GEOLOGY

Evolution of alluvial mudrock forced by early land plants

William J. McMahon and Neil S. Davies*

Mudrocks are a primary archive of Earth's history from the Archean eon to recent times, and their source-to-sink production and deposition play a central role in long-term ocean chemistry and climate regulation. Using original and published stratigraphic data from all 704 of Earth's known alluvial formations from the Archean eon (3.5 billion years ago) to the Carboniferous period (0.3 billion years ago), we prove contentions of an upsurge in the proportion of mud retained on land coeval with vegetation evolution. We constrain the onset of the upsurge to the Ordovician-Silurian and show that alluvium deposited after land plant evolution contains a proportion of mudrock that is, on average, 1.4 orders of magnitude greater than the proportion contained in alluvium from the preceding 90% of Earth's history. We attribute this shift to the ways in which vegetation revolutionized mud production and sediment flux from continental interiors.

Earth's stratigraphic record preserves a number of trends in biogenic and chemogenic sedimentary rocks through time, reflecting secular changes at the surface of the planet (*1*). Siliciclastic sediments, produced primarily by the mechanical and chemical breakdown of parent rock, do not have such first-order biological controls. However, subtle secular changes have been previously quantified, including both clay mineral evolution (*2*) and changes in (bio)geomorphic sedimentary structures and architecture (*3–5*). In terms of bulk lithology, it is a long-held anecdotal contention (*4*, *6–8*) that mudrock is rare in alluvium that was deposited before the evolution of land plants but is common in alluvium deposited thereafter. We quantitatively tested this contention and found it to be true, demonstrating the magnitude and timing of the onset of the increase using data recording the proportional thickness of mudrock within alluvial stratigraphic sections (Fig. 1A).

We surveyed 1196 published reports and undertook 125 original field investigations to gather data on Earth's 704 known, globally distributed Archean-Carboniferous alluvial stratigraphic units and compiled a single database (table S1). Data reduction and analysis show that mudrock is a negligible component of alluvial strata deposited during the first ~3.0 billion years of Earth's sedimentary rock record but is common or dominant after the middle Paleozoic [mudrock is defined lithologically as all rocks dominantly composed of detrital and weathered sedimentary grains of ≤0.063 mm (siltstone) (*9*)]. In Archean strata [4000 to 2500 million years (Ma) old], the cumulative stratigraphic proportion of mudrock within alluvial strata ranges between 0 and 14% (median, 1.0%), whereas in Carboniferous strata (359 to 299 Ma old) the range is 0 to 90% (median, 26.2%) (Fig. 1D). LOESS regression analysis of the data constrains the upsurge between the Late Ordovician and the Devonian (458 to 359 Ma ago) (Fig. 1B), after which the range and average proportion of mudrock in alluvium never reverted to the same low values that characterized the first 3 billion years (Ga) of Earth's stratigraphic record. Subsampling of the data shows that the amount of mudrock was 1.1 orders of magnitude greater in the Late Ordovician to the Silurian (458 to 419 Ma ago), 1.3 orders of magnitude greater in the Early to Middle Devonian (418 to 379 Ma ago), 1.45 orders of magnitude greater in the Late Devonian to the early Carboniferous (378 to 339 Ma ago), and 1.75 orders of magnitude greater in the middle to late Carboniferous (338 to 299 Ma ago) than in the Archean to the Middle Ordovician (3500 to 458 Ma ago) (Fig. 1C).

This stratigraphically unidirectional upsurge in alluvial mudrock likely rules out a cause due to episodic or cyclic geological phenomena (such as tectonic or climatic controls) that persisted on Earth throughout the Archean to the Carboniferous (*10*, *11*) (fig. S11). The first 3 Ga of the interval we studied included multiple alternations between icehouse and greenhouse conditions (*12*), the assembly of at least two supercontinents (*13*), and 16 known regional orogenies (*14*). None of these events had any apparent influence on the near-uniform global scarcity of preserved alluvial mudrock. Similarly, the onset of the trend does not correlate with other prominent potential triggers in the geological record. For example, it postdates Paleoproterozoic oxygenation by at least 1640 Ma (*15*), Neoproterozoic oxygenation by 142 Ma (*15*), and the advent of microbial life on land by 2540 Ma (*16*) and may predate the increased survivorship of nonmarine strata by up to 60 Ma (*11*, *17*). The systematic misidentification of pre-Ordovician mudrock as marine in previous studies is a potential source of uncontrolled bias in our study (*11*). However, after testing the data against various alternative hypotheses (*11*) (figs. S5 to S8 and S11 to S13), we argue that the most plausible explanation is that prevegetation Earth had distinct syndepositional controls on sedimentation that discouraged the production or accumulation of alluvial mudrock. The trend mirrors the fossil plant record (*18–20*), and the appearance of primitive plants would have introduced three mechanisms important for producing mudrock-rich alluvial strata. Plants lead to an increased production of the directly weathered fraction of fines (clays) (*2*, *18*, *21–26*). They also increase retention of all (weathered and detrital) fines in continental deposystems through binding (the fastening of masses of grains by plant parts such as roots) (*25*, *26*). Finally, the process of baffling (the capture and forced deposition of grains from within a moving fluid passing over and around plant parts) also increases retention of all (weathered and detrital) fines in continental deposystems (*27*, *28*).

Terrigenous fines are sourced into sedimentary systems through the mechanical mass wasting of chemical weathering profiles, supplying both weathered and detrital silt, mud, and clay particles (*21*). Land plants are not a prerequisite for the mechanical production of fines, and abiotic, microbial, and fungal processes could all promote the silicate weathering of clays on prevegetation Earth (*16*, *18*, *21*, *29*, *30*). The presence of minor mudrock in alluvium of all ages, in addition to known terrigenous mudrocks from prevegetation lacustrine and marine facies, demonstrates these alternative pathways (Fig. 1A). However, land plants do promote the production of clay minerals and the depth of chemical weathering profiles by increasing atmosphere-substrate connectivity through rooting, through the direct secretion of organic acids and chelates, and by developing symbiotic relationships that increase the capacity of cyanobacteria and fungi to dissolve soil grains (*2*, *18*, *21–26*). The degree to which the earliest bryophyte-grade plants could have boosted silicate weathering (*16*, *22*, *23*, *31*, *32*) remains a point of debate, but a clear global intensification followed the evolution of a deeper-rooted Devonian flora (*18*, *22*, *24*, *25*). The initial range expansion of mudrock proportions in the Ordovician-Silurian (Fig. 1B) suggests that even the earliest plants played some role in promoting mudrock in alluvium (*26*), before the pronounced rise seen after the Devonian evolution of rooting. However, even if the earliest bryophytes increased weathering, net production alone may not account for the trend. In limited instances where mudrock type has previously been distinguished, siltstone abundance exhibits the same unidirectional trend as mudstone, claystone, and shale abundance (*11*) (fig. S2), suggesting that even fines with a greater (though not exclusive) probability of having been mechanically and abiotically generated (*21*) are diminished in prevegetation alluvium.

Before vegetation, continents were colonized by microbial mats (*16*), but the lack of below-ground structure to these communities meant

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that they were prone to undercutting and reworking by fluvial channels and so had a negligible effect on the retention of sediment (*33*). In contrast, the establishment of root systems offered novel mechanical protection against the erosion of sediment in alluvial settings (*23*, *25*) and would thus have promoted the physical retention of clay, mud, and silt. This importance of below-ground stabilization would clearly have played some role in the major Devonian upsurge in mudrock, but the root systems of earlier land plants were limited (*18*, *23*), so this is an unlikely explanation for observed mud-rich Ordovician and Silurian formations.

The above-ground structures of even shallow-rooted and small-stature vegetation today can reduce near-surface flow of water and wind below a critical velocity that promotes sediment deposition (*27*, *28*). Observations of mosses and liverworts show effective trapping of individual fine grains between their stems, leaves, and thalli, incorporating sediment into cryptogamic ground covers (*26*). Even though direct physiological analogy between modern and early land plants may be inappropriate (*18*), the earliest above-ground plant structures must have introduced a wholly unprecedented biological component of roughness to Earth's surface. This suggests a large role for baffling by even primitive above-ground plant constructions, promoting the recurrence frequency of deposition of fines in the alluvial realm and contributing to the mudrock increase.

The Paleozoic increase in alluvial mudrock is an important characteristic of the global sedimentary geological record. The timing relative to the appearance of plants is unlikely to be a coincidence, as plants can greatly contribute to the development and retention of alluvial mudrocks. The source-to-sink deposition of prevegetation mud was thus profoundly different from that seen in the present day (*34*). On prevegetation Earth, all fines had limited potential for final (preserved) deposition within continental conduits, regardless of any non–vegetation-related variations in chemical weathering intensity (*29*, *30*, *35*) or sediment flux (*36*). Archean to Middle Ordovician marine settings would have received a generally greater flux of whatever terrigenous fines were being produced in continental source areas. After the Late Ordovician, and to a greater degree after the Devonian, an increasing proportion of terrigenous fines were produced and/or retained on the continents; thus, the marine realm may have received a diminished fraction of total continentally weathered fines. This need not have equated to a diminished volume because net production at the source would have been greater. A fuller understanding of mudrock in the absence of vegetation is a prerequisite for any studies that invoke ancient terrestrial mudrock strata as a primary archive of geochemical or petrological data and will have implications for understanding the context and nature of mudrocks that are increasingly detected on non-vegetated planets such as Mars (*8*, *37*).

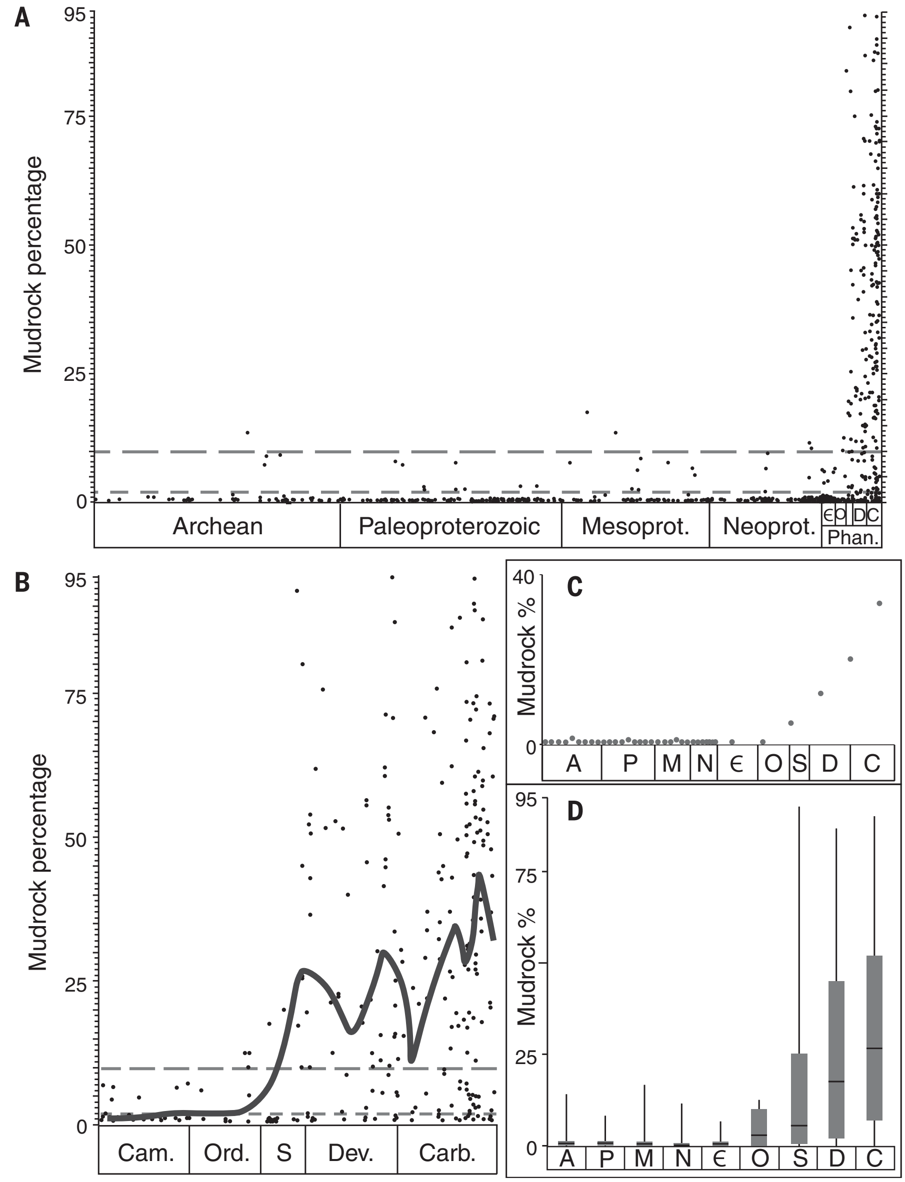

Fig. 1. The range and maximum proportion of mudrock in alluvial successions increase markedly after the evolution of vegetation. The proportion of mudrock within alluvial successions (percentage of vertical stratigraphic thickness) is plotted against geologic age [the *x* axis is scaled to numerical ages, with the start of intervals based on the Geologic Time Scale 2012 (*38*): Archean (A; 4000 Ma ago), Paleoproterozoic (P; 2500 Ma ago), Mesoproterozoic (Mesoprot. or M; 1600 Ma ago), Neoproterozoic (Neoprot. or N; 1000 Ma ago), Cambrian (Є or Cam.; 541.0 Ma ago), Ordovician (O or Ord.; 485.4 Ma ago), Silurian (S; 443.8 Ma ago), Devonian (D or Dev.; 419.2 Ma ago), Carboniferous (C or Carb.; 358.9 Ma ago), and Permian (298.9 Ma ago)]. (**A**) Each individual point records one of the known 594 alluvial stratigraphic units deposited during this interval. Long-dashed line, 10%; short-dashed line, 2%. Phan., Phanerozoic. (**B**) Enlarged plot for the Phanerozoic with LOESS regression line (solid gray line). LOESS was conducted with a smoothing parameter of 0.9. (**C**) Proportion of mudrock corrected for variation in sampling intensity by subsampling. Each individual point represents the median value seen across 100 individual subsampling trials (see supplementary materials for methodology). (**D**) Median, range, upper quartile, and lower quartile of mudrock proportion for each interval.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/359/6379/1022/suppl/DC1
Materials and Methods
Figs. S1 to S15
Table S1
References (*39*–*71*)

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Mudrocks get a vegetative assist

Mudrocks such as slate and shale are rarely found in stratigraphy older than about 500 million years. McMahon and Davies compiled a large database of mudrock occurrence over the past 3.5 billion years to help assess the origin of this ubiquitous rock type (see the Perspective by Fischer). Mudrocks appeared at the same time as did deep-rooted land plants. The interplay between plants and sedimentary rocks suggests that a change in erosion rate and the chemistry of sediments delivered to the oceans occurred around 500 million years ago.

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