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Macrostratigraphy: Insights into Cyclic and Secular Evolution of the Earth-Life System

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Abstract

Rocks in Earth's crust are formed, modified, and destroyed in response to myriad interactions between the solid Earth (tectonics, geodynamics), the fluid Earth (ocean-atmosphere, cryosphere), and the living Earth (evolution, biochemistry). As such, the geological record is an integrator of geological, biological, and climatological processes and their histories. Here we review contrasting perceptions of the processes that govern the formation and destruction of the geological record, beginning with the relationship between macroevolutionary patterns in the fossil and sedimentary rock records and culminating with contrasting models of rock cycling. Using the approach of macrostratigraphy, we present an integrated summary of the quantity-age properties of rocks in continental and oceanic crust. The predominant process signal in the rock quantity-age distribution in continental crust is one of episodic growth, whereas in oceanic crust it is one of continual destruction. Relatively abrupt shifts in the dominant locus of sediment deposition, from fast-cycling oceanic crust to long-term continental reservoirs, and attendant expansions and contractions in the area of crust that is emergent, are correlated in timing and magnitude with shifts in the concentration of oxygen in the atmosphere and major macroevolutionary transitions in the biosphere. The most recent of possibly two such first-order

transitions occurred at the start of the Phanerozoic and is marked by a prominent preserved geomorphic surface known as the Great Unconformity.

- Macrostratigraphy uses the bulk characteristics of the rock record to probe the evolution of the Earth system.
- Quantifying the creation and destruction of rock units can illuminate the long-term evolution of continents and the life that inhabits them.

1. INTRODUCTION

Qualitative patterns in the rock record, such as the high relative abundance of komatiite and iron formations in more ancient rocks or changes in the extents of shallow marine deposits on continents, are readily intuited and summarized by geoscientists. This approach works well for detecting the strongest signals encoded in rocks and targeted components thereof. However, a more systematic approach presents opportunities—a comprehensive tabulation of all rocks and their properties can validate qualitative patterns, allow measurement of their magnitude, and potentially illuminate subtle yet undetected signals. Comprehensive descriptions of the rock record can also inform our understanding of the Earth system in fundamentally different ways, ranging from reconstructing paleogeography (e.g., Ziegler et al. 1979) to building inventories of society-critical and rock-hosted resources, such as groundwater (e.g., Gleeson et al. 2016).

Despite their potential utility, the scope and completeness of data sets describing the detailed composition and age of Earth's crust are presently limited. There are many reasons for this, but three stand out. First, assembling the data required to measure the spatial and temporal properties of all rocks is difficult because it requires compiling field-based descriptions and measurements that have been made by hundreds of geoscientists working over decades. The large degree of heterogeneity of rocks in Earth's crust, our knowledge of them, and the scientific output describing them pose a challenge. Second, effectively managing and using any such compilation require informatics solutions encompassing geospatial and geochronological data structures. Third, and perhaps most important, there is a tendency among scientists to view results from large compilations with some skepticism, in part because it is always possible to identify errors of many different types among large numbers of observational records. In the case of geology, more important skepticism is often grounded in the assumption that processes resulting in the destruction of rocks—erosion and crustal assimilation—are the predominant processes governing the present-day condition of rocks. This viewpoint has a deep intellectual pedigree, with origins that trace back to one of the most influential texts in biology ever written by a geologist, *On the Origin of Species* by Charles Darwin.

Here, we briefly review how early established views of the rock and fossil records, followed by the rise of macroevolutionary theory, exposed divergent interpretations of the fidelity of the geological record and the processes that govern its present-day quantity-age distribution. We then describe macrostratigraphy, the geological analog of macroevolution, and Macrostrat, a database for assembling, managing, and disseminating the fundamental units of macrostratigraphy. We next summarize how macrostratigraphic patterns in the sedimentary rock record reproduce many macroevolutionary patterns in the fossil record and outline evidence suggesting that the primary reason is that both systems respond to common forcing mechanisms. After briefly describing early attempts to constrain rock cycling, we move on to discuss the implications of macrostratigraphy in that context. This leads us to reconsider non-steady-state growth in the sedimentary reservoir and the formation of the Great Unconformity (GUn). The possibility of an ultimate common-cause mechanism linking patterns in the rock record to the first- and second-order history of life and environment is then considered.

1.1. The Imperfection of the Geological Record

"Imperfection" was the unsubtle operative word for an entire chapter on the geological record in Darwin's *On the Origin of Species*. In this chapter, and throughout his "one long argument," the rock record was discounted as a useful archive of evolution. Darwin took this position, as a geologist, in apparent anticipation of challenges to his theory that could originate from the fossil record. The most substantive problem noted was the abrupt appearance of complex animals in the oldest (then known) fossiliferous strata. Another was the seeming lack of continuous grading between species that Darwinian evolution seemed to require. Explaining these perceived deficiencies in the fossil record as the expected consequence of geological processes was effective argumentation. In part, this was because the processes invoked were grounded in widely accepted, uniformitarian principles of the rock cycle, brought to prominence by the Scottish geologist James Hutton. In this steady-state model, the destruction of rocks, when integrated over the depth of geologic time, overwhelms all other process signals that might have originally been present. The expected degradation of the rock record with increasing age was the basis for Darwin's "tattered manuscript" metaphor for the incompleteness of the rock and fossil records.

Perhaps not surprisingly, paleobiologists were among the first to directly confront Darwin's assertions about the fidelity of the fossil record. The need to do so surfaced prominently when evolutionary theory moved beyond the consideration of populations of individuals undergoing natural selection and began to include macroevolutionary phenomena, a different set of mechanisms operating among many lineages evolving over long periods of time (Simpson 1944; Erwin 2000; Jablonski 2007, 2017). Developing some aspects of macroevolutionary theory required compiling data on the times of first and last appearance and biological attributes of fossil organisms. Much can be learned by tracing this practice in paleobiology and considering how the rock record was incorporated into our understanding of the fossil record. Doing so illuminates the origin of and motivation for macrostratigraphy and provides an example of why incorporating quantitative descriptions of the rock record into our understanding of Earth systems is important.

Compilations of the age of fossil taxa, regardless of methodology, indicate that marine animal diversity was low in the early Paleozoic, rose rapidly in the Ordovician to a volatile plateau for most of the Paleozoic, dropped across the Permian–Triassic boundary, and then rose again, irregularly, to the present (Phillips 1860, Newell 1952, Valentine 1970, Bambach 1977, Sepkoski 1997, Alroy et al. 2001). Terrestrial diversity was also found to remain low until well into the Ordovician or Silurian before rising more quickly in the Devonian to ultimately reach a maximum in the recent, with intervening declines comparable in timing to those observed in the marine realm (e.g., Benton 2001).

As new compilations of fossil taxa were being generated and used to formulate and test macroevolutionary hypotheses, Raup (1976b) noted that all such estimates of fossil diversity were subject to a well-known sampling effect: The larger the sample of specimens, the larger the number of taxa. On this basis, Raup compared preserved sedimentary rock quantity to invertebrate fossil diversity and revealed a significant positive correlation between rock quantity and diversity estimated for the same periods (Raup 1976a). Interestingly, Raup used rock volume data from Gregor (1970) (less deep sea volumes) and map area data from Blatt & Jones (1975) as his estimates for rock quantity (see Section 3.1). Raup interpreted the correlations between these estimates and diversity to be a signal of sampling bias in the fossil record: More sedimentary rock leads to more fossils, and more fossils lead to higher diversity. The conclusion was that there was a "rock record bias," and any observed increase in biodiversity during the Phanerozoic and even some of the short-term declines (Raup 1972) were more apparent than real.

The possibility that aggregate patterns in the fossil record reflected a rock record–induced sampling bias had major implications for macroevolutionary theory. However, the bias hypothesis was largely set aside in an interesting, if somewhat unsatisfying, reconciliation (Sepkoski et al. 1981), discussed by Miller (2000). This "consensus paper" encouraged interpreting at face value the iconic global marine family- and genus-level compendia constructed by Jack Sepkoski (e.g., Sepkoski 1978, 1979, 1984, 1992). Raup's cautionary note did, however, reemerge when Smith (2001) and Peters & Foote (2001) compared estimates of fossil biodiversity to new, independent estimates of rock quantity to arrive at essentially the same conclusion as Raup: There was strong covariance between various measures of the amount and type of sedimentary rock and macroevolutionary patterns in the fossil record, even across major mass extinctions (Smith et al. 2001, Peters & Foote 2002), and this suggested a rock record–induced sampling bias.

1.2. The Common-Cause Hypothesis

Long before Sepkoski completed his compilations, Norman Newell, drawing on the work of many others, compiled similar types of fossil data sets and documented similar macroevolutionary patterns (Newell 1952). In so doing, Newell seems to have coined the phrase "mass extinction" to describe the geologically abrupt, coordinated decline or disappearance of entire groups of organisms, often followed by a complete makeover of the biosphere (Newell 1963). Specifically, Newell used fossil compilations to identify major mass extinctions at the end-Permian and end-Cretaceous as well as smaller ones at the end-Ordovician, end-Devonian, and end-Triassic and within the Cambrian—the same as those later identified by Raup & Sepkoski (1982) using improved fossil data sets and statistical assessments of extinction rates (but see Bambach 2006). Notably, Newell also assessed his results within the context of the sedimentary rock record (Newell 1959, 1962), observing that each extinction had its own biological signature but that most shared a physical stratigraphic expression in the form of geographically widespread hiatuses. Newell went further to causally link mass extinctions to the process that formed those hiatuses, thereby establishing the possibility that there was a common driver that affected major changes in both the sedimentary rock record and the biosphere.

Studies in stratigraphic paleobiology (Holland 1995, 2000; Patzkowsky & Holland 2012) later demonstrated that hiatuses do impose temporal structure on fossil recovery, forcing last occurrences of taxa to artificially cluster below unconformities and surfaces of temporal condensation (and first occurrences to cluster above). However, in the marine shelf system, geographically widespread subaerial unconformities, particularly those spanning multiple basins, are also indicative of large-scale environmental changes associated with the retreat of shallow seas and the emergence of land. Unusually large examples of exactly this type of environmental shift were what Newell identified as the likely "common-cause" forcing mechanism for both widespread hiatuses and the mass extinctions that occurred during their formation. Interestingly, this hypothesis echoed Georges Cuvier, who in the early nineteenth century demonstrated extinction to be a real phenomenon based on fossil evidence and noted that extinctions often coincided with stratigraphic indications of "paroxysms" in the interchange of land and sea, a "catastrophist" view that fell out of favor after Darwin.

Sepkoski (1976) indirectly touched on aspects of Newell's hypothesis in response to Raup (1976b) because newly emerging island biogeographic theory (Simberloff 1974a) provided a mechanism by which the retreat of shallow seas could cause real drops in diversity and vice versa. Specifically, the hypothesis that a species-area effect was in operation during sea level changes had already been explored in the fossil record (Schopf 1974, Simberloff 1974b). Consistent with the expectation of the species-area effect, Sepkoski (1976) found that residuals in Raup's regression of diversity versus sedimentary rock area (and volume) were positively correlated with independent estimates for continental flooding, a proxy for the geographic area of shallow marine habitat. This suggested that there was a real signal in fossil biodiversity that transcended rock record bias and that this signal was linked to a species-area effect.

2. MACROSTRATIGRAPHY: A MACROEVOLUTIONARY APPROACH

Macrostratigraphy was developed to provide a framework with which to measure the complete range of variation present in the geologic record and to test predictions made by the rock record bias and common-cause hypotheses, among other applications (Peters 2006b, 2008b). The fundamentals of macrostratigraphy were grounded in macroevolutionary practice. That is, the goal was not to measure the amount of rock that was present in some predefined time bins, as previous studies had done (e.g., Blatt & Jones 1975, Ronov et al. 1980), but rather to assemble the fundamental, "natural" units that could be used to generate these and other quantities related to temporal and spatial variation in the formation and destruction of rocks.

The fundamental units in macrostratigraphy are genetically related successions of lithologically distinct rock bodies (sequences, in the case of sediments), their times of initiation and truncation, and their physical-chemical properties summarized over a limited geographic area and through vertical thicknesses of crust. Thus, in a very real sense, a temporally and lithologically continuous succession of rock in a single crustal transect was the analytical equivalent of a taxon in macroevolutionary analyses, with taxonomic "rank" (e.g., genus, family) analogous to the temporal resolution defining continuity (e.g., "order" of a sedimentary sequence). Many such macrostratigraphic units independently compiled for multiple transects (i.e., geologic columns) spanning a single basin or region constitute a macrostratigraphic data set. Macrostrat, the database (**https://macrostrat.org**; Peters et al. 2018), is our attempt to aggregate columns (**Figure 1**) in order to generate aggregate macrostratigraphic quantities that are reflective of processes operating above the level of individual stratigraphic successions.

Although the approach of macrostratigraphy, and the Macrostrat database, can be applied at the scale of cores and measured sections within a single basin (Aswasereelert et al. 2013, Fraass et al. 2015), in order to test the common-cause hypothesis for macroevolutionary patterns, the temporal and spatial scale of analysis must encompass a sufficiently large sample of the crust to reflect global-scale controls on patterns of sedimentation and erosion. Here we focus on the 949 regional columns comprising the North American data set (e.g., Peters & Husson 2017, exclusive of Caribbean) and 132 of the continuously cored basement (or very near basement) penetrating offshore drilling sites (e.g., Peters et al. 2013, Fraass et al. 2015) that are now in Macrostrat (**Figure 1**).

2.1. Support for Common Cause

The initial application of macrostratigraphy to the rock record of North America yielded strikingly familiar patterns to those observed in the macroevolutionary history of marine animals (Peters 2005, 2006b, 2008a; Heim & Peters 2011; Peters & Heim 2011). Consistent with conclusions from Raup (1976b), there was some degree of convergence between marine genus diversity estimated in temporal bins through the Phanerozoic and the macrostratigraphic quantities for rock quantity. However, there were two important differences relative to previous studies. First, Macrostrat included subsurface rocks in its tabulation, thereby more closely capturing variation in the entire rock record, not just that exposed at the surface. Second, Macrostrat provided some degree

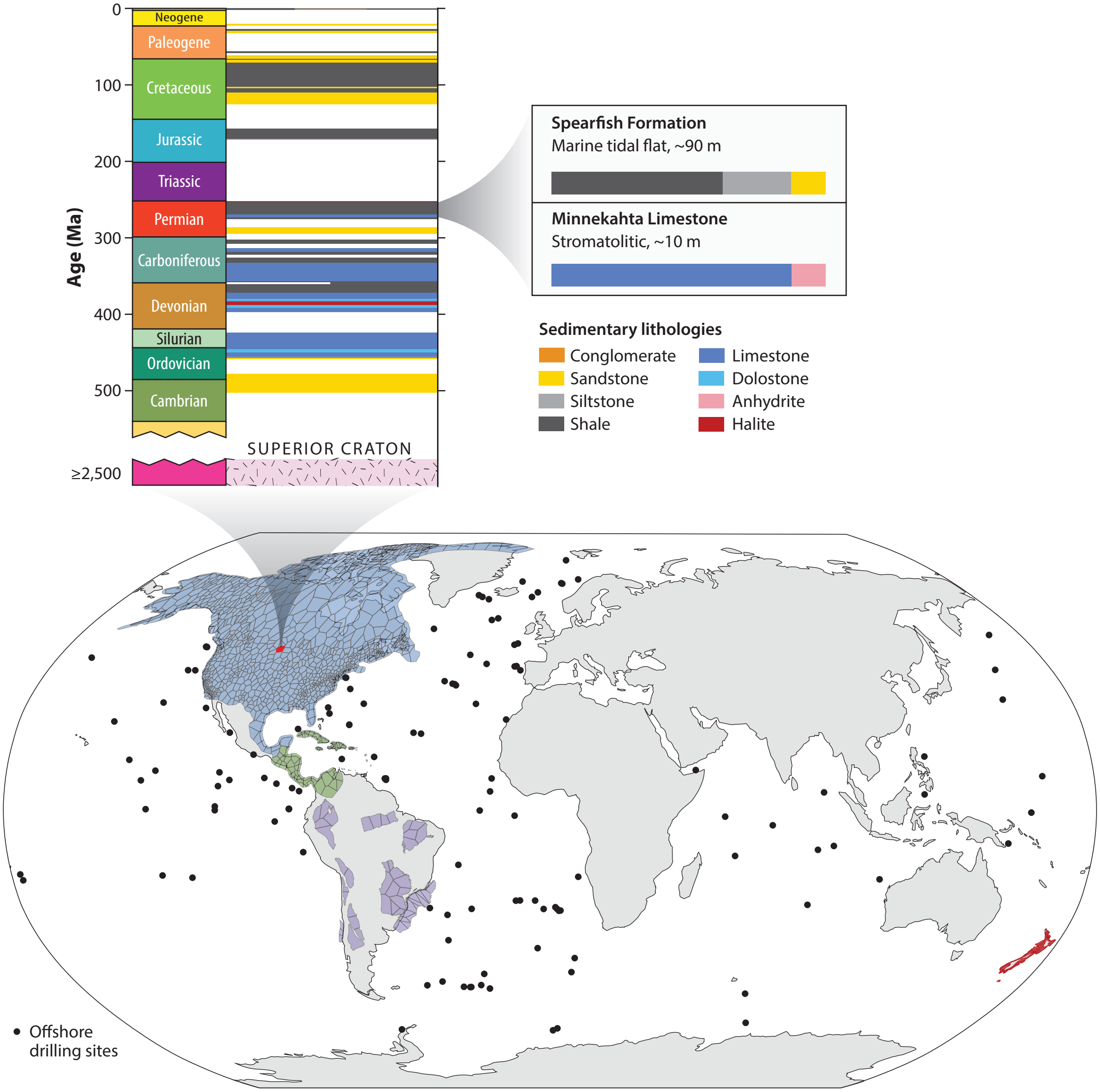
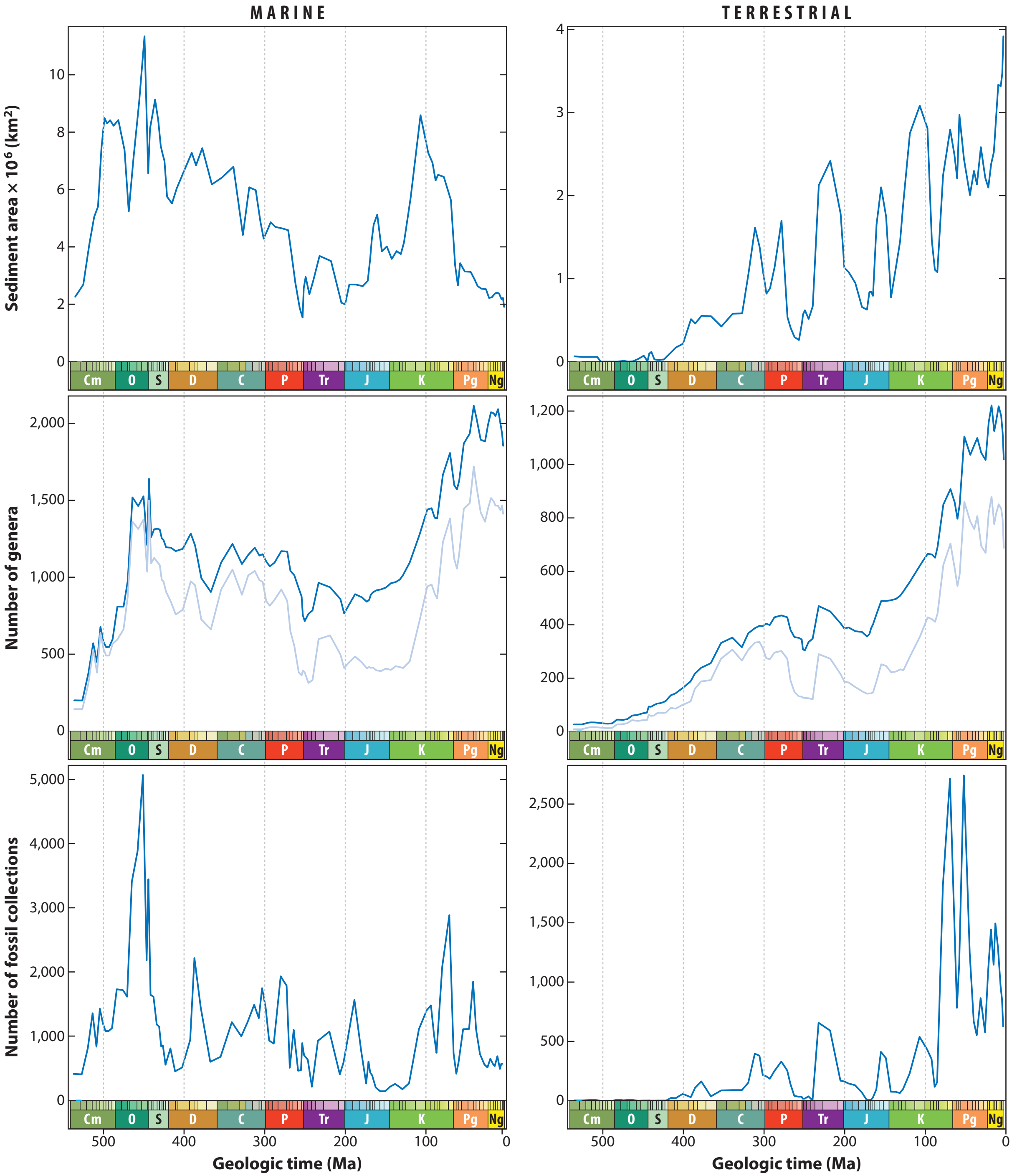


Figure 1

Spatial distribution of Macrostrat columns and a schematic representation thereof. Polygons on continents are the approximate area covered by columns.

of environmental resolution, meaning that nonmarine and marine sedimentary deposits could be separated from one another, and these were found to be very different in their long-term trends (**Figure 2**).

Similarities between macroevolutionary and macrostratigraphic patterns among Phanerozoic marine animals also included last occurrences and rates of extinction of genera compared to analogous quantities describing the truncation of sedimentary successions at hiatuses (Peters 2005, 2006b, 2008b). This was a quantitative measure validating Newell's original hypothesis linking



(Caption appears on following page)

Figure 2 (*Figure appears on preceding page*)

Marine and terrestrial (nonmarine) sedimentary rock area in North America (*top row*), genus diversity (*middle row*), and total fossil collections (*bottom row*) in the Paleobiology Database for the United States and Canada binned into international ages. Quaternary is not shown. Diversity for North American–occurring genera was tabulated using the times of first and last occurrence of genera, as determined by all of their occurrences globally (*upper dark blue lines*) or in North America (*bottom light blue lines*). A total of 11,389 marine and 3,907 nonmarine genera from all taxa contributed to diversity estimates. Environment assigned to each collection determined environmental classification; 1,346 genera occur in both environments, with overlap due mostly to reworking and organism transport in transitional environments. Abbreviations: C, Carboniferous; Cm, Cambrian; D, Devonian; J, Jurassic; K, Cretaceous; Ng, Neogene; O, Ordovician; P, Permian; Pg, Paleogene; S, Silurian; Tr, Triassic.

mass extinctions to widespread hiatuses. Interestingly, origination of genera and the initiation of sedimentary successions following those mass extinctions were not as strongly correlated in initial analyses. This was prima facie evidence for the common-cause hypothesis, as a simple rock quantity-related sampling bias similarly distorts patterns in both origination and extinction (Foote 2000). Analysis of the durations of gaps in the rock record following mass extinctions would further demonstrate the inability of sampling bias to explain the observed increases in genus extinction rates (Peters 2006a). The spatial magnitude and environmental impact of the hiatus predicted extinction intensity, not the duration of the sampling gap that occurred in its wake. Additionally, independent analytical methods developed to correct patterns of extinction and origination for incomplete and variable rates of fossil recovery (Foote 2000, 2001) demonstrated a large degree of fidelity in the face-value fossil record of extinction (Foote 2003, 2007), as well as indicated rates of preservation that covaried with independent estimates of rock quantity (Foote 2003).

2.2. Common Cause Extended

Support for the common-cause hypothesis among marine animals goes beyond biodiversity and extinction related to expansions and contractions of shallow seas and includes shifts in the dominant groups of marine organisms via extinction selectivity, imposed primarily by differential turnover among carbonate and siliciclastic marine shelf environments (Peters 2008a). Common cause also incorporates elements of long-term tectonics and the role that supercontinent formation and breakup has on connectivity of the biosphere (Valentine & Moores 1970, 1972; Valentine 1971; Zaffos et al. 2017) and on patterns of sedimentation (Ronov et al. 1980; Berry & Wilkinson 1994; Peters 2005, 2006b, 2008a) as well as interactions among sulfur and carbon cycling and continental flooding (Hannisdal & Peters 2011).

Notably, the common-cause hypothesis extends off of the continental shelf and into deep sea environments. There, the macroevolutionary history of planktic foraminifera covaries with macrostratigraphic quantities sensitive to the extent and continuity of deep sea sedimentation (Peters et al. 2013, Fraass et al. 2015). Prior work suggested that there was a preservation bias in the deep sea (Lloyd et al. 2011), but a priori evidence suggested that a sediment quantity–linked fossil sampling bias was unlikely to be a dominant factor, in part because only a few cubic centimeters of sediment from a few sites are all that is needed to capture the entire global diversity of planktic foraminifera today (Peters et al. 2013). Instead, correlation between deep sea macrostratigraphic and macroevolutionary patterns was interpreted as a different type of common-cause signal, one in which bottom water chemistry, controlled by patterns of ocean circulation and surface water productivity, determined the spatial distribution and continuity of deep sea sedimentation (Van Andel 1975, Moore et al. 1978, Fraass et al. 2015, Keating-Bitonti & Peters 2019) while simultaneously influencing the macroevolutionary trajectory of surface-dwelling protists.

Nonmarine diversity and macroevolutionary patterns have also been considered in the context of the rock record (e.g., Barrett et al. 2009; Benton et al. 2011; Butler et al. 2011; Rook et al. 2013; Dunhill et al. 2014; Close et al. 2017, 2020b). The general relationship between North American nonmarine diversity and macrostratigraphic quantities for nonmarine sedimentary rocks is also broadly similar to that in the marine realm. The most notable difference is that nonmarine sediments do show a volatile but overall increase in quantity toward the recent, mirroring the increase of nonmarine genus diversity (**Figure 2**).

It is reasonable to view the nonmarine correlations (**Figure 2**) as the signature of a pervasive rock record–related sampling bias, as Raup did in the predominately marine case. However, the fossil record of terrestrial colonization by many groups, such as tetrapods, is also very rich and preserves a succession of transitional forms chronicling the change from fully aquatic to fully terrestrial modes of life during the Devonian–Carboniferous (e.g., Shubin et al. 2006). Thus, it is not plausible that the near-absence of terrestrial sedimentary rocks in the early Paleozoic has warped our understanding of terrestrial evolution to the point that the basic diversity trajectory is entirely spurious. Instead, the dearth of terrestrial sedimentary rock in the early Paleozoic is likely a real signal indicative of the essentially complete drowning of North America from Late Cambrian through Late Ordovician–Silurian time (**Figure 2**). Much of the variation in terrestrial rock quantity after that is also a geologic expression of the tectonic evolution of North America, a signal of landscape evolution that is also relevant to the evolution and ecology of the terrestrial biosphere (e.g., Park & Gierlowski-Kordesch 2007; Badgley 2010; Finarelli & Badgley 2010; Nelsen et al. 2016). In addition, the origin and initial diversification of terrestrial ecosystems were occurring as the supercontinent Pangaea was coalescing. By the Triassic, when most major groups of organisms on land today evolved, Pangaea was starting to break apart, becoming fully fragmented by the Late Cretaceous. These types of longer-term links between the biosphere and tectonics (Valentine & Moores 1972, Zaffos et al. 2017) provide an additional set of mechanisms to induce real covariation in macroevolutionary and macrostratigraphic patterns on land and in the sea.

2.3. Lessons from Macroevolution Concluded

Comparing the rock and fossil records has shown that Darwin was correct in a limited sense: The rock record at any one place is composed mostly of gaps, and the fossil record is an incomplete archive of evolution. However, almost everything we know about history and the world is incomplete. The question is, to what extent has incompleteness affected our understanding of natural processes? In the case of major macroevolutionary patterns in the marine fossil record, a face value analysis of large numbers of fossil lineages, compiled over continental and oceanic scales and over the entire history of major branches in the tree of life, reveals many robust signals, despite a wide range of overprinting biases (e.g., Sessa et al. 2009; Cherns et al. 2011; Vilhena & Smith 2013; Close et al. 2020a,b; and many others). Continuing to improve our understanding of the fossil record and making sampling protocols as comparable as possible through time and space will refine the precision of macroevolutionary patterns and is, therefore, a priority. However, doing so is unlikely to expose major macroevolutionary features as artifacts of an overwhelmingly strong rock record bias.

Perhaps most importantly, macrostratigraphy has shown that Darwin did not fully appreciate how the "gappiness" of the rock record is structured and what it means environmentally when considered on the temporal and spatial scale of species and higher taxonomic lineages. As Cuvier recognized, and as Newell articulated, some widespread gaps in the rock record, and associated changes in sedimentary rock and fossil quantity, are formed in response to profound changes in the contemporaneous environment, rather than reflecting the overprint of much later degradation or preservation biases. To borrow a phrase from Claude Debussy, "music is the space between the notes," and so it is in the macroevolutionary and macrostratigraphic views of the history of Earth and life. The relationship between the gap-riddled rock record and the long-term evolution of life and environment is, however, intertwined on a much deeper level, one that can be fully revealed only by measuring the mass, chemical composition, and age of rocks in Earth's crust.

3. THE ROCK CYCLE REVISITED

The first comprehensive, quantitative descriptions of the quantity, lithology, and age of rocks in continental crust were assembled for the Devonian through Jurassic systems by Alexander Ronov and collaborators and were published system by system in Russian from 1954 (Ronov & Khain 1954) through 1962 (Ronov & Khain 1962) and in summary form (Ronov 1959). One of Ronov's motivations for compiling these data was the recognition that there is an incredibly large volume of rocks in Earth's crust and that the chemistry of those rocks spans nearly all of the mobile and reactive elements in the surface environment. This meant that the rock record contained, for many elements, such as carbon, thousands of times more mass than was present in all of the active surface reservoirs (ocean-atmosphere, biosphere) combined. They also knew that mass is exchanged among crustal and surface reservoirs with some degree of irregularity in time and space due to geological, climatological, and biological processes and interactions, and that the history of mass exchange could be reflected in, and also influenced by, heterogeneity in the rock record.

Thus, rather than viewing the geological record as an imperfect and passive recorder of Earth history and environment as Darwin did, Ronov and his collaborators viewed it in almost exactly the opposite way: Rocks were a critical player in driving the long-term evolution of the Earth system. Quantifying the mass-lithology-age properties of the crust was, therefore, essential to understanding the long-term evolution of Earth and life (Ronov 1959; Ronov & Migdisov 1971; Budyko et al. 1985, 1987; Ronov et al. 1991a,b). However, exactly what the rock record revealed about cycling would remain entangled in the uniformitarian conceptual model that had been entrenched since the days of Darwin.

3.1. Exponential Decay and Steady State

Gregor (1970) used Ronov's published Devonian–Jurassic compilations of sediment quantity in an effort to compare modern, human-influenced rates of erosion to background geological rates. To do this, Gregor used modern river sediment flux data and started from first principles, deriving a mathematical expression that was grounded (implicitly) in Darwin's view of the sedimentary cycle: Rocks were being continually destroyed by erosion at some (stochastically constant) rate, and sedimentary rocks were continually being formed from the detritus (at that same rate), leading to

$$S(t) = S_0 e^{-rt}, \qquad 1.$$

where $S(t)$ is the surviving volume of sediment of age t, S_0 is the original amount deposited, and r is a stochastic constant describing the rate of the destruction process operating continuously over t. If decreasing quantity versus age was found and if that decrease was well described by an exponential decay function (Equation 1), then one could solve the equation for S_0, which Gregor expressed as a rate by taking the surviving volume of sediment of a given age and dividing it by the duration over which it accumulated. Although Gregor wanted continental erosion rates, the assumption was that erosion and sedimentation were synonymous, interchangeable terms in a steady-state world.

Gregor (1970, p. 274) did note that "unfortunately, volume estimates are not common in stratigraphic literature," but he used Ronov's five data points for the Devonian through Jurassic periods to constrain global sediment volume and then took the remainder of Ronov's estimate for the total global continental sedimentary volume and divided it between seven time intervals

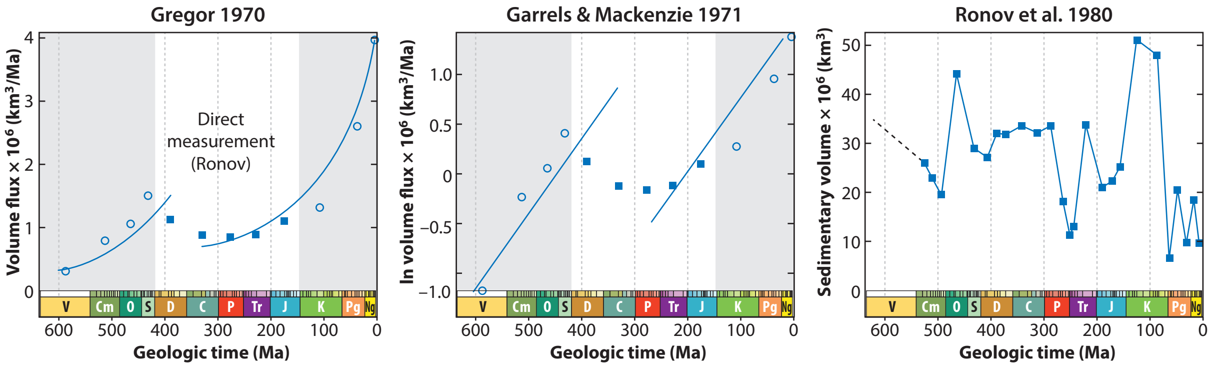


Figure 3

Sedimentary rock volume per Myr versus age from Gregor (1970), its reexpression by Garrels & Mackenzie (1971), and the completed data set from Ronov et al. (1980). The five well-constrained Ronov data points used by Gregor are shown by solid blue points; gray areas show time intervals for which volume was extrapolated by Gregor. All data are plotted using current age and interval duration estimates; updates to the timescale significantly modified the exponential patterns noted by Gregor (1970) and Garrels & Mackenzie (1971), shown schematically here. The Precambrian "Vendian" line is dashed in Ronov's estimate because this volume was not included in tables, and its value is inferred from figures presented by Ronov et al. (1980). Abbreviations: C, Carboniferous; Cm, Cambrian; D, Devonian; J, Jurassic; K, Cretaceous; Ng, Neogene; O, Ordovician; P, Permian; Pg, Paleogene; S, Silurian; Tr, Triassic; V, Vendian.

(Late Precambrian through Silurian, and Cretaceous through Pleistocene), in proportion to the maximum known (at the time) thickness of strata in each. Gregor also included a rough estimate of deep sea sediment, that portion of sediment located on oceanic crust, which was added to the estimates for the Cretaceous, "Tertiary," and Pleistocene in proportion to their durations.

Although these volume-age data, when extrapolated beyond the bounds of Ronov's Devonian–Jurassic compilation, did show a decline in quantity with increasing age (**Figure 3**), there was one prominent deviation: an increase in surviving quantity with increasing age during the Paleozoic, captured by Ronov's actual measurements. To address this, Gregor chose to separate the time series into two components—Precambrian to Devonian and Carboniferous to Pleistocene—and to fit them individually with modified exponential functions.

Gregor (1970, p. 274) considered the reason for the departure from his expected exponential decay pattern (Equation 1), stating: "It has been suggested that the earlier Paleozoic systems have been selectively preserved by burial under younger systems.... On the other hand (the deviation from uniform exponential) could be fossil remnants of an erosional pattern that could be reconstructed and analyzed." Garrels & Mackenzie (1971) immediately seized upon this aspect of Gregor's results, using the same data but plotting them on semilogarithmic axes, to conclude that each cycle was individually well described by nearly identical exponential decay functions defined by the slope of the semilog fit (**Figure 3**). They interpreted this as the signature of "normal" sedimentary cycling and constancy thereof, as they had previously suggested (Garrels & Mackenzie 1969). In order to generate two cycles (as well as avoid the inconvenient total destruction of essentially all sedimentary rock after only a few hundred million years), they proposed a model in which a cycle was defined by a reset in the way in which erosion affects older sediments. Specifically, at the start of a new cycle, all older sedimentary rocks were no longer subject to the same constant rate of erosion. Instead, rocks from previous cycles would undergo much slower rates of destruction, with an overall rate determined by the amount required to maintain constancy in total sedimentary rock volume.

Garrels & Mackenzie (1971) and Li (1972) incorporated Gregor's extrapolated data and other (mostly hypothetical) older sedimentary surviving rock quantities to speculate that these types of cycles were relatively minor variations superimposed upon a single exponential decay function. This was interpreted as quantitative support for a rock cycling model that had "a constant rate of sediment birth, a constant total death rate, and, of course, a constant total mass" (Garrels et al. 1976, p. 307).

The allure of an exponential fit and steady state as a vehicle for modeling and understanding the Earth system was understandable. Gregor (1970) was trying to identify a long-term baseline constant against which to compare humans as erosive agents; Mackenzie & Garrels (1971) were among the visionaries defining the emerging new field of sedimentary geochemistry and biogeochemical cycling, at least among Western scientists. If the rock record, this heterogeneous behemoth in the Earth system, conformed to the uniformitarian expectations of the Huttonian rock cycle, then all of its complexity and the diverse range of geological processes governing it could be tamed, effectively reduced to a single mass flux (erosion = sedimentation) and a decay constant in the governing equations for life and environment. This assumption had the effect of elevating life and the evolutionary process as the primary mechanism for driving any long-term change in the Earth system. There would still be some complexity in this worldview: For instance, biologically driven changes in the composition of sediments entering the geologic record would ultimately lead to changes to the composition of rocks eroded out of it (Berner & Canfield 1989, Bluth & Kump 1991). But, even so, emerging geochemical tracers seemed to make compilations of rock quantity and age obsolete for the study of biogeochemical cycles in deep time, especially as assumptions that rock cycling rates and the total mass of the sedimentary reservoir were constant became widely accepted.

In an interesting, if indirect, acknowledgment that an exponential fit to Ronov's five data points and seven additional extrapolated data points might have been carried a little too far, Gregor had this to say in a 1992 retrospective (p. 2998):

> The steady-state (sedimentary) reservoir, which had started as a convenient approximation and had served as the basis for many a productive model, had acquired the sort of reality that comes from habitual use. The linear-accumulation model (in which total sedimentary mass was not constant) was a reminder of something obvious but forgotten: there was no reason why secular and cyclic evolution shouldn't go on together, albeit on different time scales.

Curiously, Gregor (1992) did not comment on the fact that Ronov and company had gone on to complete their compilation of rock quantities for the remaining Phanerozoic systems (Khain et al. 1976, 1978, 1981; Ronov et al. 1976, 1977, 1979) and some of the Precambrian (Ronov et al. 1982). Doing so made it clear that the temporal pattern of variability that was evident in Gregor's five "real" data points was not the exception but was in fact the rule. Gregor's other seven extrapolated data points, used to make an exponential fit that was in turn taken as evidence for a steady-state model, were very far off the mark (**Figure 3**). Ronov et al. (1980, p. 324) would point out the discrepancy between their data and the already entrenched steady-state, constant mass model:

> [Garrels & Mackenzie (1971)] ascertained that the relative mass of the sedimentary rocks decreases with time from the recent epoch on according to an exponential lawlaw. . . . Contrary to our expectation, [our completed data compilation] does not show any regular decrease of the relative mass of rocks with increasing age and demonstrates only its periodic fluctuation.

3.2. Fast Cycling and Slow Growth of the Sedimentary Reservoir

It is easy to forget today that the theory of plate tectonics was only beginning to gain ground when Gregor fitted an exponential decay curve to surviving sedimentary rock quantity versus rock age. A fundamental issue related to tectonics was that Gregor had combined sediment volume estimates from both oceanic and continental crust, two end-member components of the plate tectonic system. This was critical because oceanic crust is subducted within 10^0–10^8 Myr following its creation, whereas continental crust can persist for essentially all of Earth history, making any exponential fit to combined oceanic and continental sediment quantity problematic.

Veizer (1984) in particular, but also others, did this by applying the same basic principles of rock cycling but fitting different exponential decay functions to each tectonic group of sediments. The recognition that there were multiple different fast (deep oceanic) and slow (continental) cycling sedimentary reservoirs with different sizes and half-lives was an important step, but it was still readily possible to formulate a model in which steady state (i.e., constant sedimentary rock volume, constant rates of erosion and sedimentation) occurred over all (Garrels & Mackenzie 1972, Mackenzie & Pigott 1981) or most (Veizer & Jansen 1985) of Earth history. This approach did, however, have the advantage of making it easier to drive shifts in the bulk composition of sedimentary rocks (Garrels & Mackenzie 1972), a requirement for building new models describing changes in Earth's atmospheric composition and isotopic records (e.g., Berner & Canfield 1989).

Veizer (1988) also noted that a steady-state (recycling) view of the sedimentary reservoir and a non-steady-state or evolutionary view, in which the sedimentary reservoir did undergo significant changes in mass over time, were not mutually exclusive. The relative importance of each depended on the timescale over which changes were being considered and on the timescales over which any changes to the non-steady-state term could be affected (if they ever did occur). In the absence of complete or improved data on the surviving mass and age of sedimentary rock spanning all of Earth history, and with the prevalence of exponential decay fits to scant (often hypothetical) rock quantity data, it was difficult to assess the non-steady-state term. When it was incorporated, non-steady-state growth in sedimentary mass was typically ascribed to only the earliest stages of Earth history (e.g., Veizer & Jansen 1985). At the other end of the spectrum, non-steady-state growth could be viewed as a background constant, with a rate defined by the total mass of surviving sedimentary rocks divided by the duration over which that mass accumulated (Gregor 1992). Using Ronov's 1959 estimate for a total global sediment mass of 2.23×10^{18} metric tons and spreading accumulation of that mass uniformly through 4 billion years, growth in the sedimentary reservoir would have proceeded for all Earth history at a rate of 557 megatons per year, comparable to the rate at which the Amazon River delivers sediment to the ocean today (Mouyen et al. 2018).

3.3. Macrostratigraphic Constraints on the Rock Cycle

The global Phanerozoic (and limited Precambrian) compilations of Ronov et al. (1980) have been used widely as the constraints on the mass, age, and composition of rocks in Earth's crust. Macrostratigraphy takes a fundamentally different, more granular informatics approach to producing estimates for these same quantities. Nevertheless, results from macrostratigraphy show a remarkable degree of convergence with those of Ronov (Husson & Peters 2017, Peters & Husson 2017). We do not focus here on the evidence indicating that the macrostratigraphy of North America contains a globally relevant signal but instead focus on the implications macrostratigraphy has on our understanding of the rock cycle and long-term evolution of the Earth-life system. It is, however, worth noting that Ronov et al. (1980, p. 324) analyzed their lower-resolution but comprehensive global data continent by continent, concluding that in the quantity-age data for sedimentary rocks, "(a) global rhythm exists in spite of obviously discoordinated movements of separate. . .continental platforms; this is indicative of a global tendency predominating over regional ones."

Contrary to the fundamental predictions of most rock cycling models, the surviving quantity-age data for sedimentary (Ronov et al. 1980, Peters & Husson 2017) and igneous (Peters et al. 2021) rocks in continental crust in North America exhibit little or no decline in surviving quantity with increasing age (**Figure 4*a*,*b***). Instead, as noted by Ronov et al. (1980), the data for both sedimentary and igneous rock quantities are dominated by episodic fluctuations with little long-term trend. Indeed, in the case of igneous rocks in continental crust, there is possibly even an increase in quantity with increasing age (Peters et al. 2021) (**Figure 4*b***). Within the Phanerozoic, macrostratigraphic quantities describing sedimentary rock quantity carry little discernible overprint of erosion and are instead dominated by a process signal that reflects changes in the extent of continental basin formation and marine flooding. Ultimately, changes in these terms over time are forced by the combined influences of the Wilson cycle of supercontinent breakup-assembly-breakup, higher-frequency marginal tectonic dynamics (Sloss 1963, Sloss & Merriam 1964, Meyers & Peters 2011), and large-scale glaciation (Finnegan et al. 2012). The nature of these ultimate controls on continental sedimentation is likely why rock quantity in North America has parallels that are recognizable globally (Sloss & Speed 1974, Ronov et al. 1980, Husson & Peters 2017, Peters et al. 2021).

Oceanic crustal reservoirs, by contrast, are characterized by exactly the type of quantity-age pattern that is expected under Darwin's conceptualization of Hutton's rock cycle, the mathematical formulation of it by Gregor (1970), and the integrated biogeochemical and rock cycling models of Mackenzie & Garrels (1971), Li (1972), Garrels & Mackenzie (1972), and subsequent researchers: There is a decline in rock quantity with increasing age, and that decline is approximately exponential. This exponential decay signal in quantity-age data is pervasive among oceanic crustal reservoirs because, unlike continental crust, oceanic crust is continually being produced at spreading ridges and an equal amount is continually being consumed at subduction zones in an age-independent fashion (Rowley 2002). These are the precise conditions required for generating an exponential decline in surviving quantity with increasing age.

Rocks in continental crust, by contrast, can form and then persist for essentially the entire duration of Earth history. This fact imposes a quantity-age pattern in the continental rock record that is dominated by variation in how much rock was originally incorporated into the crust and not by subsequent destruction via erosion and crustal assimilation. If the latter two processes were the predominant process signals affecting continental rocks, then the data on quantity-age would reflect this fact by exhibiting, at minimum, an overall decrease in quantity with increasing age. The only way to satisfy the data (**Figure 4*a***) while at the same time elevating the importance of rock destruction to the point of balancing crustal input (i.e., reaching steady state) is to construct models with extreme age selectivity in the process of rock destruction. So strong is this signal in continental rocks that the need to invoke just such a model was evident from the very start, as the five Devonian–Jurassic data points that disrupted Gregor's exponential fit (**Figure 3**).

Macrostratigraphy's view of the quantity-age properties of the continental crust not only affirms Ronov's global results but also further disrupts the steady-state model by indicating that there have been two large and relatively abrupt shifts in net continental sedimentation, the most recent of which occurred at the Neoproterozoic–Phanerozoic boundary. Thus, from the physical perspective of macrostratigraphy, the transition from the Precambrian to the Phanerozoic is the most prominent feature of the entire sedimentary rock record (**Figure 4*a***). It is also clearly expressed in the field in the form of a profound, long-recognized discontinuity known as the GUn.

4. THE GREAT UNCONFORMITY

A good first-order description of the rock record of North America is Precambrian crystalline igneous and metamorphic rocks overlain by undeformed Cambrian and younger sedimentary deposits. Macrostratigraphy allows this first-order feature to be quantitatively measured in several different ways, but it is so prominent that it has been identified qualitatively for well over

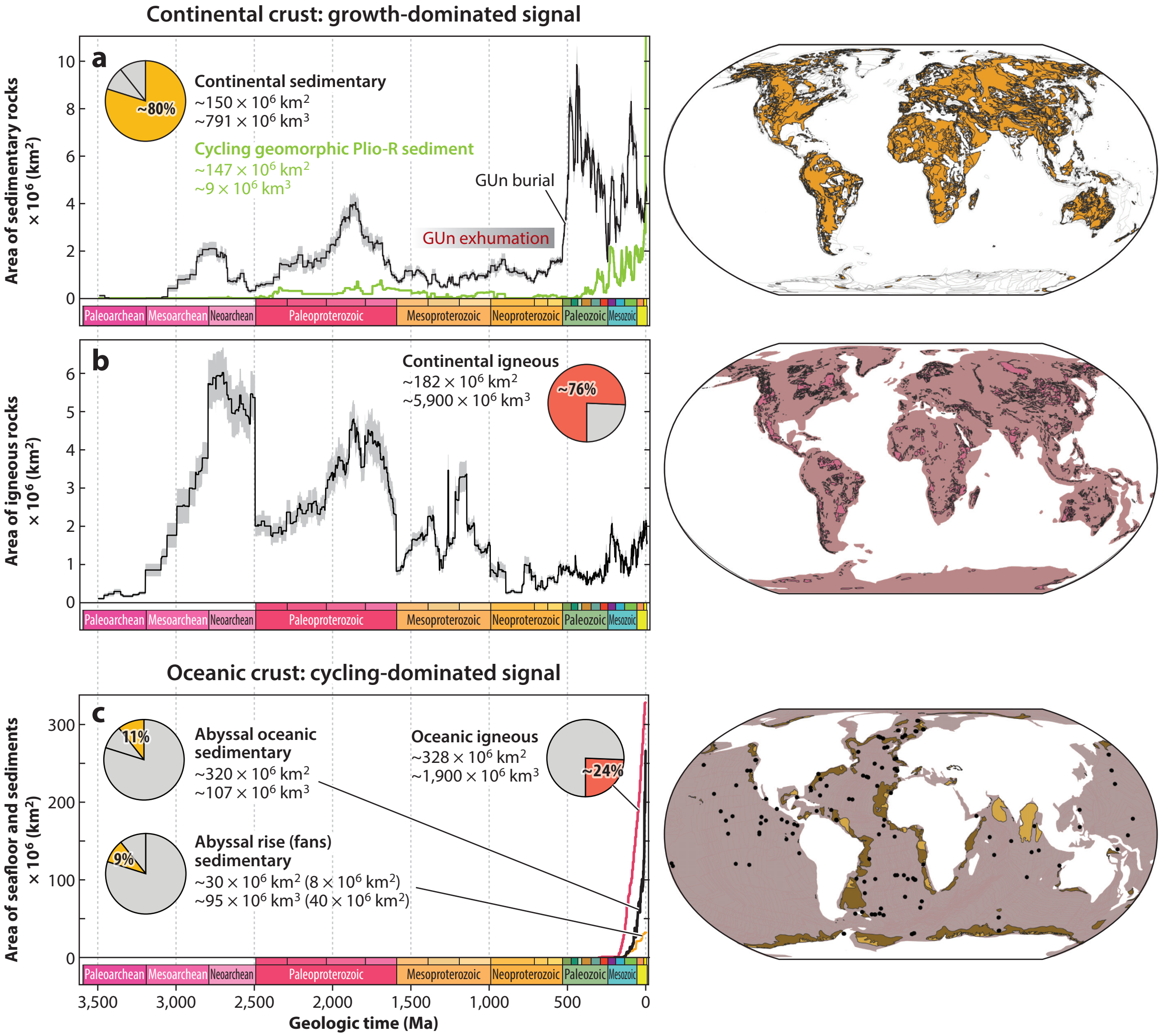


Figure 4

Inventory of quantity and age of sedimentary and igneous rocks in continental and oceanic crust. (*a*) Area of sediments in continental crust (in North America) and total volume (globally scaled). The green line shows the nonmarine sediment area subset. Pliocene to Recent alluvial sediment is separated from continental volume and reported in green text. The map shows sedimentary rock at continental surface in Macrostrat's map compilation (Chorlton 2007, Peters et al. 2018); the time series are based on Macrostrat's chronostratigraphic columns (**Figure 1**). (*b*) Igneous rocks in continental crust measured as in panel *a*. The total volume estimate is based on area and a mean thickness of approximately 38 km (including sediments). The map shows continental crust and distribution of igneous rocks at the surface. (*c*) Igneous and sedimentary rocks in oceanic crust. The black curve from Macrostrat is as in panel *a*; the total area and volume were obtained by regressing sediment thickness versus crustal age for all offshore drilling control points (*black dots*). The oceanic igneous rock volume was obtained from area and average crustal thickness of 6 km. The abyssal continental rise sediment area is from Harris et al. (2014). The subset of the rise classified as fans is also shown (*orange*; values in parentheses), with assumed mean thickness of 5 km, a likely overestimate (Bouma et al. 2012). The volume for the nonfan portion of rise (*brown*) assumes mean sediment thickness of 2.5 km. The age-area curve for the continental rise uses the age of underlying seafloor for the initiation of deposition. Abbreviation: GUn, Great Unconformity.

a century. For example, John Wesley Powell, after recruiting Native American experience to successfully float the Colorado River through the Grand Canyon in 1869, called the prominent surface separating over a kilometer of flat-lying Cambrian and younger Paleozoic sedimentary rocks from tilted and eroded Precambrian rocks the "Great Unconformity." The widespread hiatus in sedimentation that is evident at the Precambrian–Cambrian boundary was also the basis of Walcott's "Lipalian" time interval, a Precambrian veil behind which the puzzle of an abrupt Phanerozoic appearance of diverse animals could be hidden. Sloss (1963, p. 96) also began his unconformity-based physical classification of the North American sedimentary rock record with the Sauk Sequence, the Cambrian–Early Ordovician marine succession deposited on an unconformity that "over the greater part of the cratonic interior…was cut on Precambrian crystalline rocks and deformed metasedimentary rocks."

There are two ways in which the GUn is identified by macrostratigraphy as the most important transition in the entire rock record. The first, from the bottom-up point of view, is that the GUn marks a large and relatively abrupt (<60 Myr) increase in preserved sedimentary rock quantity (**Figure 4*a***), climbing from a sustained Meso- to Neoproterozoic low and reaching an all-time high by the Early Ordovician that would not be approached again until the Late Cretaceous (**Figure 4*a***). This is fundamentally why Ronov found no decrease in rock quantity with increasing age in Phanerozoic global compilations and instead noted only periodic fluctuations. Essentially all of the decrease in sedimentary rock quantity with increasing age—long expected to be the predominant pattern—takes place entirely within the first 10% of Phanerozoic time. Although Cambrian sediments overlie the GUn surface over large areas, those sediments were in turn often buried by significant quantities of younger Phanerozoic sediments; the average thickness of Phanerozoic cover over the GUn is more than 3 km.

The second way in which the GUn is unique, from the top-down point of view, is that there is an unprecedented area of crystalline igneous and metamorphic rock that is overlain by sediments of a narrow age band (**Figure 5**). Indeed, the GUn as a surface of erosion is best characterized by its reach horizontally and vertically, extending far beyond active continental margins or orogens and into the interiors of the continent, where deeply formed and metamorphosed basement rocks of even the innermost craton were exhumed before being buried by early Paleozoic and younger sediments.

4.1. Formation Mechanisms

The first-order features of the GUn—a large increase in sedimentary rock quantity to a plateau that persisted for the Phanerozoic and an unusually large area of basement rock exposed at the surface prior to being buried in the early Paleozoic—provide clear constraints on first-order timing and mode of formation: a shift from widespread net continental denudation over some amount of late Precambrian time to widespread net reburial beginning in the Cambrian. Although there can be little doubt about this general pattern and sequence of events, there are multiple models to explain how and when they happened.

4.1.1. Cryogenian glaciation. The aligned timing between Neoproterozoic glaciation and crustal recycling signals in detrital zircon data sets has led some researchers to suggest that glacial erosion is responsible for most of the GUn denudation (Keller et al. 2019). This hypothesis has the desirable property of both creating an unusually widespread erosion surface and significantly thinning the continental crust by pushing exhumed detritus off of the continental shelf and ultimately into oceanic trenches, thereby leading to marine flooding and creating the accommodation space required to rebury the GUn erosion surface. However, there is a temporal lag between the isostatic

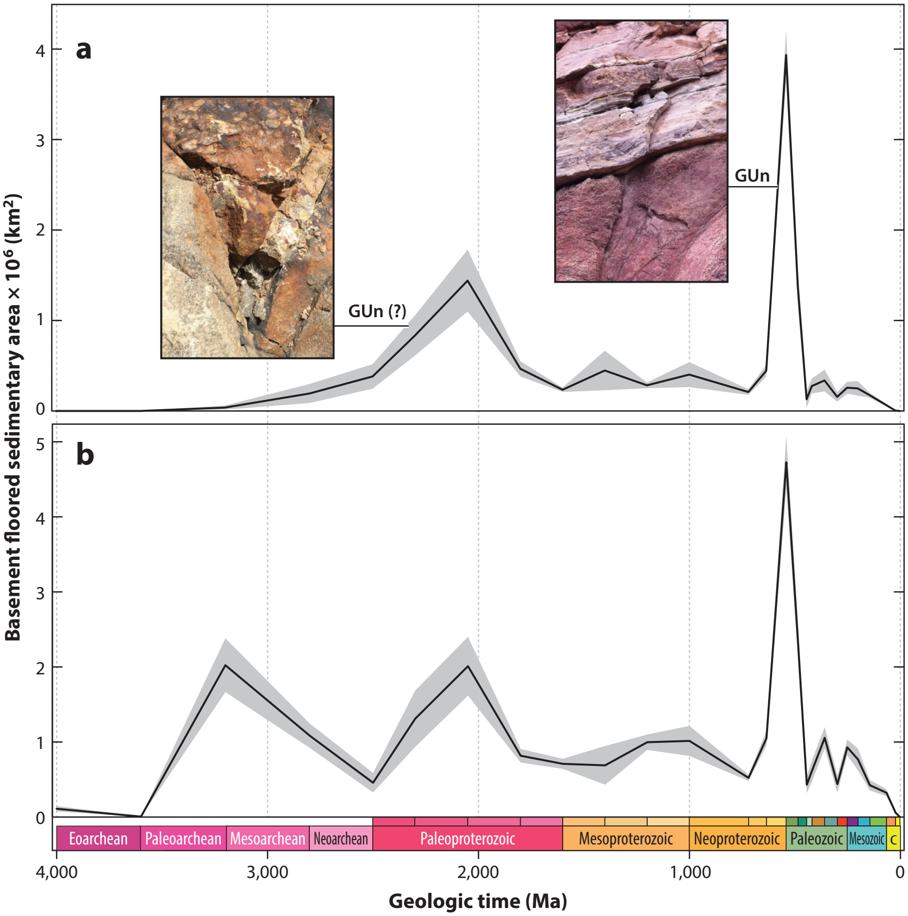


Figure 5

Area of sediments in Macrostrat columns (North America; **Figure 1**) that overlie igneous or metaigneous basement rocks. In this conservative chronostratigraphic definition of overlie, any older sedimentary or metasedimentary rocks present in a column will prevent all younger sedimentary units from being counted, even if those younger sedimentary units also overlie older basement in structurally tilted blocks. Both panels show total area of sediment that initiates in each time period and that does not overlie any older sedimentary rocks, plotted at age of period base. (*a*) Igneous rocks must be present and formed prior to the period in which the initiating sediment was deposited. (*b*) Area and age of the oldest sediments initiating in columns, regardless of age of underlying basement (if known). The photo at the Cambrian GUn shows a typical example (Cambrian marine Sawatch Formation in contact with the ~1,000 Ma Pikes Peak Granite in Colorado, USA). The photo at the possible Paleoproterozoic GUn shows a basal detrital pyrite-bearing conglomerate of the Huronian Supergroup in contact with Archean tonalitic basement (Ontario, Canada). Gray areas show one standard deviation based on 100 random samples of columns. Abbreviations: C, Cenozoic; GUn, Great Unconformity.

prediction of abrupt glacial denudation and the observed onset of significant sediment accumulation on the continent. A comprehensive reassessment of the Ediacaran system in North America demonstrates that this lag is neither an artifact of completeness or resolution in the Macrostrat data set used here nor a signature of limited sediment supply (Segessenman & Peters in press). The geochemical indicators of crustal recycling in zircons formed at this time are compelling in that they are compatible with a pulse of sediment supply to subduction zones, but they provide no direct constraints on when the erosion that produced that sediment occurred. More importantly, it remains an open question as to whether Snowball Earth is a symptom or the cause of the GUn. Exposing large areas of silicate minerals to the weathering environment has a consequence for global climate by drawing down CO_2, raising the possibility that denudation and attendant silicate weathering evidenced by the GUn were actually a contributing factor for initiating Snowball Earth (Swanson-Hysell et al. 2010, DeLucia et al. 2018).

4.1.2. Composite surface amalgamation. Multiple phases of erosion are often evident in rotated structural blocks beneath the GUn surface, and this surface is in some limited areas overlain by later Paleozoic and even younger sediments. This observation, in combination with diverse thermochronlogical histories modeled for sub-GUn rocks, has led some researchers to hypothesize that no unusual formation mechanism is required. Instead, it is proposed that the GUn is one of a number of composite surfaces formed from many smaller surfaces that amalgamated in response to multiple independent tectonic events (e.g., Karlstrom & Timmons 2012, Flowers et al. 2020, Shahkarami et al. 2020, Ricketts et al. 2021, Sturrock et al. 2021). It is indeed hard to imagine that the detailed exhumation history for the incredible diversity of rocks (igneous and sedimentary) beneath the continent-scale GUn surface was anything but heterogeneous in timing, mechanism, and magnitude. However, the physical expression of the GUn requires amalgamation by the start of the Cambrian over an area and thickness of crust that was not repeated in the Phanerozoic. It is noteworthy in this context that the effects of a complete supercontinent cycle, the formation and breakup of Pangaea, are evident within the Phanerozoic cover on the GUn (**Figure 4*a***), but that cycle did not result in the formation of a comparable erosion surface. The several other large and margin-focused tectonic events that occurred after the Cambrian, such as the Ancestral Rocky Mountain and Laramide orogenic episodes, are evident in the Phanerozoic cover (**Figure 4*a***) and in basement-cover contact relationships (**Figure 5**), but they also induced nothing comparable in magnitude or extent. Thus, something about the extent of denudation and surface amalgamation during the Precambrian phase of GUn exhumation must have been unique. An unusually long-lived supercontinent, Rodinia, and its assembly and breakup (Li et al. 2008) may have been the difference.

4.1.3. A repeated event? The GUn erosion surface of Laurentia, which cuts across the core crustal blocks of the entire continent, has a multistoried, complex history of exhumation that varies in rate and magnitude from region to region. Insofar as Snowball Earth glaciation was global and extensive, this event also undoubtedly contributed to some amount of the denudation that is evidenced by the GUn. The two mechanisms described above are, therefore, not mutually exclusive. As a singular (albeit prominent) feature of the rock record, resolving the relative importance of tectonics and glaciation and determining an ultimate formation mechanism of the GUn as a surface of erosion may prove difficult.

Interestingly, the early Paleoproterozoic seems to have many features in common with the Phanerozoic, raising the possibility that a GUn-forming sequence of events is not completely unique. Both the Phanerozoic and Paleoproterozoic are associated with peaks in continental sediment coverage (**Figure 4*a***), and much of that sediment rests on basement rocks that were exposed at the surface prior to being buried (**Figure 5*a***). An apparent global glaciation also occurs tantalizingly close to the base of each pulse of sedimentation, reinforcing the possibility that subaerial exposure of igneous rocks over large areas of the continents is a mechanism by which to enter glacial conditions and/or denude a continent prior to reburying it. There are also some similarities in the geochemical signatures of crustal recycling in zircon, suggesting a similar episode of denudation preceding growth in sedimentary cover (Keller et al. 2019). These possible similarities, even if they do hold up to scrutiny, do not help resolve the ultimate formation mechanism of the GUn. However, uncertainty about when and how this physical feature formed does not detract from our ability to understand the impacts that its formation had on the long-term evolution of the Earth-life system.

4.2. Implications

The stepwise transition from continental denudation to sedimentation evidenced by the GUn has several major implications for environmental change and biogeochemical cycling during at least one of the most important transitions in the entire evolutionary history of life and environment, the Neoproterozoic–Paleozoic transition.

4.2.1. Exposure of basement. Formation of the GUn required the exhumation of large areas of heterogeneous Precambrian-aged rocks that formed and/or were metamorphosed at crustal depths; exhumation at the ∼10-km scale is commonly indicated (DeLucia et al. 2018, Ricketts et al. 2021). Rocks exposed by this crustal-scale exhumation spent an unknown amount of time at the surface prior to being reburied beneath early Paleozoic and younger sedimentary cover. Thus, for at least some of the later Neoproterozoic and early Cambrian, there was an unprecedented area of crystalline igneous and metamorphic basement rock at or very near the surface over essentially the entire continent of North America and many other paleocontinents globally, prominently Baltica, Siberia, Gondwana, and North China (Brasier 1980, Laird et al. 1991, Sears & Price 2003, Avigad et al. 2005, He et al. 2017, Wan et al. 2019, Hall et al. 2021). Within just a few tens of millions of years after the start of the Cambrian, this was no longer the case; most (if not all) of this crystalline rock was progressively buried, and it largely remains so today.

The exposure of deeply formed crustal rocks to atmospheric weathering in Earth's surface environments has significant implications for both the reactants and the products of the chemical weathering process. Global rates of chemical weathering are controlled to a first order by the exposure of fresh mineral surfaces to the atmosphere (Raymo & Ruddiman 1992, Millot et al. 2002, Mortatti & Probst 2003). Prior to reburial of the GUn surface by Cambrian and younger sediments, atmospheric weathering processes acted on the vast area of exposed crystalline basement, as evidenced by paleoweathering features developed into the uppermost basement (Driese et al. 2007, Liivamägi et al. 2015, Medaris et al. 2018, Colwyn et al. 2019, Pevehouse et al. 2020). Extensive continental weathering is further evidenced by a peak in $^{87}Sr/^{86}Sr$ that represents a high in at least the past 900 Myr. This peak is strong additional evidence for elevated rates of continental weathering relative to seafloor spreading (Maloof et al. 2010a). Other evidence for enhanced weathering at the Neoproterozoic–Cambrian transition comes from Hg anomalies and isotope values (Liu et al. 2021) and $\delta^{26}Mg$ and whole rock geochemistry of marine shales (Zhang et al. 2021).

Although enhanced continental weathering consumes atmospheric CO_2 [and O_2 (see Section 4.2.3)] leading to climate deterioration, greenhouse conditions in the Cambrian, modeled at less than 20 times pCO_2 (Berner 2006, Hearing et al. 2021), were sustained by high rates of arc volcanism (McKenzie et al. 2014, 2016), likely enhanced by an increased CO_2 contribution from metamorphism of sediments deposited on oceanic crust in the Precambrian. Together, these observations are congruent with a model of the early Cambrian carbon cycle in suggesting unusually high throughput of carbon (Maloof et al. 2010b). As described below, marine sedimentary rocks of the Sauk Sequence bear distinct properties that reflect an elevated input of chemical weathering products to the oceans across the Cambrian period and into the Early Ordovician, as reactive basement rock exposed in continental interiors was gradually covered by predominately shallow marine sediments.

4.2.2. Transgressive shoreface erosion and chemical weathering flux. The final transition from net denudation and weathering of the GUn to reburial and isolation from the surface environment is recorded over most of the continent by shoreface erosion associated with the Sauk transgression (Peters & Gaines 2012). This had the effect of stripping away the regolith, soils, and saprolites that were developed on the GUn surface in most areas, exposing more competent bedrock during transgression. It is important to note that, at all localities studied across several paleocontinents, this bedrock still shows prominent signs of chemical weathering under the Ediacaran–Cambrian atmosphere (Avigad et al. 2005, Driese et al. 2007, Medaris et al. 2018, Pevehouse et al. 2020), and basement at these localities is interpreted to represent the lower portions of paleoweathering profiles, with unknown thicknesses of saprolite and soil removed from above them. Basement rock was then reburied by the detritus mobilized from the continental surface by the transgressive shoreface system.

In the basal Cambrian sedimentary succession, the shift from shoreface erosion to marine sediment deposition manifests in several different ways. First, on the whole, Cambrian marine sandstones in North America and beyond are well known for their textural and compositional maturity (e.g., Dott 2003, Avigad et al. 2005) but are often arkoskic at their base. Shoreface reworking of erg-like aeolian sands and deeply weathered basement across the continent during transgression would have produced just this kind of sharp juxtaposition. By the Ordovician, continental shelves, which were previously much more limited in their extent along the margins of continents, had expanded to encompass essentially the entire cratonic platform, reaching a peak in continental flooding in the early Paleozoic that was likely unmatched in at least the last billion years.

Cambrian sedimentary environments of North America and many other paleocontinents are characterized by deposition in three broad facies belts, an inner detrital clastic belt, a carbonate platform belt, and an outer detrital belt that occupied outer shelf settings. Distinct signatures of chemical sedimentation in each setting suggest an enhanced flux of continental weathering products, most prominently HCO_3^-, Ca^{2+}, and Fe^{3+}, to the oceans. For example, inner detrital belt settings are characterized by a peak in the relative abundance of glauconite-bearing units (Peters & Gaines 2012). Several aspects of the occurrence of this ferruginous authigenic clay mineral also suggest more rapid formation across a broader range of environments than known from the modern or classically interpreted from the rock record (Odin & Matter 1981, Chafetz & Reid 2000). The abundance of glauconite and its nonanalog mode(s) of formation appear to require an abundant supply of iron and kaolinite to the oceans (Choudhury et al. 2021), both as products of intense continental weathering. In the Sauk Sequence, kaolinite delivered to the oceans was formed as a product of basement weathering (Avigad et al. 2005, Liivamägi et al. 2015, Pevehouse et al. 2020, Hall et al. 2021). The formation of kaolinite and its delivery to the ocean would have been accompanied by iron oxides, also derived from weathering of basement rocks and often associated with clay mineral surfaces in particulate form (Stucki et al. 2012). An elevated supply of iron to the ocean is congruent with other notable features of Cambrian sandstones, such as Fe-ooids and cements (Van Houten 1990).

The Cambrian shelf carbonate factory also reached an all-time high in area and burial flux in North America (Peters & Gaines 2012). Characteristically, Cambrian carbonates are grain poor compared to later Paleozoic carbonates, and they exhibit characteristics consistent with direct precipitation from seawater (Pruss & Clemente 2011). As long recognized, high sea level and elevated CO_2 (greenhouse) are also important controls on carbonate production (Mackenzie & Morse 1992), but sustained input of HCO_3^- and Ca^{2+} to the oceans from chemical weathering of the continents is also required to account for high rates of carbonate production. High throughput of carbon from the atmosphere to the oceans via continental weathering and to the sedimentary reservoir is predicted by carbon cycle modeling (Maloof et al. 2010b).

Shale-dominated outer detrital belt environments of the Sauk Sequence are characterized by pervasive patterns of near-seafloor carbonate precipitation and elevated carbonate content when compared to shale composite standards (Peters & Gaines 2012). Whereas carbonate cements in mudstones typically form slowly in diagenetic settings as a product of anaerobic decay of organic matter, petrographic and isotopic evidence from carbonate cements in Cambrian shales indicates rapid precipitation at or near the seafloor that was forced by high alkalinity of bottom waters, rather than by organic carbon cycling in sediments (Gaines et al. 2012, Gaines 2014). Even some examples of Cambrian carbonate concretions, which are otherwise similar to those found throughout the Phanerozoic (Raiswell & Fisher 2000), nucleated around sites of organic decay, but, volumetrically, they incorporated far more bicarbonate sourced from seawater than from microbial activity (Gaines & Vorhies 2016).

In sum, these observations from Cambrian–Early Ordovician sedimentary rocks provide evidence of transgressive shoreface erosion and unusual patterns of chemical sedimentation indicative of an enhanced continental weathering flux to the oceans. We relate these patterns directly to the unprecedented exposure of basement rock across continents and their interiors during the Neoproterozoic and earliest Phanerozoic. We interpret this as evidence of a transient episode of seawater chemistry during the late Neoproterozoic rise of animals and their subsequent Cambrian diversification. This transient episode was characterized not only by elevated alkalinity but also by enhanced input of Fe^{3+} and likely of P, a bedrock-derived nutrient, as the delivery of P to the oceans is coupled to that of Fe (Filippelli 2008). This transient episode may have directly influenced the early evolution of animals via the control of seawater chemistry on early biomineralization (Tucker 1992; Knoll 2003; Porter 2007; Zhuravlev & Wood 2008; Wood 2011, 2018; Wood et al. 2017; Porter et al. 2020) as well as via sustained delivery of iron and phosphorus, two of the most important limiting nutrients for marine productivity.

4.2.3. Continental sedimentation and oxygenation. The Phanerozoic burial of the GUn surface indicates a dramatic change from the Precambrian in how sediments are partitioned between oceanic and continental sedimentary reservoirs. Oceanic crust can (and does) accumulate appreciably large sedimentary volumes, holding $\sim 202 \times 10^6$ km^3 of sediment (**Figure 4*c***). Yet this accumulation is considerably smaller than the total volume of sediments buried on continental crust [$\sim 791 \times 10^6$ km^3 (**Figure 4*a***)]—a difference made more striking when one considers that only ~35% of Earth's surface is floored by continental crust (**Figure 4*b***). One (but not the only) reason that Earth's sedimentary shell is mostly continental is the fast cycling of oceanic crust (red line in **Figure 4*c***). As oceanic crust is consumed at subduction zones, sediments deposited on it are subjected to the same destructive processes, resulting in persistently downward trajectories in quantity-age time series for those sediments (black and orange lines in **Figure 4*c***). In other words, the oceanic sediment reservoir cycles in a fashion exactly as modeled by Gregor (1970), meaning that its extant total mass could potentially be constant throughout geological time. By contrast, the continental sediment reservoir, while also subject to destruction, can grow over geologic time, owing to its position on more tectonically stable crust. This growth-dominant signal is expressed in the continental rock quantity-age pattern (**Figure 4**), which contrasts sharply with that of oceanic crust.

Viewed through this lens, a key implication of the GUn is that it encompasses a major shift in the locus of sedimentation, up from fast-cycling oceanic crustal reservoirs and into long-term continental storage. In North America, sedimentary area (**Figure 4*a***) is persistently low throughout the Proterozoic Eon (mean ±1 standard deviation = $1.5 \pm 0.9 \times 10^6$ km^2) compared to the Phanerozoic ($5.7 \pm 2.0 \times 10^6$ km^2). These differences imply that net rates of sediment sequestration on continental crust were dramatically lower in the Proterozoic than in the Phanerozoic. Such a change does not require that *total* gross sediment flux, which is tied to processes such as global weathering, erosion rates, and river sediment delivery, was lower in the Proterozoic. Rather, it requires only that a smaller proportion of this gross flux was trapped in continental basins and depocenters in the Proterozoic, with a larger proportion being shunted off the continents and into the faster-cycling, deeper ocean basins (**Figure 4*c***). Indeed, the volume of sediment that would have been produced during the exhumation evidenced by the GUn, integrated over the entire continent, cannot be accounted for in the surviving Neoproterozoic rock record. It is, therefore, likely that most of the sediments were transferred off of the continents and into ocean basins along continental margins and then recycled back onto the continent as Precambrian-aged seafloor was consumed during the Paleozoic (Peters et al. 2021).

An accelerated growth phase of the continental sedimentary shell also meant that the continental inventory of all buried sedimentary phases grew at a faster rate and reached a larger total mass, sequestering with them compounds and elements that exert an important control on surface chemistry, such as organic carbon. Organic carbon, when created as a result of oxygenic photosynthesis (e.g., $CO_2 + H_2O \rightarrow CH_2O + O_2$), releases free oxygen in the surface environment. However, while photosynthesis—a biological process—is a necessity for accumulating large quantities of atmospheric oxygen, its operation alone does not guarantee an O_2-rich atmosphere (21% by volume today). For example, evolution for oxygenic photosynthesis may have predated the first permanent rise of atmospheric oxygen (the 2.2–2.4 Ga Great Oxidation Event) by hundreds of millions of years (e.g., Satkoski et al. 2015), with modern levels of atmospheric oxygen not reached until sometime in the late Neoproterozoic to Paleozoic (Lyons et al. 2014). The disconnect between biological activity and atmospheric composition is also demonstrated by modern O_2 production fluxes. Global net primary production is estimated to be 104.9×10^{15} g C per year (Field et al. 1998), a flux that would double the amount of O_2 in our atmosphere in just 4,200–4,300 years. This does not happen because very nearly all this oxygen is consumed through respiration by heterotrophs. Only when some organic carbon is sequestered in sediments, and protected from respiration, can O_2 accumulate in the atmosphere. Intriguingly, even this is not sufficient to maintain an oxygen-rich atmosphere because there are other sinks for O_2 that are continually being produced by plate tectonic processes, reduced Fe-bearing minerals in particular (Lécuyer & Ricard 1999). Thus, a steady-state rock cycle, in which organic carbon (and sulfur) burial is matched by organic carbon (and sulfur) weathering, is potentially problematic for maintaining an oxygen-rich atmosphere.

Given this dependence of net O_2 production on the sequestration of organic carbon (and biogenic pyrite) in sedimentary rocks, it is sensible that the empirical history of continental sediment accumulation (**Figure 4*a***), which indicates net growth in mass over geologic time, has strong similarities to the history of atmospheric oxygen (Husson & Peters 2017, 2018). It remains possible that total organic carbon burial was similar between the Proterozoic and Phanerozoic, a conclusion supported by traditional interpretations of carbon isotope records (e.g., Krissansen-Totton et al. 2015). However, if most Proterozoic sediments were deposited on fast-cycling oceanic crust, the residence time of organic carbon in Earth's crustal reservoir would be substantially shorter compared to the Phanerozoic. If the sediment destruction that occurs on convergent margins also leads to organically produced carbon (and sulfur) oxidation (Hayes & Waldbauer 2006), a Proterozoic "cycling world" would lead to stronger O_2 sinks compared to a Phanerozoic "growth world." At the same time, in a cycling world, more of the continental crust is being denuded and its rocks exposed to subaerial weathering, potentially expanding the sinks for O_2 (and CO_2). Thus, the shift from cycling world to growth world evidenced by the GUn has the potential to affect atmospheric oxygen concentration in two reinforcing ways: by increasing the net source of O_2 through long-term organic carbon burial and by reducing the area of the continental crust that is undergoing denudation, which continually exposes O_2-reactive minerals to the surface environment.

For all of these reasons, the formation of the GUn is a clear candidate as the first-order (10^8 Myr), proximal control on the notably protracted long-term history of atmospheric oxygenation (Lyons et al. 2014). Superimposed, second-order (10^7 Myr) changes in atmospheric oxygen concentration, such as the increase that occurred in the Carboniferous (Berner & Canfield 1989, Berner 1991), have always been attributed to changes in the average composition of sediment entering the rock record, and this remains unchanged. Indeed, the Phanerozoic sedimentary volume documented here (**Figure 4*a***) exhibits shifts in composition that predict exactly these types of long-recognized, second-order rises and falls in Phanerozoic atmosphere O_2 (Husson & Peters 2017).

5. COMMON CAUSE REVISITED

One of the most puzzling patterns in the history of life on Earth is that life appears very early and acquires a diverse range of metabolisms and organizational levels, including oxygenic photosynthesis and macroscopic eukaryotic forms, by 2 Ga. Despite this initial flourish, it takes life nearly 1.5 Gyr more to make its next big move, the origin of metazoans in the late Neoproterozoic and their rapid diversification into the Cambrian (**Figure 6**). As is the case within the Phanerozoic, there is a remarkable degree of similarity between the empirical record of sedimentary rock quantity-age in continental crust and the first-order history of all of life and of molecular oxygen in the atmosphere. It is not plausible that this similarity reflects a mega-bias in the geological record that has forced the evolution of life and environment to passively resemble the quantity-age distribution of sedimentary rocks in the continental crust. Instead, first-order patterns in the sedimentary rock record are likely indicative of real changes in the fundamental boundary conditions that define the surface environment and that these changes have paced the timing of biological evolution and atmospheric oxygenation.

The distinctly non-steady-state signal of episodic denudation and growth that is predominant in continental crustal rocks suggests a fascinating model for the long-term coevolution of Earth and life, one in which the proximal forcing mechanisms for biological evolution and atmospheric composition are encoded in the growth (and decay) of sediments in continental and oceanic reservoirs. Switches between these reservoirs as the predominant locus of sedimentation, and the attendant effects related to continental shelf area and the exposure and weathering of the continents, would provide a mechanism to drive transient (on the scale of Earth history) directional shifts in the redox conditions of the surface environment, even in the absence of anything fundamentally different about the biological system or the input of new material from the mantle.

Thus, in our view of life, evolution is generally ready to proceed quickly when the physical Earth system changes in a way that allows continents to grow sedimentary mass, but evolution can be kept in check for extended periods of time, as well as very seriously challenged, when a steady-state first- to second-order sediment cycling regime takes hold. Within the Phanerozoic, changes in the extents of shallow continental seas and associated formation and breakup of Pangea, as well as changes in the bulk composition of sediments entering the continental sedimentary reservoir, have exerted strong common-cause controls on the macroevolutionary history of life. It is an open question as to whether the Phanerozoic-like condition will persist, even with the additional resilience that has likely been acquired by Phanerozoic biological innovations and the effects they are having on organic carbon (and sulfur) burial in cycling, steady-state oceanic sedimentary reservoirs.

6. CONCLUSION AND FUTURE DIRECTIONS

Quantifying the rock record using the approach of macrostratigraphy offers many opportunities for assessing and modeling the long-term evolution of Earth's surface environment. Here we have focused on only the simplest macrostratigraphic quantities related to total surviving rock area and volume because these measurements have deep conceptual roots in paleobiology and Earth systems science and because the results for all geological time are compelling. Analyses of individual lithologic, tectonic, and environmental components of the rock record, in combination with integrated petrographic and geochemical measurements, fossil occurrences, and paleogeographic reconstructions, are now possible. Our analysis has focused on continent- and ocean basin–scale data sets, but the Macrostrat data model can be applied at many different scales of temporal and spatial resolution (Peters et al. 2018), ranging from measured sections in individual sedimentary basins (e.g., Aswasereelert et al. 2013) to centimeter-by-centimeter lithological logs from offshore drilling sites (Fraass et al. 2020) to intermediate-resolution, time interval–focused data that combine multiple proxy records into a macrostratigraphic framework (Segessenman & Peters in press). Capitalizing on the capacity of the Macrostrat data model by integrating data from other sample-based resources (e.g., Lehnert et al. 2000, Tauxe et al. 2016, Farrell et al. 2021) and developing tools to explore, analyze, edit, and enter measured section/core data and regional columns will allow the hypotheses outlined here and many others to be further tested and refined.

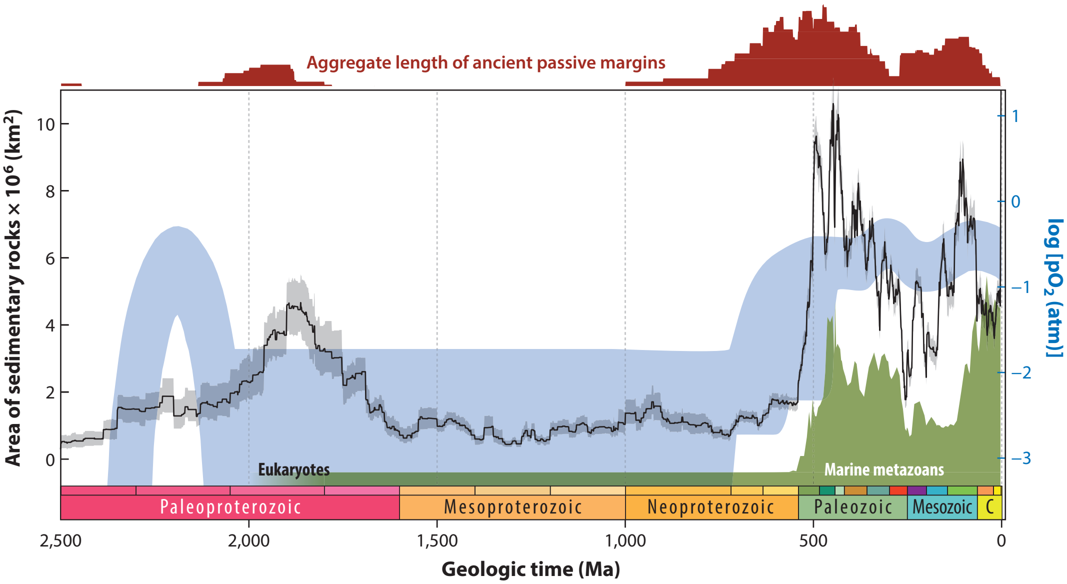


Figure 6

A representation of the coevolution of life, the environment, and the rock record. A time series of continental sedimentary rock area in North America (*left axis*, and also **Figure 4*a***) is compared to plausible levels of atmospheric oxygen throughout Earth history [*right axis* (modified from Lyons et al. 2014)] and the generic diversity (scaled) of marine metazoans (**Figure 2**). The red histogram at the top shows a normalized record of the global aggregate length of ancient passive margins (Bradley 2008). Here, ancient is defined as no longer accumulating sediments; therefore, the tabulation is inclusive for ages older than 180 Ma. Only those margins classified as passive with medium-high confidence are included (rated A or B quality by Bradley 2008). Gray areas around black line show one standard deviation based on 100 bootstrap replicate samples of units. Abbreviation: C, Cenozoic.

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Errata

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