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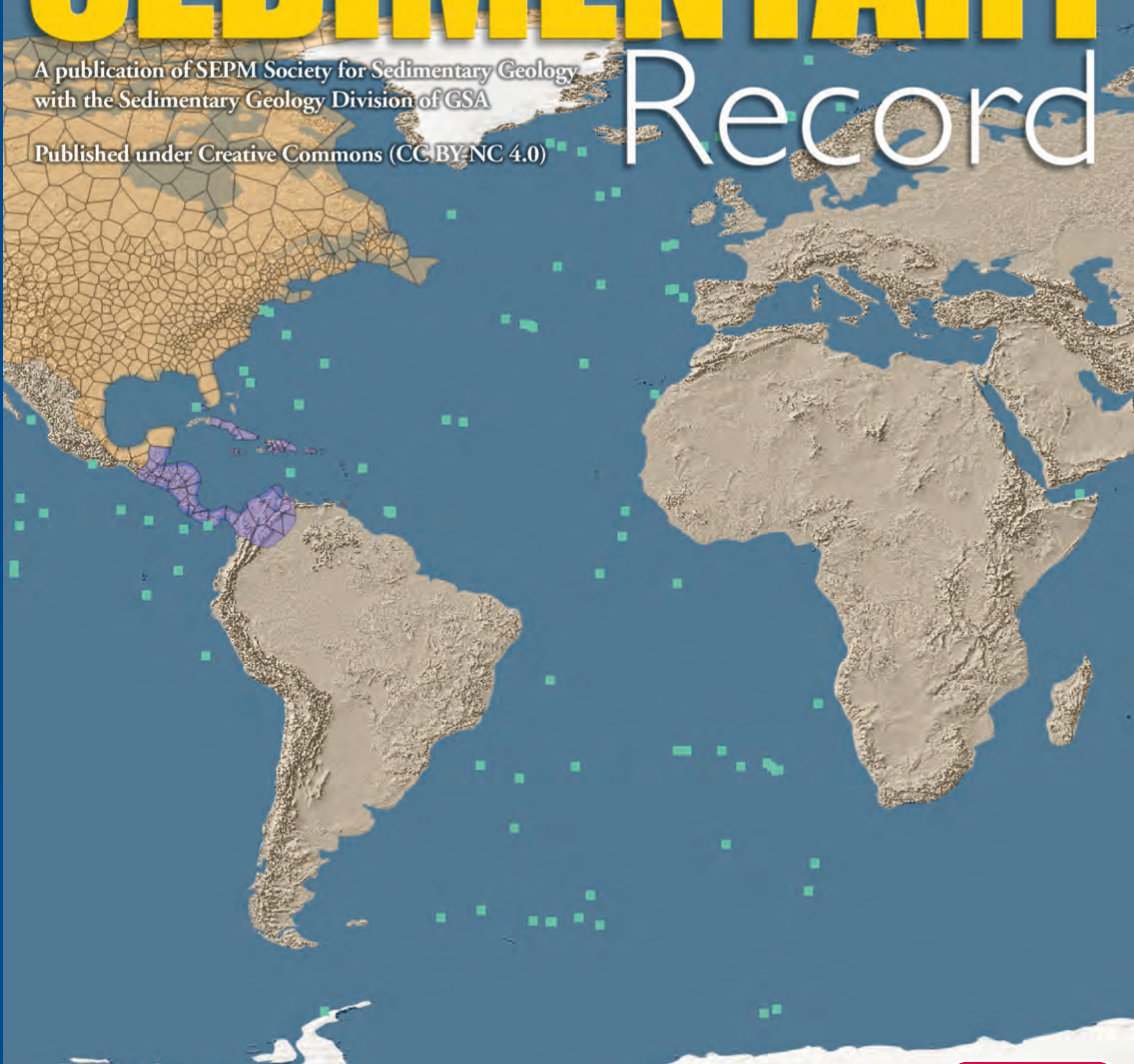

INSIDE: WE NEED A GLOBAL COMPREHENSIVE STRATIGRAPHIC DATABASE: HERE'S A START

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We need a global comprehensive stratigraphic database: here's a start

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Major transitions in the abundance, diversity, and composition of life on Earth are readily detected by a survey of a coarsely-resolved stratigraphic fossil record. However, calibrating the magnitude and impacts of biological diversification, mass extinctions, and key biological transitions requires a discipline-wide, multi-scale and hierarchical approach. Finding and describing new fossils and refining biological systematics are foundational to paleontology, but synthesizing temporally-, geographically-, and taxonomically-resolved fossil occurrences from around the globe is also required to address many paleobiological problems, such as the trajectory of global biodiversity (Alroy et al., 2008). Multiple scales of data collection and analysis are necessary because without field- and specimen-based work we would have no basis to interrogate life history and because macroevolutionary processes cannot be understood simply by scaling-up processes observed within individual populations or species (Jablonski, 2017).

Sedimentary geology is, in many respects, similar. Understanding sediment transport and depositional processes, the mechanisms that govern stratal geometries and the formation of basin fill successions, and then applying that understanding to the characterization and correlation of sedimentary successions, is essential. However, global-scale processes and events can propagate downward to affect the behavior of individual sedimentary systems, and the processes that govern the formation and destruction of the global sedimentary rock record cannot be revealed by scaling-up basin-scale mechanisms. Instead, synthesizing temporally-, geographically, and sedimentologically-resolved stratigraphic data from across continents and then quantitatively interrogating those data are required in order to fully characterize the large-scale sedimentary record and to understanding processes governing long-term sedimentary processes. Here we summarize some basic results from one attempt to synthesize stratigraphic data in this capacity and then make a case for why building a globally comprehensive stratigraphic database is a worthy disciplinary priority.

MACROSTRAT DATABASE

Just as "macroevolutionary" research involves the analysis of multiple lineages and the interrogation of evolutionary processes operating above the species-level, "macrostratigraphy" involves the analysis of multiple stratigraphic successions and the interrogation of processes operating at or above the level of individual sedimentary basins (Peters 2006; Hannisdal and Peters, 2010; Aswaserleet et al., 2013). Macrostratigraphy is not a different approach to stratigraphy; it is an approach to systematizing and analyzing stratigraphic data and quantitatively summarizing spatial and temporal patterns in the rock record.

Macrostrat, a relational geospatial database designed to facilitate quantitative analyses of the upper crust, contains general, but also comprehensive, chronostratigraphic summaries of 34,931 lithologically and temporally-resolved surface and subsurface geological rock units distributed across 1,342 regions covering 26.7 million km2 in North and South America, the Caribbean, New Zealand and from 132 offshore drilling sites (Fig. 1). Rock units in each column are linked to general lithology descriptions and lithostratigraphic nomenclatural hierarchies. In addition, many units are linked to field- and sample-derived data, including fossil occurrences in the Paleobiology Database and more than 180,000 geochemical and outcrop-derived measurements from multiple sources (Peters et al., 2018). Because Macrostrat columns characterize the chronostratigraphic distribution of rock bodies, not their physical contact relationships (e.g., a dike in a Macrostrat column is referenced to its temporal position, not its physical contacts), we have also integrated more than 2.2 million bedrock map polygons from over 180 different geological map sources, thereby providing constraints on 2D surface expression and laying the groundwork for physical 3D modeling. Field-based descriptions of units associated with map publications augment Macrostrat unit properties and, reciprocally, Macrostrat units matched to map units can improve age constraints (https://macrostrat.org/map). Most Macrostrat data are accessible via an Application Programming Interface (API: https://macrostrat.org/api), which is used by a variety of third-

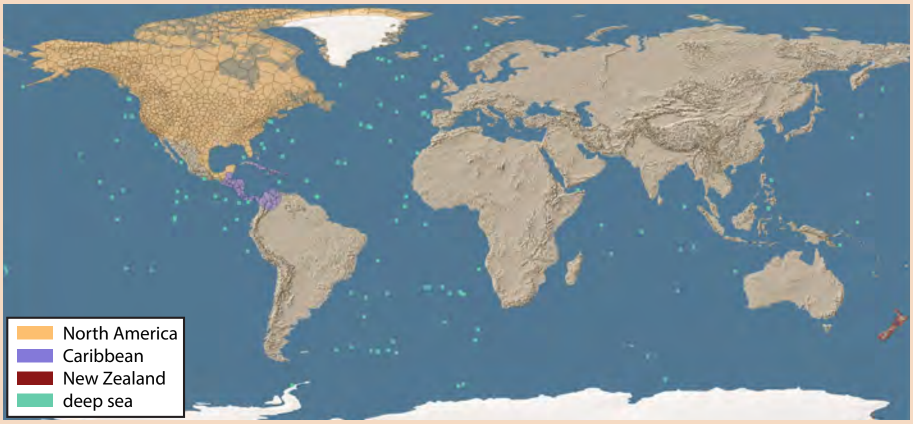

Figure 1: Distribution of Macrostrat columns.

party mobile applications, including Rockd, a Macrostrat team product, and Flyover Country, built by an independent collaborative group. The API serves as the basis for the results presented here.

SURVIVING ROCK QUANTITY

How much sedimentary rock is on Earth and what is its distribution through space, lithology, environment, and time? This is a fundamental question that Earth scientists should be able to answer in a principled way. Some general expectations are reflected in the prevalent view of rock cycling, traceable all the way back to Hutton's "sedimentary cycle" and Darwin's "tattered manuscript" metaphor for the geologic record. If, in adhering to this view, we assume that the formation and destruction of sediments is a continuous random process, then a basic prediction is that the strongest signal in the surviving sedimentary record should be one of continual destruction. Degradation of this type would be expressed as exponential decline in sediment quantity with increasing age (Gregor, 1970; Blatt and Jones, 1975). If we further assume that rates of formation and destruction of sediments are equal and stochastically constant, then the prediction is that the total mass of sediment is invariant over time, with only a small and constant mass fraction cycling through the surface environment (Garrels and Mackenzie, 1979; Mackenzie and Pigott, 1981). Bob Berner used this type of steady-state model of the sedimentary record to characterize the carbon and sulfur cycles and, in turn, produce one of the first models of atmospheric pO_2 across Phanerozoic time (Berner and Canfield, 1989). Because the total mass of sedimentary rock does not change in this conceptualization, shifts in the composition of the sedimentary reservoir (i.e., changing proportion of carbonates vs. shales) were invoked to vary the total amount of reduced phases (namely, organic carbon and pyrite) buried per unit time, which in turn drove a time-varying geologic flux of oxygen into and out of the surface environment.

Most work in studying Earth's surface history has since moved to isotope-based methods of constraining organic carbon and pyrite fluxes (Des Marais et al., 1992; Canfield and Teske, 1996), as well as more theoretically-based models of atmospheric O_2 (Bergman et al., 2004; Goldblatt et al., 2006; Laakso and Schrag, 2014). A Huttonian view of the sedimentary cycle, however, is still widely held and this view affects how geologic records are interpreted. The total surviving amount of sediment in the North American and Caribbean (NAC) regions covered by Macrostrat (Fig. 1) does not, however, exhibit the expected exponential decline with increasing age (Fig. 2). Instead, we observe two separate states in sediment quantity, one during the Precambrian and one during the Phanerozoic, each of which differs dramatically in mean but exhibits no prominent long-term trends. Superimposed on these two states are fluctuations that, at least during the Phanerozoic, closely correspond to Sloss's (Sloss, 1963)

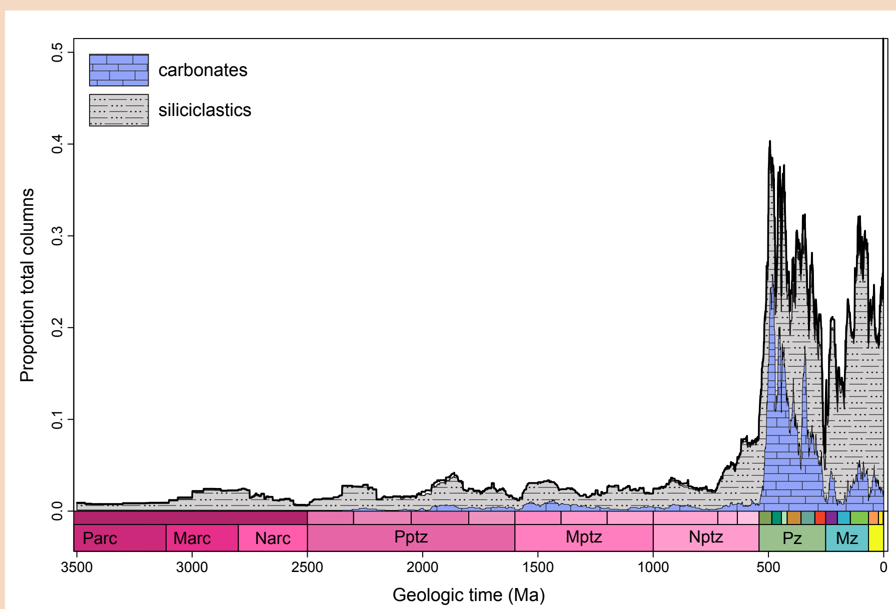

Figure 2: Total sedimentary rock quantity in the North America-Caribbean region. Quantity is measured as proportion of 1,013 columns in this area that contain sedimentary and/or metasedimentary units. Units are weighted by the proportion of the unit that is sedimentary (e.g., a unit composed of 50% basalt and 50% volcaniclastic sediment would contribute 0.5/1,013 over its duration).

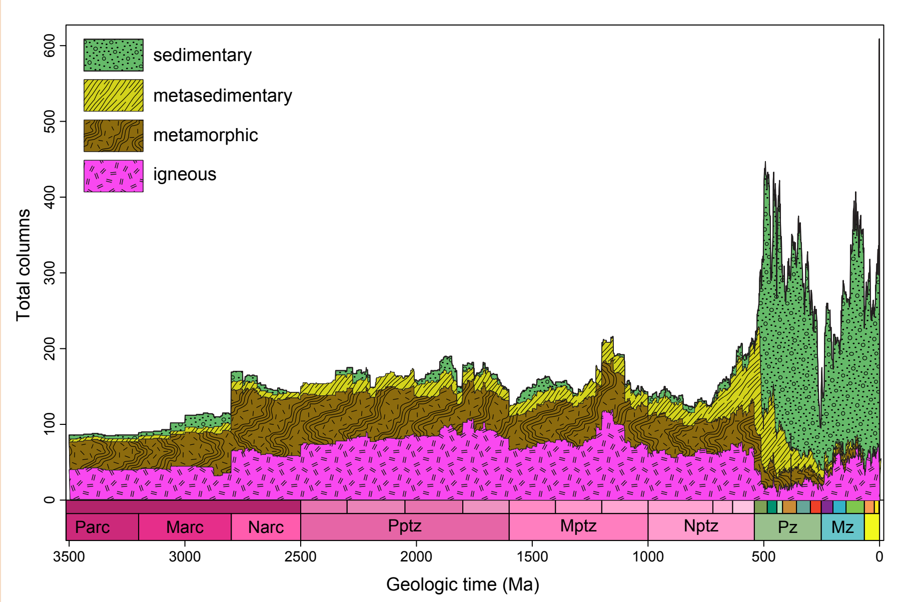

Figure 3: Total rock quantity, measured as in Fig. 2 for all rock types.

"tectonostratigraphic" units and the supercontinent cycle (Meyers and Peters; Zaffos et al., 2017). Several shorter-term fluctuations in are also evidenced, including a large drop in quantity corresponding in time to the sea level fall during the late Ordovician glaciation (Finnegan et al., 2012).

The results in Fig. 2 provide prima facie evidence for the hypothesis that the traditional erosion-dominate view of sedimentary cycling is not the primary process signal in the surviving sedimentary rock record. Instead, the weight of evidence indicates that, in aggregate, the sedimentary record at this temporal and spatial scale (Fig. 1) preserves a time-varying process signal that reflects tectonic- and climate-driven changes in rates of net sediment accumulation. If we extend the analysis to include all rock types (Fig. 3), the picture remains largely the same.

Portions of the sedimentary record do strongly support the standard model of sediment cycling, however. Sediments deposited on oceanic crust are represented in Macrostrat by 132 completely- or nearly completely-cored offshore IODP, DSDP, and ODP drilling sites (Peters et al., 2013; Fraass et al., 2015). Deep sea sediments are well-described by an exponential decline (Fig. 4). Non-marine sediments, which include a geomorphologically and tectonically diverse assemblage of sediments in various stages of transport and storage on the landscape, also exhibit approximately exponential decrease in quantity with increasing age, suggesting a strong overprint of erosion in their mass-age relationship (see Peters and Husson, 2017). Interestingly, in the Phanerozoic, there is an approximately exponential increase in the number of metasedimentary rock units with increasing age (Fig. 4), suggesting that once sediments are deposited on (or are accreted to) the continent, there is a continuous random probability that they will become sufficiently modified to be described as metasedimentary (though it should be noted that there is currently no quantitative assessment of metamorphic grade for Macrostrat units and many usages of the general field term "quartzite," for example, should be replaced by "well-cemented quartz arenite").

Although erosion isn't the dominant signal in the large-scale sedimentary record (Fig. 2), some signatures of erosion are masked by the spatial resolution of Macrostrat columns. For example, epicontinental columns (Fig. 1) cover areas that are often larger than the footprint of erosional features. For example, the unambiguously erosional topography that often separates Sloss-scale sequences in the cratonic interior are not fully quantitatively captured by the data shown in Figure 2. Similarly, areas of crustal deformation in which whole crustal blocks have been rotated and truncated appear, from Macrostrat's chronostratigraphic view, to not

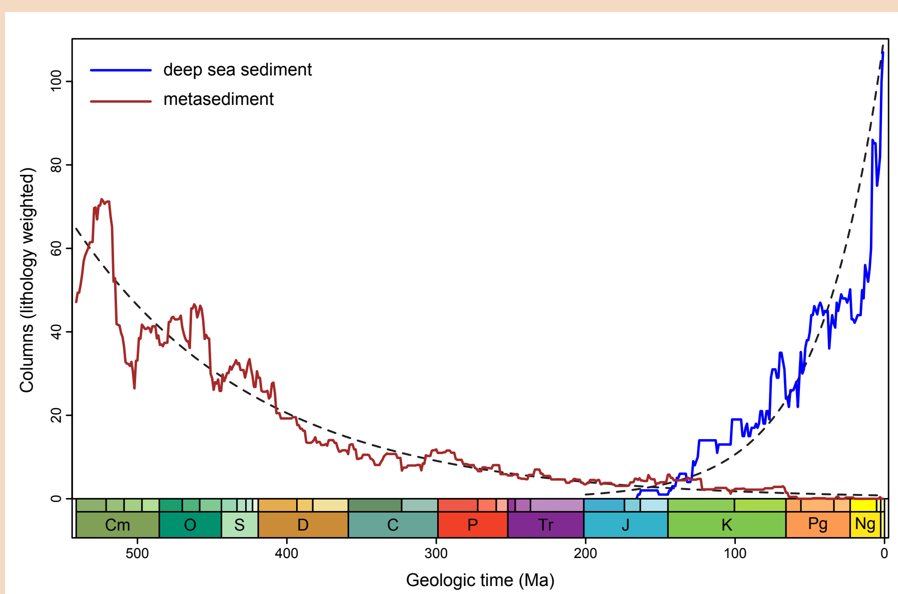

Figure 4: Total number of columns in the deep sea (on oceanic crust) that contain sediment and the total number of metasedimentary columns. Units are weighted by rock type as in Fig. 2 and 3. Dashed lines show exponential fits to the data. For metasediment, y=

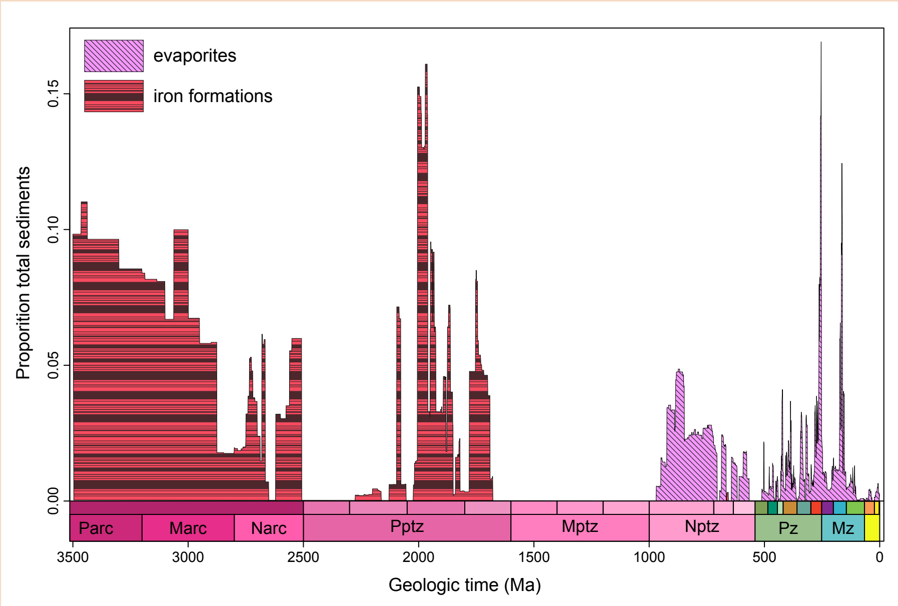

Figure 5: Abundance of evaporite- and iron formation-bearing units measured as a proportion of total sedimentary units, which varies over time as shown in Fig. 2.

have been eroded at all. For example, the Precambrian Grand Canyon Supergroup is represented "intact" in Macrostrat's chronostratigraphic view for all columns that intersect it, despite the fact that it is prominently truncated by an angular unconformity in which the entire supergroup and underlying Vishnu Schist are covered by Cambrian sediments (Karlstrom and Timmons, 2012). An analogy, then, is to view Macrostrat's scale of analysis as equivalent to the wooden frame of a building that is infested by termites. The whole sedimentary record is perforated by multiple generations of erosional processes, operating at many different scales, and that signature of erosion is evident upon close inspection. Nevertheless, the framework itself still stands, as originally constructed.

Changes in sediment accommodation and the properties of the sediments that fill it are driven by changes in the state of the Earth system, which manifest in several different ways. For example, the abundance of banded iron formations and evaporites changes markedly over time (Fig. 5). Most aspects of their age-quantity patterns in the surviving rock record are not artifacts of preservation. Instead, this pattern reflects major changes in the state of the surface environment - namely, rising levels of atmospheric O_2 and sulfate in the global ocean (e.g., Isley and Abbot, 1999; Horita et al., 2002), with shorter-term variability caused by shifts in the availability of environments suitable for evaporite formation (Halevy et al., 2012). Similarly, the "Great Unconformity," a surface of non-deposition and variable amounts of erosion separating Phanerozoic sediment from Precambrian crystalline basement rocks (and a much lesser amount of Precambrian sediment), is not easily accounted for, accept by invoking a large increase in net sediment accumulation on the continents (Peters and Gaines, 2012; Husson and Peters, 2017). Whether or not the large increase in net sedimentation across the Great Unconformity was accentuated or driven by a period of prolonged continental denudation during the late Precambrian, remains to be tested.

IMPLICATIONS AND UTILITY

Major features in the history of life and atmospheric oxygen are mirrored by a simple quantitative description of the timing and magnitude of changes in the total amount of surviving sediment vs. age (Fig. 2). This is true over the past 3.5 billion years (Husson and Peters, 2017) and within the confines of the Phanerozoic, when the temporal pattern of sedimentation

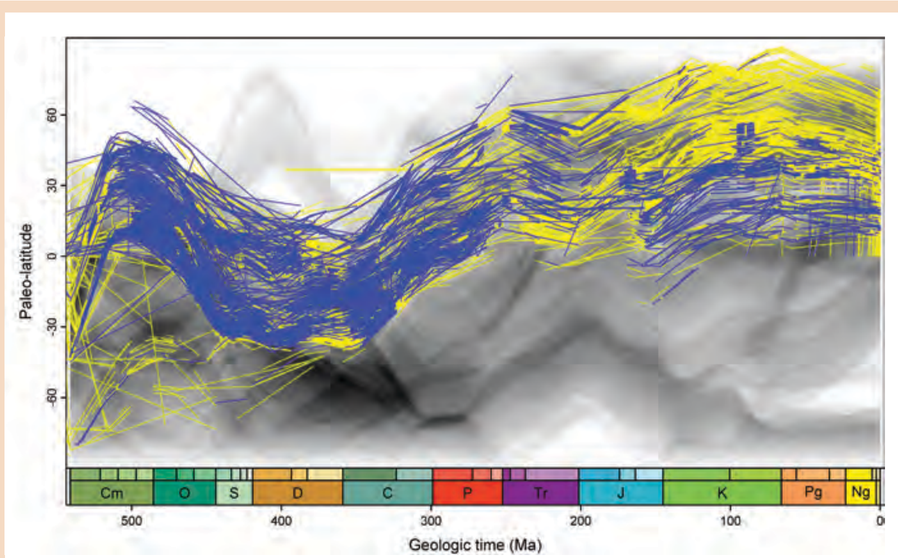

Figure 6: Paleolatitude vs. time in the Phanerozoic. Yellow and blue lines show paleolatitude and ages of all sedimentary units (yellow) and carbonate-bearing units (blue). Lines that slope indicate latitudinal range of start and end of deposition of unit according to the age model. Background grayscale indicates the global latitudinal distribution of continents over time from the EarthByte model. Darker gray indicates more area at that latitude; white indicates latitudes with no continental blocks.

and shifting lithological composition predicts major features in the macroevolutionary history of marine animals (Foote, 2003; Peters 2005, 2008, but see Smith, 2001; Smith and McGowan, 2007). Elsewhere we make the case that similarities between the sedimentary record (Fig. 2) and biological and geochemical proxy records for atmospheric oxygen concentration are more than coincidental (Husson and Peters, 2017). The sedimentary record isn't likely to be a passive and incomplete recorder of the history of atmospheric oxygenation; rather, its unsteady growth was the proximate driver.

Regardless of whether or not one finds the patterns derived from Macrostrat-scale analyses compelling from an Earth system process point of view, the database has wide utility. As a digitally-accessible source of information about the spatial, temporal, and lithological properties of rocks in the surface and subsurface, the database and software application ecosystem growing around it can be used for planning field trips, teaching, informatics initiatives, assessing the geological distribution of samples, or just basic question-answering about the geologic record ("where can I go to see Cambrian glauconitic sandstone?"). Perhaps more importantly, a large amount of proxy data have been extracted from the rock record and some of those data are managed independently of any quantitative understanding of it. This is done partly out of a need for expediency on the part of the data compilers and partly because the geologic record is typically viewed as an undesirable filter that must be worked around, not leveraged as a process signal in its own right.

A comprehensive, geospatially-informed characterization of the upper crust is a natural informatics framework for everything from assessing potential stratigraphic overprints on fossil data (Holland, 2016), to characterizing the distribution and properties of groundwater (Gleeson et al., 2016) and energy resources. A characterization of the space-time-lithology properties of the upper crust might also hold the key to understand how Earth systems are integrated and how they have combined to drive the long-term evolution of the Earth and life.

GOING GLOBAL

An obvious criticism of Macrostrat in its present form is that any results deriving from it are unique to the geographic area that it covers and therefore not a globally-relevant signal. This is a valid criticism, but it also articulates a hypothesis that has been preliminarily tested, most substantively by Alexander Ronov and colleagues (Ronov et al. 1980; Ronov 1994). Ronov's tabulation of rock quantity and type is coarse in geographical and temporal resolution, but it is also global in scope (excluding Antarctica). Ronov used his global compilation of rock quantity and age to perform an initial test of the standard model of the sedimentary cycle, which he rejected. Ronov et al. (1980) also concluded that global trends in sediment quantity were evidenced on continental crustal blocks, despite some regional differences.

Our results and comparisons to global data (and biological and geochemical proxy records) leads us to the same conclusions. Macrostrat reproduces total global sedimentary reservoir size, as estimated by Ronov, as well as other major features of his global tabulation, even when North America is removed from Ronov's data (Peters and Husson, 2017). Quantitative comparison is restricted to the Phanerozoic, however, and does not obviate our need for a global dataset. Climate-sensitive sediments, including carbonate, for example, are likely to be influenced by the particulars of paleogeographic and tectonic history of the sampled region. The paleolatitude of Phanerozoic Macrostrat sediments in NAC, superimposed on the global paleolatitudinal distribution of continental area from the EarthByte paleogeographic model (Wright et al, 2013) is shown in Fig. 6. As Laurentia was assembled into North America during the Phanerozoic, there has been a net northward-drift in the position of the continent. Carbonates tend to be most abundant at low latitudes, and the passage of North America from lower to higher latitudes during the Phanerozoic is, at least in part, reflected by the abundance of carbonate through time in this region (Fig. 2). Other factors driving a long-term decline in carbonate abundance on the continents include a decline in overall average continental flooding and the evolution of pelagic calcifying protists during the Triassic (Wilkinson and Walker, 1989; Bown et al., 2004). North America is not a random sample of the crust with respect to paleolatitude, and this impacts our ability to make predictions about the nature of the global sedimentary record.

A PATH FORWARD

The Macrostrat team, supported in part by the USGS, ACS, NSF, and UW-Madison Dept. of Geoscience, has invested in building a data and informatics foundation that is capable of facilitating rapid geographic expansion. We are continuing the process of compiling regional map and column data second hand, but there is a better way forward. The basic information required to construct Macrostrat columns can be viewed as a general rock-time scaffolding that could, at least in some cases, be efficiently constructed by geoscientists with regionally-comprehensive geological knowledge and expertise. Like all scaffoldings, the initial framework would only be expected to provide a general picture of the eventual edifice to be completed. However, harnessing regional geological expertise and rapidly creating a comprehensive space-time-rock scaffolding that describes, in even a basic capacity, the known rock record globally would have many positive impacts. No measured section, annotated thin section, geochemical measurement, fossil, or any other information extracted from the rock record, would find itself orphaned and could immediately contribute to a growing quantitative body of knowledge on the upper crust. Such a data resource would be a valuable addition to the disciplinary scope of sedimentary geology.

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