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Paleozoic vegetation increased fine sediment in fluvial and tidal channels: Evidence from secular changes to the mudrock content of ancient point bars

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ABSTRACT

The amount of mudrock preserved globally in alluvium increased in stratigraphic synchrony with the Paleozoic evolution of land plants. This observation has been explained by vegetation promoting both the retention of mud through baffling, stabilization, and flocculation, and the production of mud through chemical weathering. However, the latter explanation has been challenged on the basis that it is perceived to require imbalance in the long-term global carbon cycle. We present a compendium of empirical evidence that is supportive of increased global fine sediment supply, and thus the contention that land plants did, in fact, promote the production of mud on the continents. We refine previous broad-brush analyses of Paleozoic mudrock content by specifically tracking shifts in the mudrock content of regions of alluvial and tidal landscapes that remained locally unvegetated even after the greening of the continents, namely inclined heterolithic stratification (IHS) that records submerged in-channel bars. We show that the Paleozoic mudrock increase was pronounced even within these areas, away from any biomechanical binding and baffling effects of plants. Precambrian and Cambrian IHS are composed almost exclusively of sandstone, whereas Silurian through to Carboniferous examples show a steady increase in total mudrock content. This progressive rise in the mudrock component of channel bars cannot alone be explained by physical retention of mud by vegetation and requires heightened fine sediment concentrations from the hinterland, which suggests that plants increased the volume of mud available at source. The muddying of Earth's preserved IHS serves as a proxy that suggests evolving Paleozoic land plants triggered a global increase in the production and supply of fine-grained sediment.

LAND PLANTS AND MUD

Alluvial sedimentary strata deposited after the evolution of land plants contain a proportion of mudrock that is, on average, 20 times greater than equivalent strata from the preceding 90% of Earth's history (Davies and Gibling, 2010a; Fischer, 2018; McMahon and Davies, 2018; Dahl and Arens, 2020; Brückner et al., 2021; Zeichner et al., 2021). Two categories of non-exclusive explanations have been proposed to account for this material stratigraphic shift, which invoke the known influences of extant plant life on muddy sediment: (1) plants increased total mud production on the continents through heightened silicate weathering (e.g., Knoll and James, 1987; Moulton et al., 2000; Quirk et al., 2012; Mitchell et al., 2016, 2019; Dahl and Arens, 2020); and (2) plants promoted the retention of mud on the continents, preventing it from being bypassed out into the marine realm through below-ground stabilization of sediment (Dalrymple et al., 1985), above-ground baffling of fluids and sediment (Kleinhans et al., 2018), and the release of organic by-products that promoted flocculation and therefore deposition (Zeichner et al., 2021). Understanding the balance of mud production and retention is important because mud is integral to our comprehension of the ancient Earth system. The weathering of clay minerals is an important function within the carbon cycle, and any shifts in its intensity or distribution would have had cumulative effects on the nature of global biogeochemical cycling (Galvez et al., 2020). Mudrocks and their associated clay minerals are also significant archives of ancient climate (Porada et al., 2016), ocean chemistry (Kalderon-Asael et al., 2021), and fossil life (Anderson et al., 2021), and determining why and how their global volume fluctuates can highlight potential biases in our understanding of the evolution of these phenomena.

Some model-driven arguments have suggested that the rise in alluvial mudrock must be dominantly a result of physical retention, assuming that over long timescales, the production of mud through chemical weathering must be self-limiting because it is reliant on a finite supply of CO_2 supplied by volcanic degassing (Fischer, 2018; D'Antonio et al., 2020; Zeichner et al., 2021; Ielpi et al., 2022). However, other lines of evidence suggest that a Paleozoic increase in continental mud production cannot be ruled out, even if that increase is balanced out elsewhere by a counteracting carbon input (D'Antonio et al., 2020). Pre-vegetation mudrocks have been shown to be predominantly products of physical erosion rather than pedogenic clay mineral formation (Rafiei and Kennedy, 2019; Rafiei et al., 2020), global geochemical data suggest that the primary locus of the global "clay mineral factory" shifted from the oceans to the land in the early Paleozoic (Kalderon-Asael et al., 2021), and the isotopic signatures of zircon formed at subduction zones show a marked shift that is coeval with vascular plant evolution and linked to the greater mudrock content of subducting slabs (Spencer et al., 2022). Any empirical evidence that the evolution of land plants did increase global chemical weathering products necessitates a reevaluation of our understanding as to how the global carbon cycle was balanced in deep time.

The physical sedimentary record can yield clues as to whether physical retention was the sole explanation for the Paleozoic mudrock

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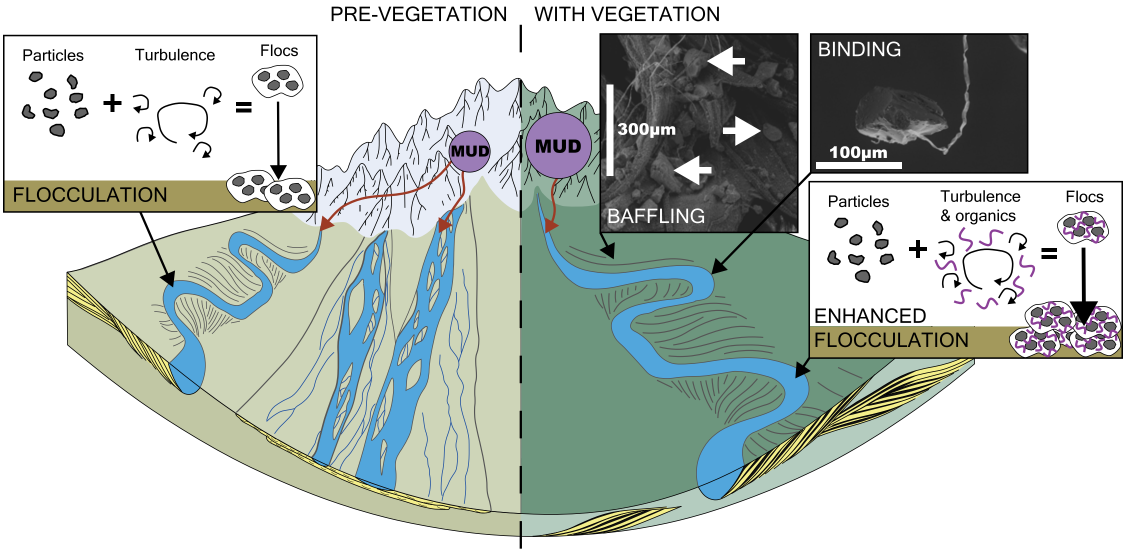

Figure 1. Mechanisms suggested to account for the shift in alluvial mudrock coeval with the evolution of plants. Flocculation: following the onset of vegetation, plant organics promoted aggregation of clay into flocs in rivers and facilitated mud deposition on floodplains (Zeichner et al., 2021). Binding: scanning electron microscope (SEM) image depicts moss (*Racomitrium* sp.) rhizoids binding soil. The fastening of masses of grains by plant parts such as roots mechanically strengthened channel banks, increasing the likelihood of out-of-channel mud retention (Davies and Gibling, 2010a). Baffling: SEM image of moss baffling sediment. Above-ground plant parts trapped grains (white arrows), with the greater abundance of the muds deposited elevating local floodplain topographies and reducing the strength of overbank flows (Kleinhans et al., 2018). Increased abundance of inclined heterolithic stratification deposited by meandering channels following the expansion of vegetation reflects previous assessments of the rock record (Davies and Gibling, 2010b).

surge. Mud retention in isolation would be restricted to those environments where land plants were living and offering biomechanical binding and baffling effects, or quiet water settings where volumes of flocculated mud could accumulate (Fig. 1). Thus, retention alone could explain the abundance of later Paleozoic muddy floodplains (McMahon and Davies, 2018), but mud within more motile or submerged alluvial landscape elements would require an alternative explanation, as these would have been less hospitable to colonization by plants (especially the earliest, diminutive vegetation; Edwards et al., 2015). Modern analogues show that the mud content of fluvial channel bars is directly relatable to external fine sediment supply from upstream reaches, because barform topography creates locally variable flow conditions that capture fine-grained material to deposit if available (Szupiany et al., 2012). Increased fine sediment supply also heightens the propensity for flocculation and mud aggregation to occur, particularly in distal, tidally influenced channels where transported clay suspensions encounter saline

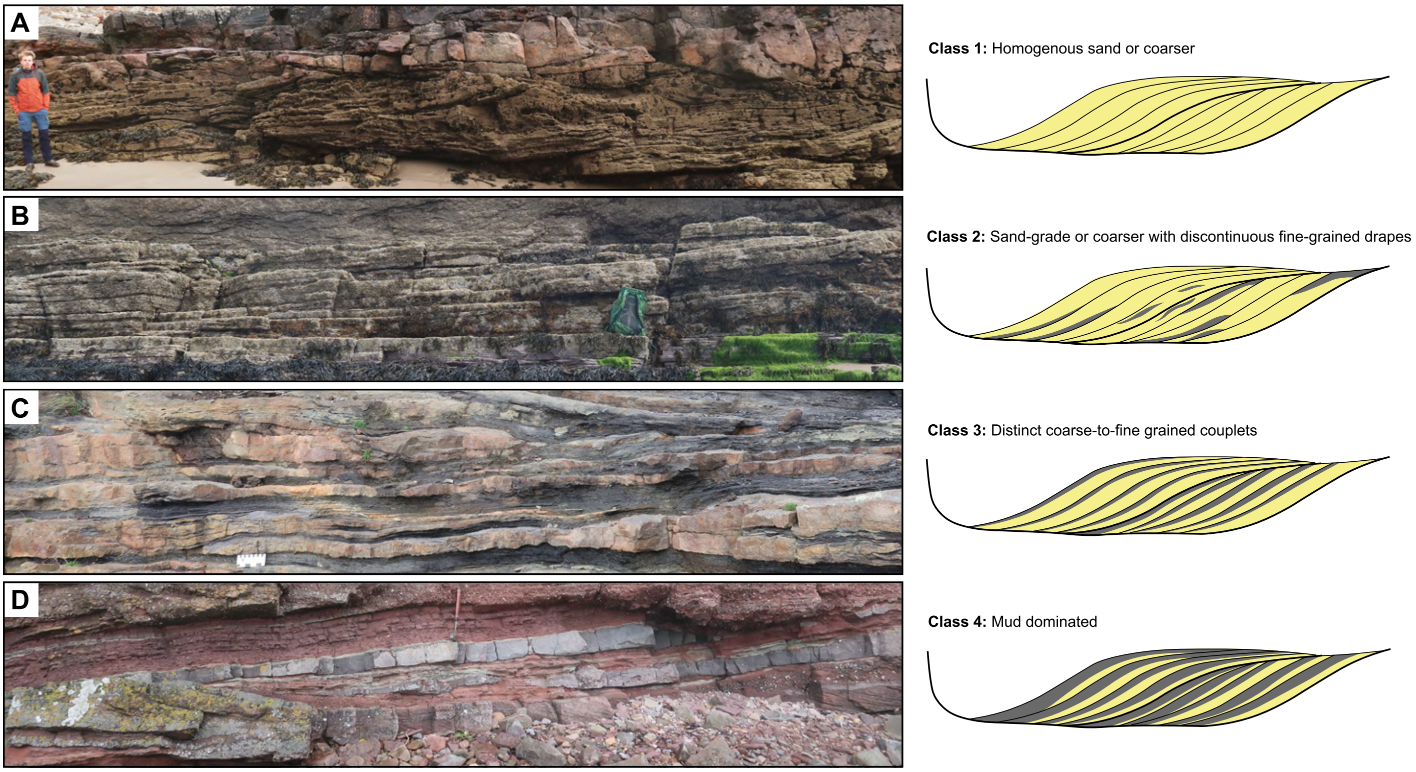

Figure 2. Examples of inclined heterolithic stratification (IHS): (A) class 1 IHS from the Visean Largysillagh Formation, Ireland (person is 187 cm tall); (B) class 2 IHS from the Pragian Traeth Lligwy Beds, Wales (backpack is 35 cm high); (C) class 3 IHS from the Visean Shalwy Formation, Ireland; (D) class 4 IHS from the Emsian Black Nore Sandstone Formation, England (hammer is 28 cm long).

waters (Seiphoori et al., 2021). The flux of mud through a system is thus a dominant control on in-channel volumes of deposited fine-grained sediment (Wysocki and Hajek, 2021), meaning the net quantity of mud observed to be preserved internally within channel barforms can act as a coarse proxy for the net volume of fine sediment supplied from upstream regions of mud production.

Our study refines previous, coarsely resolved studies of alluvial mudrock abundance in the Paleozoic (McMahon and Davies, 2018) and specifically focuses on the abundance of mud within sedimentary architectural elements that were deposited in submerged channel areas uncolonized by land plants. Because they have been commonly reported in the published literature, we focus specifically on Precambrian–Paleozoic-age point bar deposits, which are most frequently revealed as inclined heterolithic stratification within alluvial strata (Fig. 2).

INCLINED HETEROLITHIC STRATIFICATION

Inclined heterolithic stratification (IHS) (sometimes referred to as "lateral accretion" [LA], LA-IHS or epsilon cross-strata) is the alluvial architectural element that records point-bar sedimentation (Thomas at al., 1987). The grain-size of sediments that form IHS can be highly variable (Fig. 2), and Thomas et al. (1987) referred to three broad classes: (1) dominantly homogenous, usually sand-grade or coarser material (also known simply as "inclined stratification" [Thomas et al., 1987]); (2) sand-grade or coarser IHS, with each set capped with a discontinuous fine-grained component; and (3) IHS with a continuous fine-grained component, either covering the entire sigmoidal surface or occurring within repeated coarse–fine-grained couplets. Our study differentiates a fourth class: IHS composed of >50% mudrock. The term "mudrock" is applied as an umbrella term incorporating multiple types of fine-grained sediment (<62.5 µm grains: mudstone, siltstone, and claystone). While ancient examples of IHS are frequently reported (Table S1 in the Supplemental Material[1]), few instances have been explicitly grouped into these classes. To interrogate long-term trends, we classified examples from 92 previously described Proterozoic to Carboniferous instances of IHS from ancient channels, through reference to published descriptions or images, in addition to original field investigations of 44 of these instances (Table S1). All of the original channels would have had variable mudrock content (and therefore IHS classes) along and across strike, and they were randomly sampled as natural outcrops that record only a spatial fraction of their primary forms (e.g., Davies et al., 2019). Our analysis of the IHS record encapsulates the entire collection of the random samples that were preserved, thus providing an empirical account of stratigraphic shifts in IHS class abundance that, through its inclusivity, overrides the imperfection of individual records. To identify whether IHS was tidal or fluvial, we followed published interpretations in instances where we did not ground-truth the successions, but note the caveat (after Thomas et al., 1987) that some ancient tidal IHS may have been misinterpreted to be fluvial, particularly as tidal currents can propagate landward through meandering channels for several kilometers with only cryptic sedimentary signatures (Ghinassi et al., 2021).

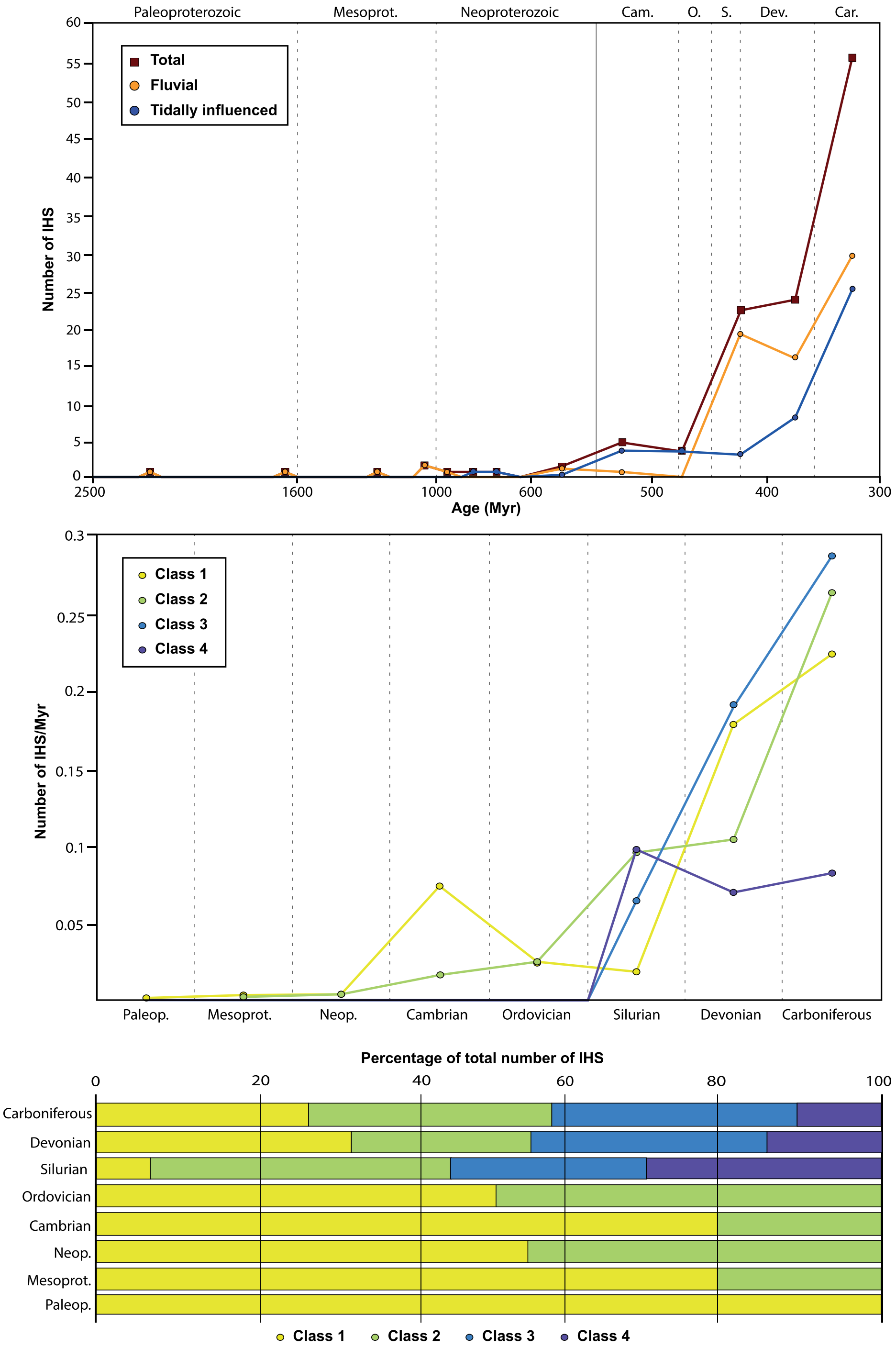

Figure 3. (A) Reported inclined heterolithic stratification (IHS) by age and environment. Cam.—Cambrian; O.—Ordivician; S.—Silurian; Dev.—Devonian; Car.—Carboniferous. (B) IHS by type per million years. (C) Percentage of total number of IHS reported from the Paleoproterozoic to end Carboniferous.

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[1] Supplemental Material. Methodology followed for the database construction and analysis, and Table S1 (reports of inclined heterolithic stratification). Please visit https://doi.org/10.1130/GEOL.S.21520941 to access the supplemental material, and contact editing@geosociety.org with any questions.

PROTEROZOIC–PALEOZOIC EVOLUTION OF POINT-BAR SEDIMENTATION

Our data show that tidal IHS increased in abundance through the Paleozoic; a trend previously reported for fluvial IHS (Davies and Gibling 2010b; Fig. 3). Within this overall trend, mudrock-rich IHS components become particularly prominent. Mudrock is a minimal component of both tidal and fluvial IHS in the Precambrian–Ordovician but becomes a common or dominant lithology from the Silurian onwards. Class 1 IHS accounts for 75% of Precambrian to Ordovician examples (n = 18). In the Silurian, this value drops to 7% (n = 9) and remains under 33% for each subsequent interval studied (n = 89). Class 3 IHS forms an increasingly large percentage of the total number through the Silurian (27%), Devonian (34%), and Carboniferous (35%) (n = 9, 35, and 54, respectively). The earliest class 4 IHS occurs in the Silurian and account for 10% of Silurian to Carboniferous examples (n = 98). Both fluvial and tidally influenced IHS display comparable IHS muddying through the Paleozoic (Fig. 4), though class 1 IHS is more common in purely fluvial examples (36% vs. 19% of total number; n = 74 and n = 48, respectively).

DISCUSSION

Paleozoic trends in the abundance and character of IHS demonstrate that not only did mesoscale point bars become more commonly interred in the stratigraphic record, but also that the amount of mud that was trapped in these landforms, in both their emergent and submerged flanks, increased synchronously with the global increase in net alluvial mudrock (McMahon and Davies, 2018) and the advent of widespread land plants (Wellman et al., 2022). Significantly, pervasive muddying occurs across submerged and flowing water parts of both fluvial and tidal channels (Figs. 3 and 4). Such instances cannot be accounted for by a universal explanation of global mud retention by land plants because they are located away from in situ vegetation that could promote physical retention and quiet water settings where volumes of flocculated mud could accrue. The incorporation of mud into IHS fundamentally requires sufficient clay suspensions (Wysocki and Hajek, 2021), regardless of whether its deposition is forced through tidal influence (Johnson and Dashtgard, 2014), varying fluvial discharge (Bridge and Jarvis, 1976), scroll-bar passage (van de Lageweg et al., 2014), local topography (Szupiany et al., 2012), or the mixing of riverine and saline waters (Seiphoori et al., 2021). An overall trend toward muddier IHS (Figs. 3 and 4) thus implies increased availability of clay-grade sediment from the Silurian onward and incorporates a number of source-to-sink conduit environments, in both their submerged and emergent reaches, and irrespective of locations where vegetation would have been growing. Such an increase is implicit for increased mud availability from the hinterland, presumably for mud both directly weathered from bedrock in the source area and recycled from and neoformed within increasingly stable staging areas such as floodplains, where liberated sediment could undergo multiple additional rounds of weathering. Increased fine sediment supply would also promote greater aggregation of clay into flocs (Lamb et al., 2020; Wysocki and Hajek, 2021), a mechanism which, in conjunction with the rise in terrestrial organics associated with early plants (Zeichner et al., 2021), would enhance mud settling and deposition on out-of-channel floodplains. A positive feedback loop therefore exists between mud production and mud retention through flocculation.

The progressive Paleozoic muddying of both preserved IHS and total alluvium (McMahon and Davies, 2018) supports the contention that the evolution of land plants increased both mud production and retention on the continents. While the relative contributions of mud production versus mud retention remain unknown, this geological evidence for heightened mud production by early plants fits our understanding of the integral roles played by modern land plants in chemical weathering (e.g., by promoting chelation, hydrological connectivity between atmosphere and lithosphere, and the depth of CO_2 diffusion in substrates; e.g., Berner, 1992; Moulton et al., 2000; Quirk et al., 2012). The empirical evidence for increasing mud production is in apparent conflict with mass-balance models of the long-term carbon cycle (e.g., D'Antonio et al., 2020; Ielpi et al., 2022). A similar census of mudrock distribution in Precambrian and Paleozoic marine environments is thus overdue, as this could provide insights into the universal distribution of mud on ancient Earth.

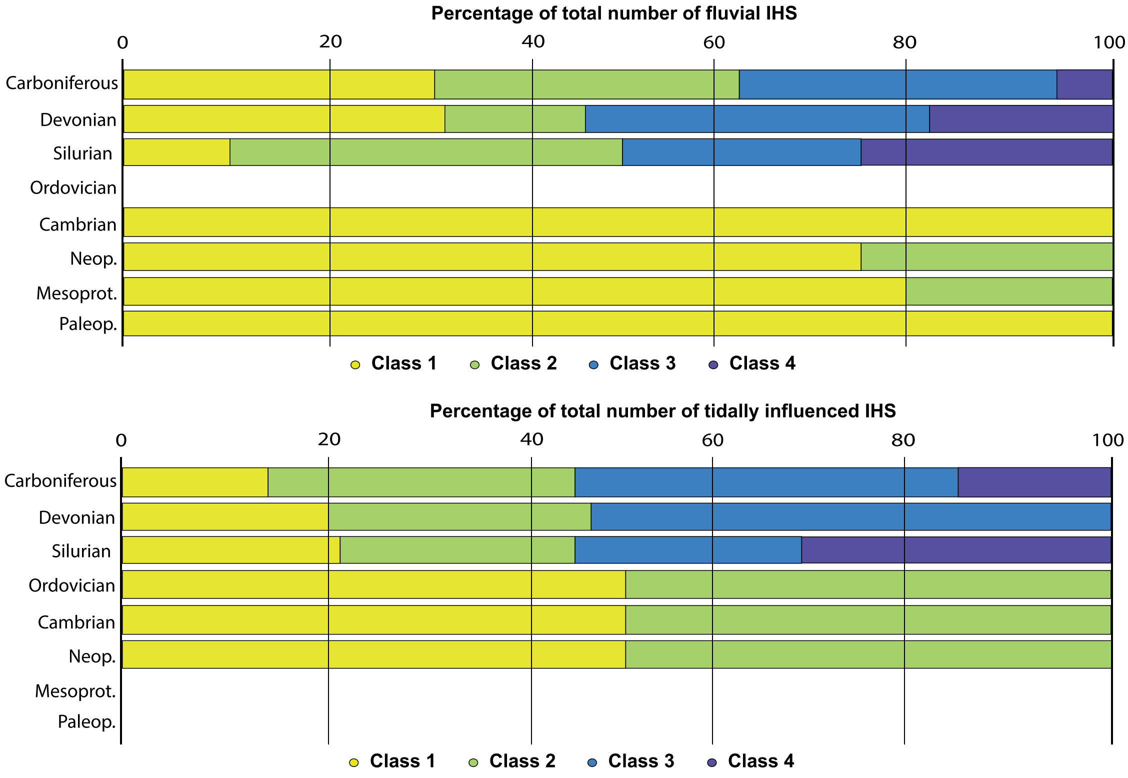

Figure 4. Percentage of fluvial (top) and tidally influenced (bottom) inclined heterolithic stratification (IHS) reported from the Paleoproterozoic to end Carboniferous.

CONCLUSION

The fine-grained component of inclined heterolithic stratification (IHS) increases in abundance through the Paleozoic. Whereas instances of IHS in the Precambrian and Cambrian are dominantly composed of sandstone, from the Silurian onward they are more frequently organized into distinct sandstone-mudrock couplets or mudrock-dominant IHS. This progressive rise in the fine-grained component of IHS is synchronous with the rise of terrestrial vegetation, which has been implicated in the concomitant rise in bulk alluvial mudrock that is attributed to both the production and retention of mud by plants. Significantly, the mudrock shift occurs across both fluvial and tidal environments, requiring that the volume of fine-grained sediment in these conduits increased, and cannot be explained solely by the physical retention of fines by land plants as biomechanical agents. This empirical observation strongly supports hypotheses that the Paleozoic expansion of land plants not only acted to stop mud from leaving the continents but also reorganized the carbon cycle by enabling new pathways in chemical weathering, mud production, and source-to-sink sediment fluxes.

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