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Sediment cycling on continental and oceanic crust

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ABSTRACT

Sedimentary rocks are often described as declining in quantity with increasing age due to the cumulative effects of crustal deformation and erosion. One important implication of such a model is that the geological record becomes progressively less voluminous and less complete with increasing age. Here we show that the predictions of a model in which the destruction of sedimentary rock is the predominant process signal are borne out only among sediments deposited on oceanic crust and among sediments deposited above sea level in non-marine environments. Most of the surviving volume of sedimentary rock (~75%) was deposited in and adjacent to shallow seas on continental crust and does not exhibit any steady decrease in quantity with increasing age. Instead, shallow marine sediments exhibit large fluctuations in quantity that were driven by shifting global tectonic boundary conditions, such as those that occur during the breakup and coalescence of supercontinents. The accumulation of sediments on the continents has not been uniform in rate, but it does record a primary signal of net growth that has many implications for the long-term evolution of Earth's surface environment.

INTRODUCTION

Exponential decrease in surviving quantity with increasing age is a basic prediction of any model in which sediments, once deposited, are subjected to a continuous random probability of destruction. Among the first studies to present quantitative data on the surviving quantities and ages of sediments suitable for testing and calibrating such a model were Gregor (1968) and Garrels and Mackenzie (1969). Both depended upon comprehensive global Phanerozoic rock volume compilations of Alexander Ronov (Ronov et al., 1980). Notably, because Ronov's global sediment volume compilations prior to 1970 included only the Devonian through Jurassic, Gregor (1968, 1970) augmented Ronov's volumetric data with geological map–based estimates for the Cretaceous–Cenozoic. The key pattern to emerge was that the quantity of sedimentary rock is greatest in the geologically recent and decreases approximately exponentially with increasing age. Subsequent studies (e.g., Veizer and Jansen, 1979; Blatt and Jones, 1975; Garrels et al., 1976; Gilluly, 1969; Hay et al., 1989; Wilkinson and Walker, 1989; Wold and Hay, 1990; Wilkinson et al., 2009) have elaborated upon this work, often using the same data, and all have similarly found that total sedimentary rock quantity declines with increasing age, either in an uninterrupted exponential fashion, or with minor increases in rates of sedimentation superimposed on a dominant signal of long-term decay (Garrels and Mackenzie, 1971a, 1971b; Mackenzie and Pigott, 1981).

Here we use comprehensive surface and subsurface data in North America as well as regional and global geological maps to show that decreasing sedimentary rock quantity with increasing age is not a prevalent pattern in the sedimentary rock record. Instead, the sedimentary record has at least three distinct components—non-marine sediment, deep-marine sediment deposited on oceanic crust, and shallow marine sediment deposited on continental crust. Only the first two contain strong signals of rock destruction that manifest as decreasing quantity with increasing age.

DATA SETS

Surface and subsurface data derive from the Macrostrat database (https://macrostrat.org; Peters, 2006, 2008; Heim and Peters, 2011; Meyers and Peters, 2011; Hannisdal and Peters, 2011; Peters and Gaines, 2012; Peters et al., 2013). The geological map data are from two sources: the Geological Survey of Canada (GSC) global geological map of the world (https://mrdata.usgs.gov/geology/world/) (Figs. DR1 and DR2 in the GSA Data Repository[1]) and the Geologic Map of North America (GMNA; Garrity and Soller, 2009; Fig. DR3). The GSC map consists of 7705 polygons covering 146×10^6 km^2. Each polygon is assigned to one of eight generalized lithologies; sedimentary rocks are 61% of the total area. The GMNA was clipped to the region covered by Macrostrat (Figs. DR2 and DR3A) and comprises 25,880 polygons covering 24×10^6 km^2. There are 52 lithology types assigned to GMNA polygons; sedimentary deposits and sediment-associated volcanics cover 71% of the area (68% of the Macrostrat-clipped GSC map is sedimentary).

A total of 1013 Macrostrat columns containing 22,282 sedimentary rock units and covering 26×10^6 km^2 in North America and the circum-Caribbean region (Fig. DR2) were used to estimate surface and subsurface sedimentary rock quantities and to constrain environments of deposition, the latter of which were identified using multiple sources (as in Rook et al., 2012). Data compiled from 132 offshore drilling sites (Peters et al., 2013; Fraass et al., 2015) were also used. To allow direct comparisons between continental and oceanic crustal records, we measure sedimentary rock quantity as the proportion of Macrostrat columns with strata of a given age. This quantity is positively correlated with sedimentary rock volume and area in the continental data (first differences, Spearman's $\rho = 0.38$ and 0.66, respectively, $p < 2 \times 10^{-16}$).

RESULTS

Sedimentary rock quantity, measured as the proportion of Macrostrat columns that contain strata of a given age (Fig. 1), is highest in the most recent time interval (1 Ma) and lowest in the oldest time interval (2500 Ma). Thus, in the most general sense, there is a decline in sedimentary rock quantity with increasing age. However, an exponential fit ($y = 0.16e^{-0.001t}$) provides a poor description of the data. Residuals are not normally distributed (Shapiro-Wilk test, $P = 5 \times 10^{-16}$), and the time series of residual sedimentary rock quantity is similar to that of the original data (Fig. 1, inset). The reason for the poor fit is that all of the decrease in sedimentary rock quantity occurs during two relatively brief intervals of time: (1) the Quaternary (0–2 Ma) and (2) at the beginning of the Paleozoic (ca. 410–550 Ma). The latter has been identified as a major transition in sedimentation on the continents that is marked by the Great Unconformity (Peters and Gaines, 2012). Chronostratigraphically above this surface there is a large volume of Phanerozoic sedimentary rock (~110×10^6 km^3) that exhibits little temporal trend in quantity from ca. 10 to 500 Ma; below this surface there is a comparatively small amount of Proterozoic sedimentary rock (~30×10^6 km^3) which also displays little temporal trend in quantity over 1.9 b.y. (ca. 600–2500 Ma). Instead, within each eon there are temporal variations, the longest-period component of which in the

[1]GSA Data Repository item 2017095, graphical representations of spatial data used here, and data contained in the main figures, is available online at http://www.geosociety.org/datarepository/2017/, or on request from editing@geosociety.org.

Data Repository item 2017095 | doi:10.1130/G38861.1

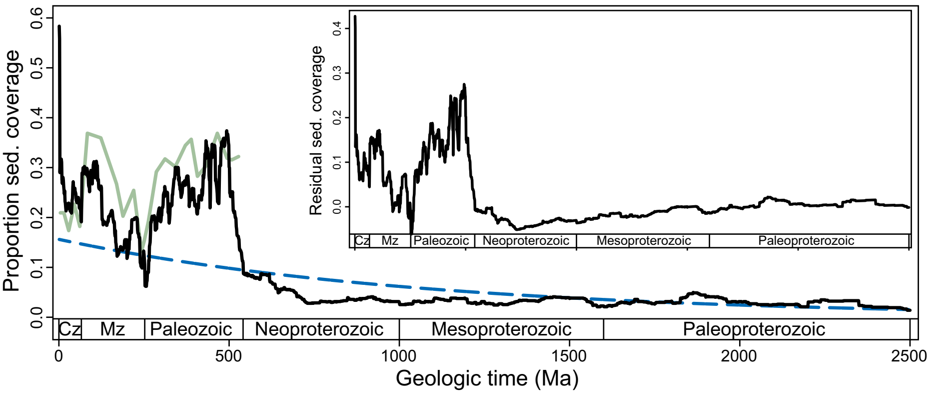

Figure 1. Proportion of Macrostrat database (https://macrostrat.org) columns with sedimentary (sed.) deposits versus geologic age (Cz—Cenozoic; Mz—Mesozoic). Green line in Phanerozoic shows proportion of total continental area covered by sedimentary deposits in Ronov et al. (1980) global compilation. Exponential fit is shown by dashed line. Inset shows residuals of sedimentary rock coverage on exponential fit plotted versus time.

Phanerozoic has been attributed to the supercontinent breakup-coalescence cycle (Meyers and Peters, 2011).

Sediments deposited on oceanic crust (deep sea; Fig. 2A) are widespread in the most recent time interval and decline in coverage with increasing age; an exponential fit provides a good description of the data ($y = 0.84e^{-0.023t}$; $R^2 = 0.86$; Shapiro-Wilk test of normality for log residuals from 0 to 145 Ma, $P = 0.06$) and suggests a half-life of 30 m.y.

Non-marine sedimentary deposits, which constitute <25% of the total Macrostrat epicontinental sedimentary rock volume, also decrease in quantity with increasing age (Fig. 2B). An exponential fit from the recent through the Silurian (443 Ma) is a reasonable description of the data ($y = 0.14e^{-0.007t}$; $R^2 = 0.71$; Shapiro-Wilk test of normality for log residuals through the Devonian, $P = 0.02$) and indicates a half-life of 99 m.y. However, the most recent 2 m.y. have large positive residuals, and non-marine sediments occur in varying but comparatively small quantities all the way back to 2500 Ma, making any exponential fit to all the data less satisfactory.

Shallow marine sediments deposited on continental crust (Fig. 2C) show no exponential decrease in quantity with increasing age ($y = 0.15e^{-0.001t}$; Shapiro-Wilk test of normality for log residuals, $P < 2.2 \times 10^{-16}$, residuals similar to original data, as in Fig. 1 inset). Instead, there is an overall increase in shallow marine sedimentary rock coverage with increasing age from the recent to an all-time high in the early Paleozoic (ca. 490 Ma). From this peak, there is a large and steady decrease until the start of the Paleozoic (541 Ma). From ca. 650 Ma to the beginning of the Proterozoic, there is little trend. Instead, sedimentary rock coverage varies on a time scale that is comparable to that of the primary mode of variability in the Phanerozoic (i.e., the supercontinent cycle). Because shallow marine sediments constitute the bulk of the volume of the sedimentary carapace (~75%), the time series of shallow marine sediment (Fig. 2C) does not differ markedly from the combined data (Fig. 1).

The GMNA and GSC maps, both clipped to the North American and Caribbean region covered by Macrostrat, yield similar patterns of rock area versus age (Fig. 3), and both are correlated with Macrostrat-derived area estimates (Spearman's ρ = 0.77 for both; Fig. DR4). The entire global GSC map, by contrast, indicates a large, approximately exponential decrease in sedimentary rock area with increasing age.

The large discrepancy in the temporal trajectory of sedimentary rock quantity on the global geological map versus the North America geological maps (Fig. 3) and Macrostrat (Fig. 1) raises the possibility that North America is not a representative sample of the continental crust. However, the weight of evidence suggests otherwise. Scaling Macrostrat's sedimentary rock volume up to a global estimate, based on its proportional sampling of global continental area (~5.6× to 6.8×, depending on whether submerged or exposed continental area is used), yields a predicted Phanerozoic volume of 617–749 × 10^6 km^3, which brackets the Ronov et al.

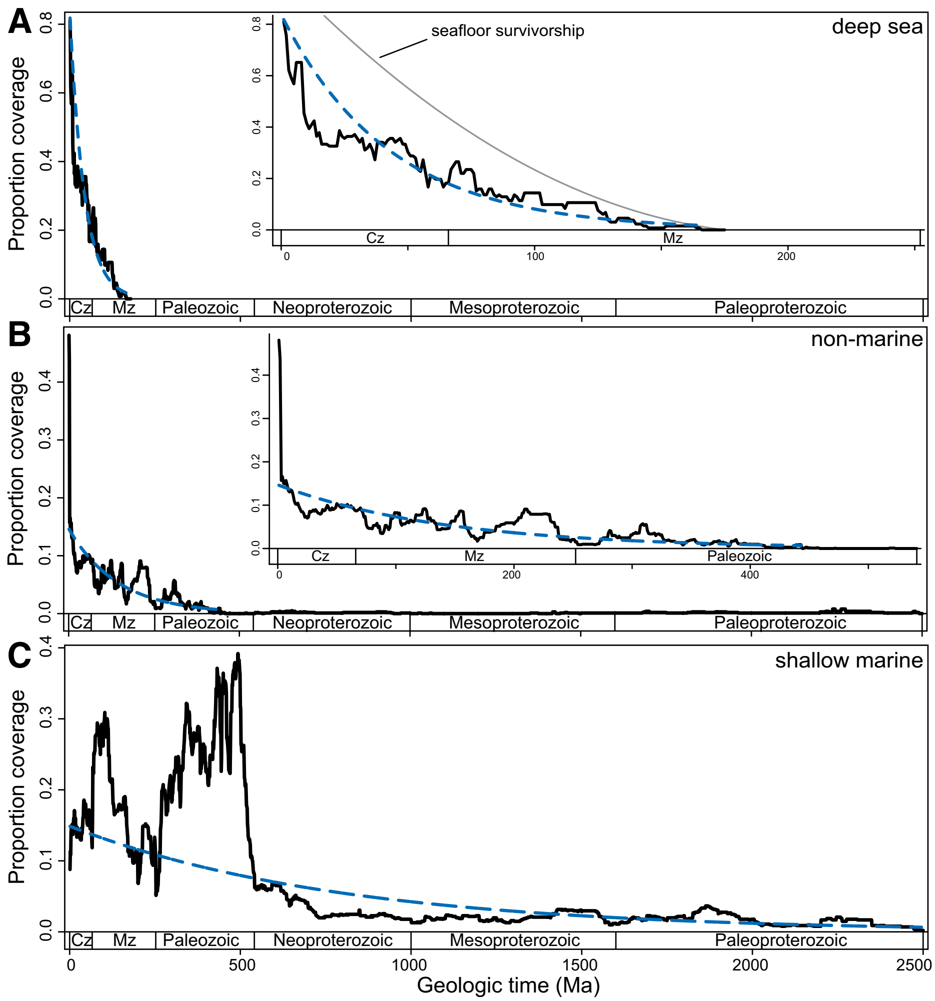

Figure 2. Macrostrat database (https://macrostrat.org) sedimentary rock quantity, as in Figure 1, partitioned into tectonic and environment subsets (Cz—Cenozoic; Mz—Mesozoic). A: Deep sea. B: Non-marine. C: Shallow marine. Dashed lines show exponential fits to data. Insets in A and B show same data as main panel, but on expanded *x*-axis. Solid line in A labeled "seafloor survivorship" is from Rowley (2002).

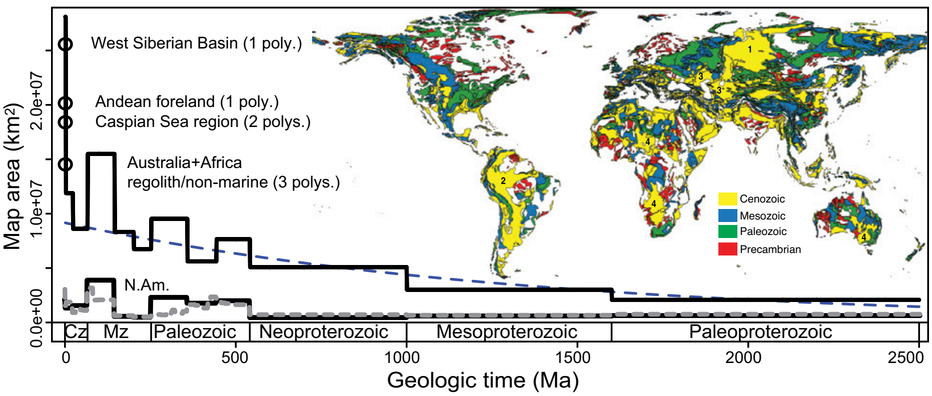

Figure 3. Top: Sedimentary rock area versus age from global geological map (https://mrdata.usgs.gov/geology/world/) (top dark curve). Cz—Cenozoic; Mz—Mesozoic. Best-fit exponential fit is shown by blue dashed line. Labeled points show estimate in final 1 m.y. that is obtained by sequentially subtracting each component (poly., polys.—polygon, polygons). Bottom: Lower two lines labeled "N.Am." show sedimentary rock area from global map (dark line) and Geologic Map of North America (Garrity and Soller, 2009) (gray dashed line) clipped to same region as Macrostrat database (https://macrostrat.org) (Fig. DR3 [see footnote 1]).

(1980) global volume estimate of ~630 × 10^6 km^3. More importantly, Ronov's Phanerozoic, epoch-level estimates of global sedimentary rock area, expressed as the proportion of total continental area (~1.7 × 10^8 km^2) covered by sedimentary rock, yields estimates that are close to that of North America, both in an absolute sense (Fig. 1) and when the volumetric data are binned and detrended by taking first differences and North America is removed from Ronov's tabulation (Spearman's ρ on first differences, with changes in interval duration held constant, is 0.47, P = 0.04). The Precambrian record is not included in Ronov's tabulation, but geological map data also suggest that North America is representative; the region (Fig. DR4B) covers ~15% of the total continental area and contains ~18% of the total global Precambrian sedimentary rock map area (Fig. DR1).

DISCUSSION

Ever since Charles Darwin described the geological record as gap riddled and decreasing in completeness with increasing age, geologists have viewed erosion and recycling of sediments as a dominant process that has overprinted the sedimentary rock record. However, the only data that exhibit the approximately exponential decrease in sediment quantity with increasing age predicted by this scenario are those of deep-sea sediments (Fig. 2A), non-marine sediments (Fig. 2B), and when global sediment quantity is measured using a geological map (Fig. 3).

Sediments deposited on oceanic crust decline approximately exponentially in quantity with increasing age (Fig. 2A) because ~3.4 km^2 of seafloor of all ages is consumed at subduction zones per year and an equivalent amount is formed at mid-ocean ridges (Rowley, 2002). Rowley's curve describing the proportion of surviving seafloor as a function of age is not equal to proportional sediment coverage because sedimentation occurs only over some fraction of the seafloor at any given time (Van Andel, 1975; Wilkinson and Walker, 1989; Fraass et al., 2015). Nevertheless, in the deep sea, where destruction of sediments by subduction is a dominant process, there is a clear signal of that process in the form of exponentially declining sediment quantity with increasing age.

Non-marine sedimentary deposits also exhibit an approximately exponential decline in coverage with increasing age over the past 440 m.y. (Fig. 2B). The poorer overall exponential fit is sensible because non-marine sediments are much more heterogeneous in their tectonic and environmental contexts than deep-sea sediments. For example, non-marine sedimentary deposits include thin alluvial and glacial sediments deposited outside of basins, intermountain basin fills, and fluvial-deltaic sediments deposited on low-elevation passive margins. Some components of the non-marine sedimentary system are effectively in the process of being transported but are sampled during transient storage on the landscape. Other non-marine sediments have made their way to sedimentary basins, which have a wide range of formation mechanisms, sizes (Nyberg and Howell, 2015), and lifespans (Woodcock, 2004). Partitioning non-marine sediments (Fig. 2B) into these different components would likely improve exponential fits indicative of different characteristic rates of cycling. Nevertheless, in the aggregate non-marine sedimentary rock data there is a clear signal of erosion and cycling expressed as an approximately exponential decline in quantity over the past ~440 m.y. (Fig. 2B).

Total sedimentary rock area on the global geological map also declines with increasing age (Fig. 3), but this cannot be interpreted as a signal of erosion and cycling. The precipitous decline in global sedimentary rock map area during the Cenozoic is driven by seven out of 4540 total sedimentary polygons. Most of the areas composed by these "Quaternary sedimentary rocks" record the burial and preservation of older sediments by younger sediments in active sedimentary basins (Fig. DR1). Others represent young, non-marine geomorphic sediments (i.e., regolith and alluvium) that have few analogues in the deep-time stratigraphic record.

Shallow marine sedimentary deposits, which constitute ~75% of the total volume of sedimentary rock on the continents, exhibit no regular decrease in quantity with increasing age (Fig. 2C). One reason is because shallow marine sediments can accumulate in the largest (Nyberg and Howell, 2016) and longest lived of all basins (Woodcock, 2004; Holland, 2016). Ronov et al. (1980) recognized the contrast between the empirical sedimentary rock record as a whole (Fig. 1) and the then already widely used models portraying it as declining exponentially in quantity with increasing age (Gregor, 1968; Garrels and Mackenzie, 1969, 1971b). Ronov et al. (1980) rightly concluded that the primary process signal in the sedimentary rock record is not erosion and destruction, but is instead changes over time in the amount of sediment that is trapped on the continents.

The fact that there is no exponential decline in total sedimentary rock quantity with increasing age (Fig. 1) does not mean that erosion plays no role in shaping the sedimentary record. However, given the global sedimentary rock quantity-age relationship, the relative magnitude of the signal that is imposed by post-depositional destruction must be localized and comparatively small in comparison to the magnitude of the signal that is imparted by changes in how much sediment was deposited in regions favoring long-term stability. At the scale of the Phanerozoic, one of the most important factors in this regard is the amount of continental crust flooded by shallow seas (Ronov, 1994; Hannisdal and Peters, 2011; Meyers and Peters, 2011; Holland, 2016). Continental flooding is a symptom of global tectonics, but it is also proximally important to sediment preservation because shifting the locus of sedimentation to near or off the continental shelf during sea-level falls subjects those sediments to either immediate or future tectonic disturbance in a zone that promotes uplift and recycling. Thus, a drop in the extent of continental flooding can have a major impact on the probability of long-term survival of sedimentary deposits, even if there is little change in overall rates of global erosion and deposition. In other words, there is an important distinction between gross and net sedimentation. Gross sediment throughput has likely been high and approximately constant throughout Earth history. The signature of gross sedimentation is represented here, in part, by non-marine and deep-sea sedimentary rock quantity (Figs. 2A and 2B). Relatively small shifts in the fraction of the gross sediment flux that is transferred to the net sedimentary record can have long-lasting, cumulative effects on the total mass of sediment that is stored in the upper crust. It is these types of temporal shifts in net sedimentation that dominate the sedimentary rock quantity-age relationship (Fig. 1).

Recognizing that variability in the bulk of the surviving sedimentary rock record reflects primarily tectonically and geodynamically driven changes in net sedimentation on continental crust, and not an overprint of erosional destruction, has many implications for our understanding of the evolving Earth system. At the most basic level, only the deep-sea and some non-marine sedimentary deposits are prone to the decline in quantity with increasing age that has been commonly ascribed to the sedimentary rock record as a whole. Shallow marine sediments, and non-marine sediments deposited in low-elevation coastal environments, bear little quantitative overprint of destruction. Instead, these sediments predominately record major, and sometimes dramatic, changes in the mean state of Earth's geodynamic-tectonic system and surface environment. Global geological map–based estimates of sedimentary rock quantity do exhibit a large-magnitude decline in area with increasing age, and this decline might have some bearing on our ability to interrogate Earth history. However, interpreting such geological map–based measures of rock quantity as indicative of the processes that govern the formation and destruction of the sedimentary rock record is, quite literally, judging the geological book by its cover.

ACKNOWLEDGMENTS

This work was supported by the University of Wisconsin–Madison Department of Geoscience and the U.S. National Science Foundation grants EAR-1150082 and ICER-1440312. J. Sajbel helped draft maps, and D.C. Kelly helped compile deep-sea data. M. Foote provided feedback on an early draft. We thank S.M. Holland, P. Burgess, and J. Howell for insightful, constructive reviews.

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Manuscript received 24 July 2016
Revised manuscript received 10 December 2016
Manuscript accepted 13 December 2016

Printed in USA

Supplementary Online Information

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Geology 45:323-326

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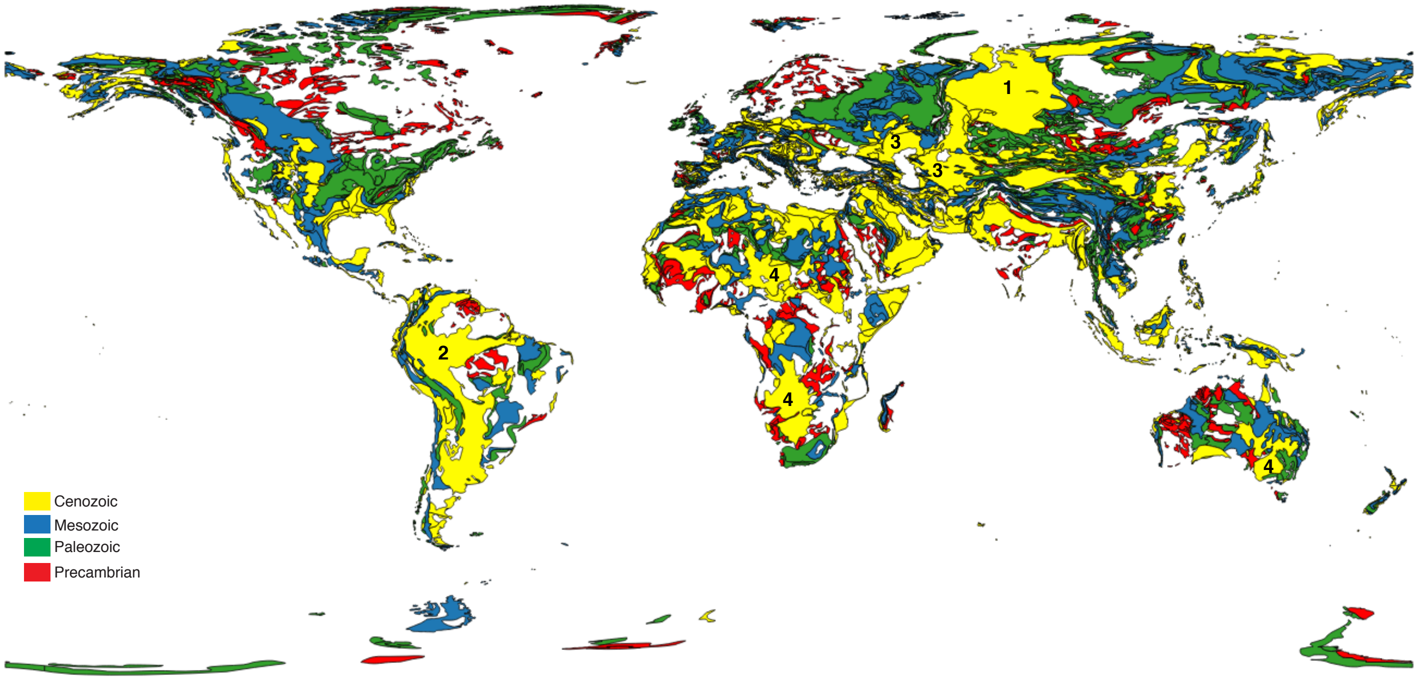

Fig. S1. Global geological map (https://mrdata.usgs.gov/geology/world) showing only polygons mapped as sedimentary/metasedimentary. Polygons are colored by era in Phanerozoic. Precambrian polygons are red. The four groups of polygons shown in main text Fig. 3 (circles) are numbered 1 through 4 in the map above.

All of the Cenozoic decrease in geologic map area of sediment in the global map (Fig. 3) can be accounted for by on the 7 orange out of 4,540 total sedimentary polygons. The effects of sequentially subtracting these polygons from global sediment map area in the last time interval (1 Ma) are shown by the circular points in Fig. 3. The West Siberian Basin (labeled 1), one of the largest sedimentary basins in the world, is represented on the global geologic map by one polygon covering $2.5x10^6$ km^2, labeled "Quaternary sedimentary rocks." However, these sediments are the most recent addition to a 2-11+ km thick succession of flat-lying Cenozoic and Mesozoic sediments that cover deformed Paleozoic accreted terranes/sediments and Siberian Trap volcanics (Cherepanova et al. 2013). Similarly, the majority of the Andean retroarc foreland basin and Amazon drainage area is represented as a single $5.4x10^6$ km^2 region labeled "Quaternary sedimentary rock" (labeled 2), most of which are recent additions to a thick succession of older sediments. In the Caspian Sea region, there are two polygons titled "Quaternary sedimentary rocks" (labeled 3) that cover $1.8x10^6$ km^2. These, too, bury and preserve primarily Phanerozoic-aged sediment. Finally, three late Cenozoic polygons from Australia and Africa (labeled 4) represent regolith and recently deposited, non-marine sediments. Together, they span an additional $3.8x10^6$ km^2, most of which is underlain by Proterozoic crystalline basement and sediments.

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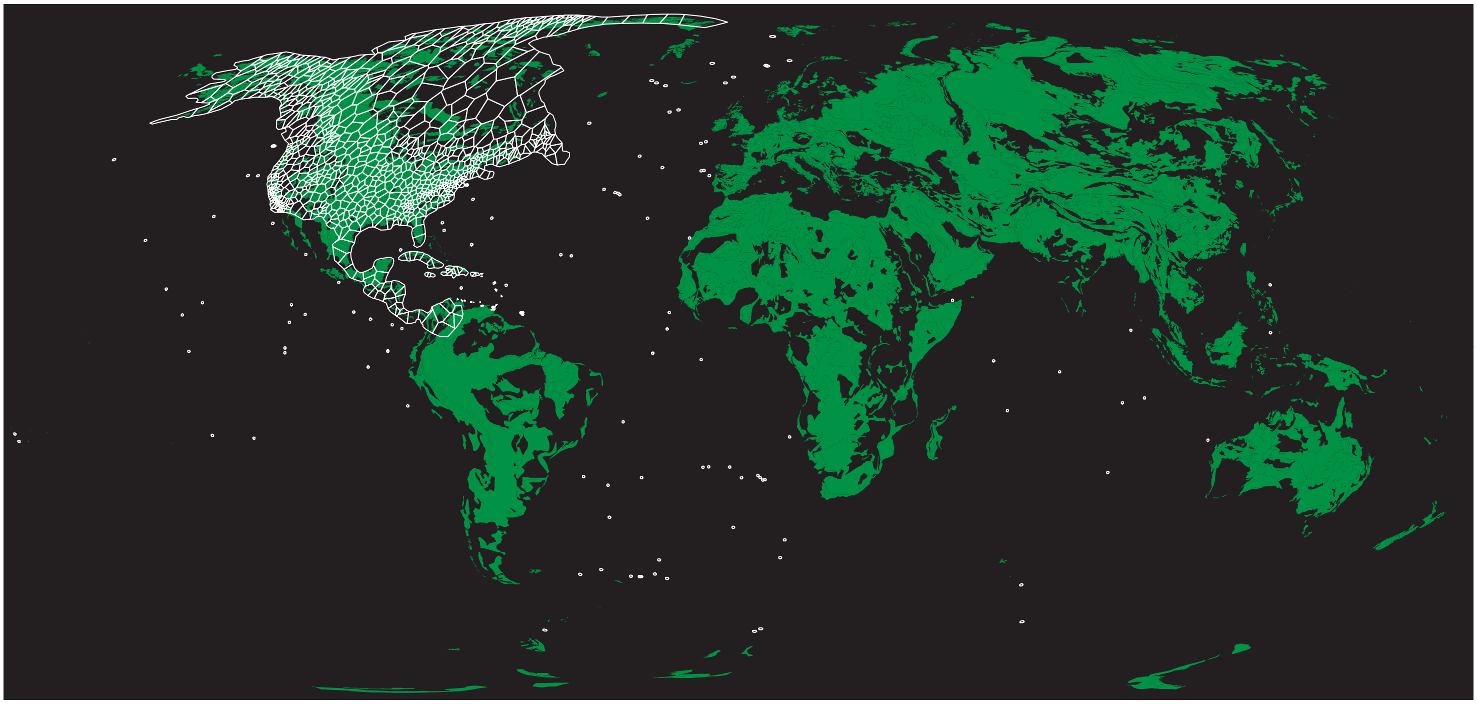

Fig. S2. Global sediment coverage, as in Fig. S1 but, not colored by age for clarity. Macrostrat column polygons in North/Central America and the Caribbean also shown, as in Fig. S1, but in white to enhance clarity. Deep sea drilling sites used here shown by white dots (see Fraass et al. 2015).

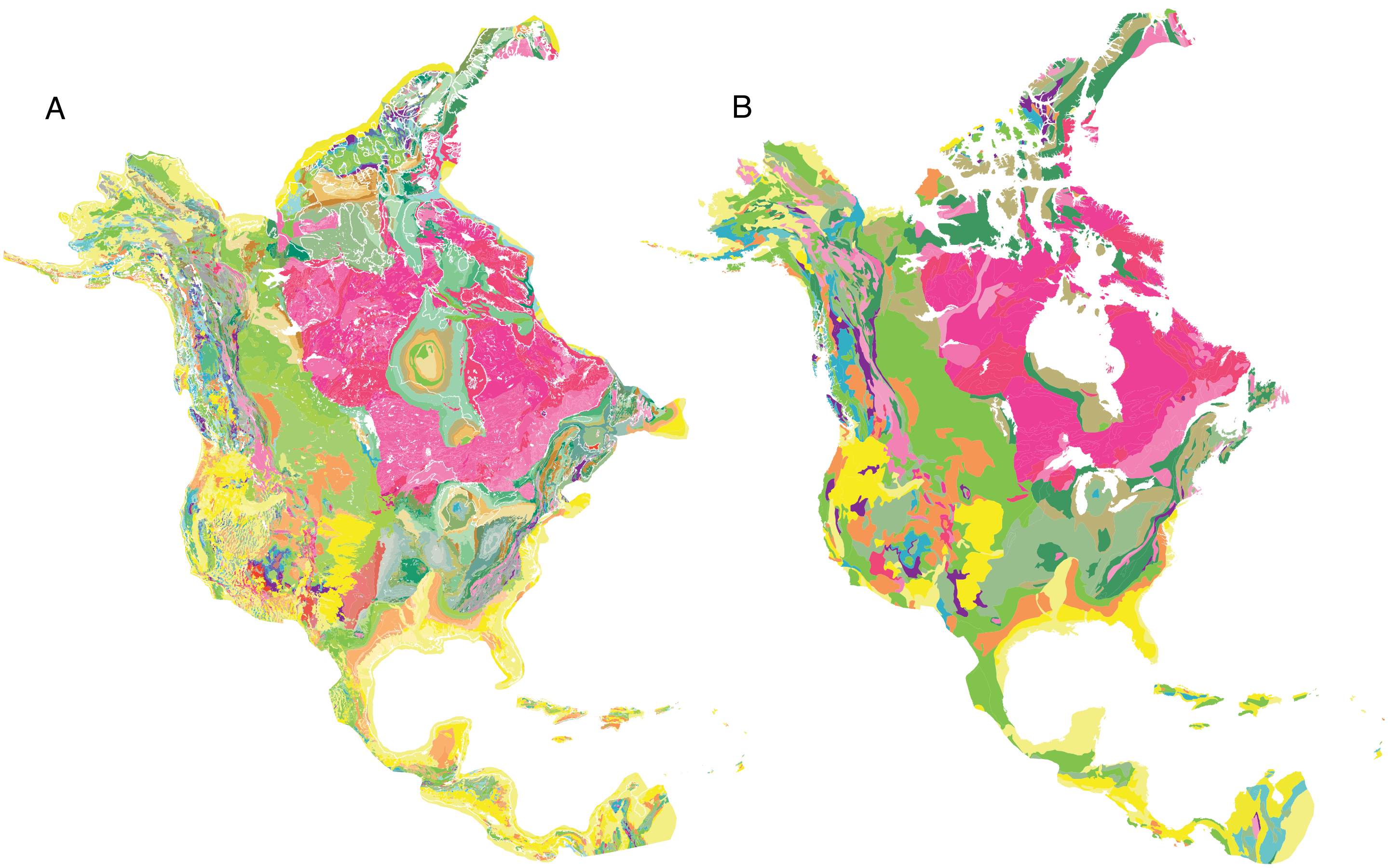

Fig. S3. Geologic maps clipped to the continental coverage area of Macrostrat (Fig. S1 and S2). A) GMNA, 2) Global geological map (as in Fig. 1), which does not included submerged areas. All mapped polygons, which include igneous and metamorphic non-sedimentary rock, are shown here.

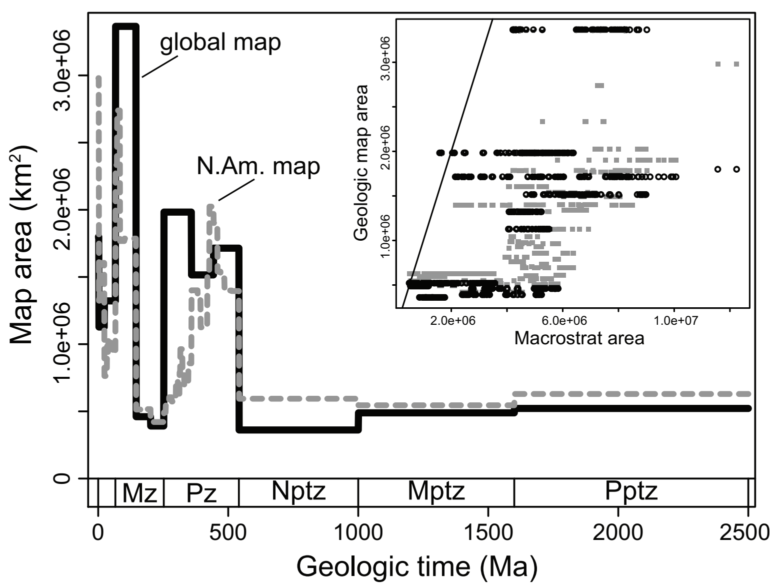

Fig. S4. Total sediment and metasdiment map area in the GMNA and global geological map clipped to area of Macrostrat (as in Fig. S3). Inset shows relationship between map area and the Macrostrat-based estimate of sediment area. The 1:1 line is also shown. Macrostrat is correlated with map-based estimates but it includes subsurface data, making the average coverage area in Macrostrat approximately 3x greater than the map-based estimates. The divergence between Macrostrat area and map-based area increases in magnitude towards the recent, reflecting the effect of burial and the inclusion of young, non-marine sediments.

SI Datasets. All Macrostrat column data are accessible online via the Macrostrat API. Basic documentation for the API is available at https://macrostrat.org/api/sections and https://macrostrat.org/columns. The specific API calls here used to obtain data, which are returned in JSON format:

Columns and spatial coverage :
Continental polygons: https://macrostrat.org/api/columns?project_id=1,7
Deep sea: https://macrostrat.org/api/columns?project_id=4

All sediments:
https://macrostrat.org/api/v2/sections?lith_class=sedimentary&lith_type=metasedimentary&project_id=1,7&response=long

Non-marine sediments:
https://macrostrat.org/api/v2/sections?environ_class=non-marine&lith_class=sedimentary&lith_type=metasedimentary&project_id=1,7&response=long

Marine sediments:
https://macrostrat.org/api/v2/sections?environ_class=marine&lith_class=sedimentary&lith_type=metasedimentary&project_id=1,7&response=long

Deep sea sediments:
https://macrostrat.org/api/v2/sections?lith_class=sedimentary&lith_type=metasedimentary&project_id=4&response=long

Output from these data service calls contains all of the data necessary to describe the area, thickness, ages and lithologies of sediments and metasediments, as well as additional information such as column sources, fossil occurrences and other rock unit attributes. For convenience, the attached supplemental table contains the time series used to generate main figures. Reported are number columns with sediment of given age. 1013 columns are present for non-marine and marine sed, 132 for deep sea (refer to locations in Fig. S2).

Data for the geological map-based analyses conducted here are available from the original sources cited in the main text. If interested readers have trouble accessing and processing these published ArcGIS files, they may contact the authors for delimited text files suitable to reproduce these analyses.