plume formation is expected to influence sedimentation on the continents by forcing eustatic sea-level changes and by affecting the average freeboard of the continents. The link between mantle plume formation and continent-scale stratigraphic patterns would be further accentuated by climate interactions (Miller et al., 2005), whereby global warming due to increased rates of mantle degassing results in higher sea-levels (e.g., via ice sheet melting and thermal expansion) and wider areas of marine sedimentation on the continents.

A longer-term Phanerozoic mode in sedimentation (Figs. 4a and 6a), linked to the well-known "M-curve" or Wilson cycle of supercontinent coalescence and breakup (Heller and Angevine, 1985; Peters, 2008), is also identified quantitatively in these data. This important Phanerozoic mode defines two mega-sequences, one that spans the Palaeozoic and another that spans the Mesozoic/Cenozoic. Our analysis indicates that this signal is indistinguishable from a stochastic autoregressive process at the 99% confidence level (Figs. 3c and 5c), although the length of the data series limits our ability to detect oscillatory modes on such timescales. This result implies that the physical mechanism responsible for the supercontinent cycle and mega-sequence formation is potentially comprised of two components: (1) a Gaussian white-noise source (for example,

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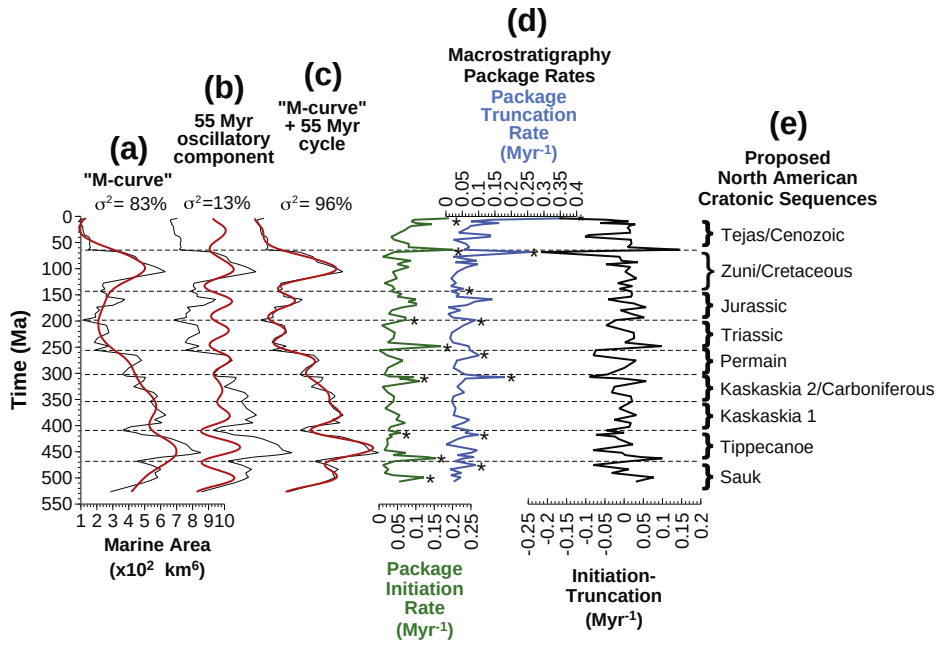

Fig. 6. Singular spectrum analysis (SSA) results for the A_{mar} data series, as compared to macrostratigraphy package rates. The A_{mar} data series is shown as a thin black line, and the SSA reconstructions are shown in red. SSA utilizes an embedding dimension of 80 with the Vautard and Ghil covariance estimator (Ghil et al., 2002), and extracts four dominant reconstructed components (RCs). a, RC 1 and RC 2 (combined), which comprise the long term Phanerozoic "M-curve". b, RC 3 and RC 4 (combined) constitute an oscillatory pair with variance concentrated at a frequency of ~1/55 Myr^{-1}. c, Total SSA reconstruction, which incorporates RC 1, RC 2, RC 3 and RC 4, and accounts for 96% of the variance in A_{mar}. d, Package initiation rate (green), package truncation rate (blue), and initiation rate-truncation rate (black), determined by macrostratigraphic analysis. Initiation and truncation rates are calculated according to the estimated per-package per million-year rate adapted from Foote (2000). e, Designation of major North American cratonic sequences based on macro-cyclostratigraphic analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

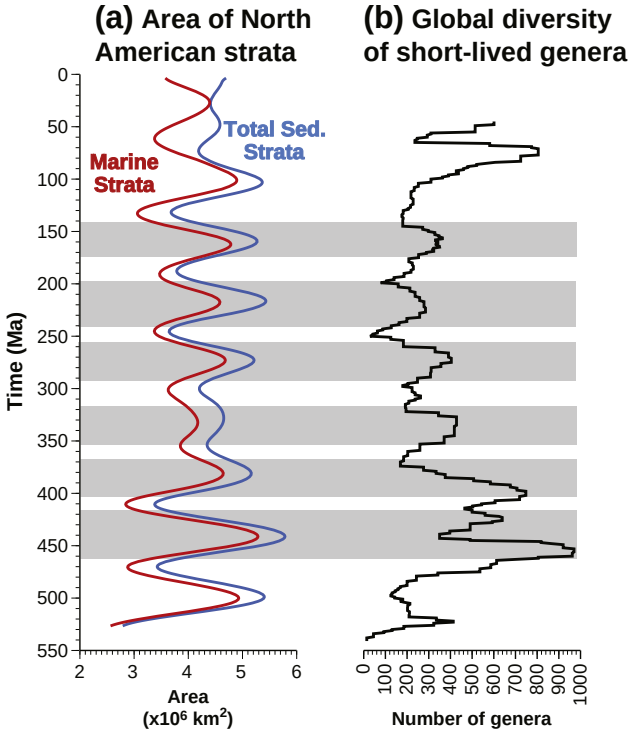

Fig. 7. Comparison of the ~56 Myr oscillatory signal extracted from the North American stratigraphic record, and global fossil biodiversity data. (a) The ~55 Myr SSA oscillatory component derived from A_{mar} (red line) and the ~56 Myr SSA oscillatory component derived from A_{sed} (blue line). (b) The diversity of short-lived genera during the Phanerozoic (Rhode and Muller, 2005). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

due to changes in heat production within the core), and (2) an Earth system component/interaction with the appropriate memory time-scale (response time) to integrate the white-noise, producing the observed "M-curve".

In addition to yielding insight into the characteristics of North American stratigraphic sequences and the nature of cyclic controls on sedimentation on the continents, our results have important implications for the Phanerozoic record of biologic diversity. Previous work has identified a pronounced 62 Myr +/−3 Myr cycle in the number of marine genera (Rhode and Muller, 2005), which is statistically similar to the 56 Myr +/−3 Myr A_{sed} cycle that we observe in North American sedimentation (Fig. 7). Thus, cyclical variation in global diversity is likely to be either the consequence of a fossil preservation bias (Peters and Foote, 2001; Smith, 2001; Smith, 2007; Smith and McGowan, 2007), or, more likely, related to global environmental changes that are directly (Hallam, 1989; Johnson, 1974; Newell, 1952; Sepkoski, 1976; Simberloff, 1974) or indirectly linked to the expansions and contractions of epicontinental seas (Hallam and Wignal, 1999; Peters, 2008). The strong covariation of sedimentologic and faunal records during the Phanerozoic is further underscored by the coincidence of many North American cratonic sequences with geologic system boundaries, most of which were originally defined on the basis of biological turnover, but that also occur in phase with a prominent, but as-yet poorly understood, large-scale rhythm in our planet.

5. Conclusions

In this study, we apply emerging macrostratigraphic and cyclostratigraphic methodologies to quantitatively evaluate temporal modes ("orders") of stratigraphic variability across the North American continent during the Phanerozoic. Macrostratigraphic

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analysis provides an estimate of the total coverage area of sedimentary strata (surface and subsurface), as well as quantitative measures of the underlying processes that generate the observed stratigraphy (rates of initiation and termination of sedimentary packages). Quantitative cyclostratigraphic methods provide the opportunity to objectively identify stratigraphic "orders" in the macrostratigraphic data, and permit the deconvolution of deterministic sinusoidal modes from stochastic variability.

Analysis of the total coverage area of sedimentary strata (terrestrial + marine) identifies two prominent modes: (1) a strongly sinusoidal mode with a periodicity of 56 Myr +/−3 Myr, and (2) a longer-term Phanerozoic mode (the "M-curve" or Wilson cycle), which is indistinguishable from a stochastic autoregressive process. Similar temporal modes are obtained from an analysis of the coverage area of marine sedimentary strata during the Phanerozoic. Based on these results we propose a quantitative redefinition of the North American cratonic sequences, with nine distinct units (Sauk, Tippecanoe, Kaskaskia 1, Kaskaskia 2/Carboniferous, Permian, Triassic, Jurassic, Zuni/Cretaceous, and Tejas/Cenozoic) and two mega-sequences (Palaeozoic and Mesozoic/Cenozoic).

The ~56 Myr beat in North American sedimentation is statistically similar to a known rhythm in number of marine animal genera in the global fossil record, indicating either a fossil preservation bias that impacts observed biodiversity, or an intimate linkage between sea-level and environmental conditions that influence biodiversity. The source of this ~56 Myr rhythm remains uncertain, but it must ultimately derive from a tectonic- and/or mantle-scale cyclic process. Importantly, these results suggest a unified oscillatory mechanism that links North American cratonic sequences, geodynamics, and changes in observed biologic diversity, throughout the Phanerozoic.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.epsl.2010.12.044.

The Supplementary data are available in two separate EXCEL files. The first is designated as "Electronic Appendix 1" and contains Macrostratigraphic data for total sedimentary strata. The second is designated as "Electronic Appendix 2" and contains Marcrostratigraphic data for marine sedimentary strata.

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