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AN EOLIAN DUST ORIGIN FOR CLASTIC FINES OF DEVONO-MISSISSIPPIAN MUDROCKS OF THE GREATER NORTH AMERICAN MIDCONTINENT—DISCUSSION

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The following is our critique of the paper by McGlannan et al. 2022, on supposed eolian contributions to Late Devonian black shales of North America:

McGlannan, A.J., Bonar, A., Pfeifer, L., Steinig, S., Valdes, P., Adams, S., Duarte, D., Milad, B., Cullen, A., Soreghan, G.S., 2022, An eolian dust origin for clastic fines of Devono-Mississippian mudrocks of the greater North American midcontinent. Journal of Sedimentary Research, v. 92, p. 1186–1206.

We post here our original submission to JSR, with additional commentary for clarification.

Added commentary in red type.

Our Original Title

Eolian Input was not a Critical Factor for the Formation of Devonian Black Shales in North America. Critique of Paper by McGlannan et al.

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In a recently published paper, McGlannan et al. (2022) posit that the detrital silt component of Upper Devonian and Lower to Middle Mississippian shales of the North American Midcontinent region is of eolian origin and provided essential nutrients that stimulated the organic productivity that is recorded by these shales. Our initial concern with their study was the fact that McGlannan et al. (2022) studied a stratigraphic interval that spans approximately 20 million years (Late Devonian to Early Mississippian), and applied conclusions reached for the Mississippian part of the succession to the underlying Devonian black shales. This was surprising because it is well known that a drastic sea-level fall occurred at the end of the Devonian and resulted in an unconformity over much of the North American craton (Frazier and Schwimmer, 1987; Over, 2021). As far as we understand from geologic literature, extrapolating the inferred sedimentary dynamics of one stratigraphic interval (Early Mississippian) across a sequence boundary to rocks that were deposited multiple millions of years earlier (Late Devonian) is neither recommended nor considered good practice.

McGlannan et al. find the preceding sentence "odd", but we maintain that the way they applied (in their 2022 paper) textural observations made in overlying Mississippian shales ("no to minimal instances of quartz overgrowths") to justify interpretations of Late Devonian black shales (across an unconformity) is poor science nonetheless. In particular, because the reader was given the impression that these textural features were shared by the substantially older Devonian black shales. Data and observations collected from the Mississippian should not be extrapolated to the underlying Late Devonian black shales as a major unconformity developed across Laurentia marks a significant drawdown of eustatic sea-level as a result of glaciation, representing vastly different depositional conditions.

The aim of this discussion is not to disqualify eolian systems in general as a potential source of fines in shale successions. It is not implausible that there were times and places in the geologic past when they may have contributed to marine or lacustrine shale/mudstone successions. We are, however, firmly convinced that in the case of the Late Devonian of North

America, no compelling case can be made for a significant eolian clastic component to its widely distributed black-shale successions.

Whereas we disagree with the validity of the McClannan et al. (2022) study at several levels, three principal lines of reasoning stand out to demonstrate that their conclusions are flawed and inapplicable to the Late Devonian black shales of North America.

First, petrographic examination of the rocks in question, collected from the same location as samples used by the authors (Woodford samples from McAlister Quarry), as well as samples from the Woodford of the Central Basin Platform (Permian Basin, Texas, samples courtesy of Kitty Milliken) does not support their assumptions about these rocks. SEM analysis shows these samples to be strongly dominated by microcrystalline quartz (Fig. 1) and indicates that it is highly unlikely that the authors could have succeeded to extract detrital quartz grains from these rocks with the method described (McClannan et al. 2022), much less using them for grain-size analysis. The abundant early diagenetic silica cementation that fed on dissolution of radiolarian tests is so ubiquitous in these shales, generating silt- and even sand- size quartz particles (Blatt, 1987; Schieber, 1996; Schieber et al, 2000) that upon crushing/processing it would inevitably have generated silt- and sand-sized quartz particles (Fig. 2). Petrographic constraints (Fig. 1), however, should readily disabuse a discerning observer from the notion that these particles are in any kind or form detrital in nature.

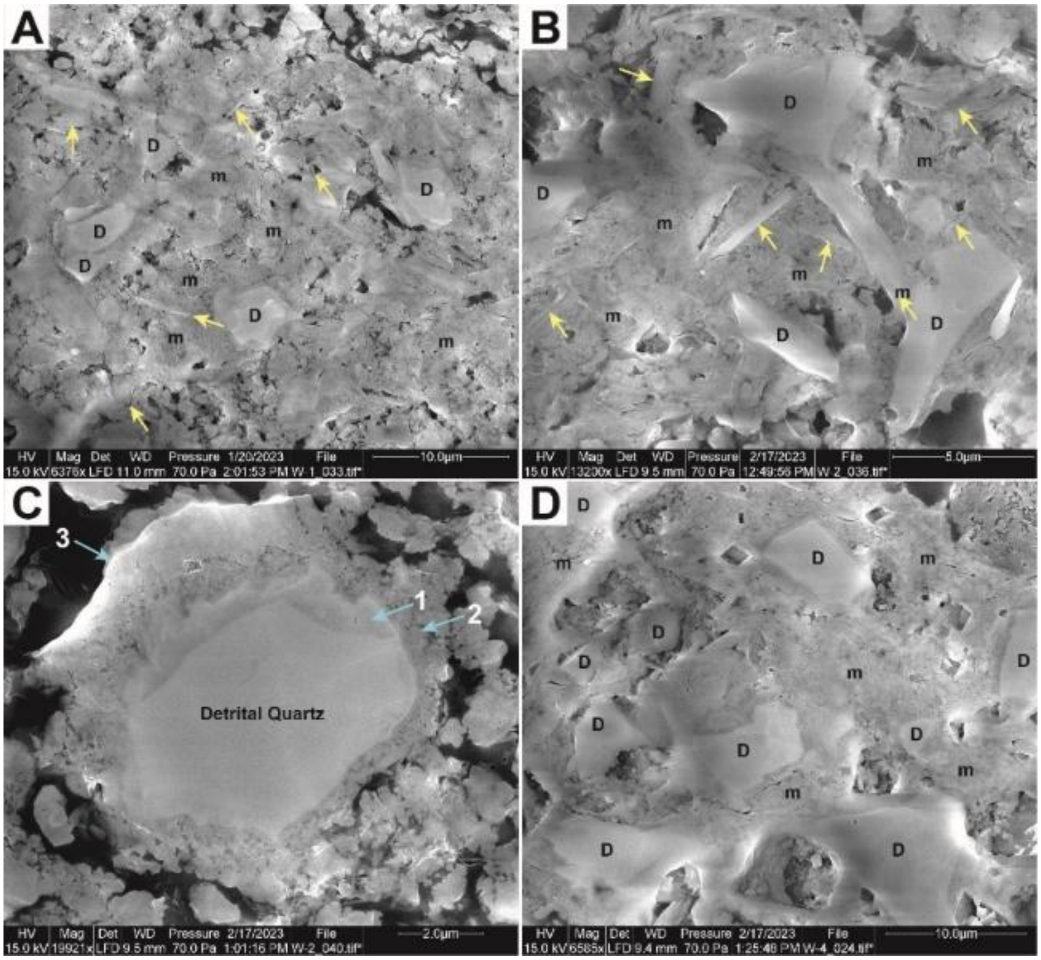

Figure 1: *Examples of diagenetic quartz cementation in the Woodford Shale of the Arbuckle Mountains of Oklahoma (secondary electron images). Only examples of fabric categories are marked, the gray-scale contrast between particles and matrix is due to charge contrast because the images were taken in low-vacuum mode. A) Typical appearance of silica cemented shale, a mixture of detrital quartz (D), phyllosilicate flakes (yellow arrows), and fine crystalline matrix (m). B) Comparable fabric in a different sample at higher magnification. Note that in both parts, A and B, the mica and clay flakes show random orientation. C) Close-up view of a single detrital quartz grain with three generations of silica overgrowth (numbered blue arrows). The dark matter is kerogen. This image also shows the clumpy nature of the diagenetic silica, comparable to what Milliken and Olsen (2017) and Longman et al. (2019) described as opal-CT lepispheres that subsequently recrystallized to microquartz. D) Another example of the intimate association of detrital quartz grains (D) and fine-grained siliceous matrix (m) containing*

randomly oriented mica and clay flakes (not marked). Holes seen in these images are due to oxidation of organic matter and dissolution of diagenetic pyrite and dolomite.

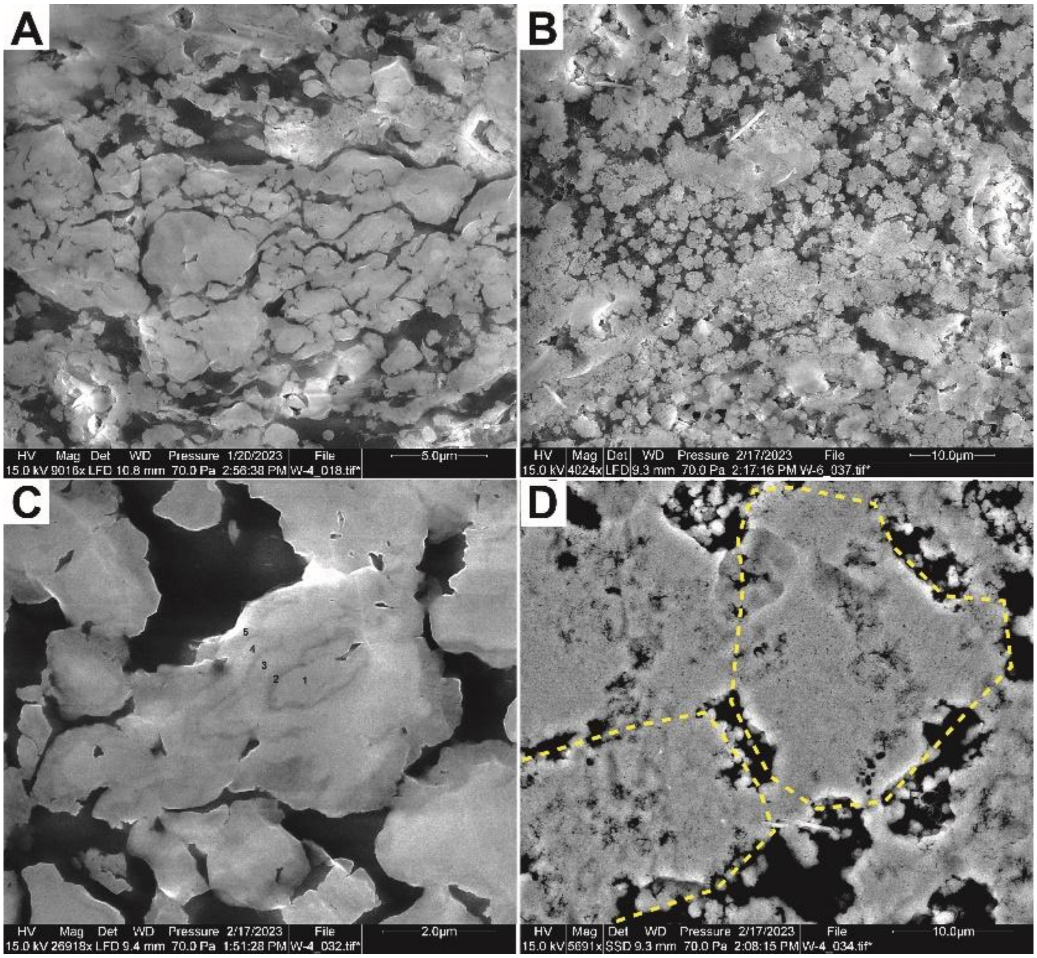

Figure 2: *Clustering and clumping of early-diagenetic silica in the Woodford Shale, and potential disaggregation sub-units (SEM images). A) Low-porosity quartz aggregates that range in size from 1 to 8 microns, and are separated by kerogen (black). B) More porous aggregates that range in size from 1 to 20 microns and are separated by kerogen (black). If such rock is crushed, or if the organic matrix is digested chemically, quartz particles in the 1 to 20 micron size range can be expected in the residue. C) Detail of low porosity aggregates that show well developed cement zonation (1 through 5). D) Better cemented and partially fused aggregates of the type shown in Part B. If crushed mechanically, fragments outlined by yellow dashed lines, several ten microns in size, are likely to form.*

Note that the quartz cement in Fig. 2 is not contiguous as it would be in a chert. It forms subunits in the micron to tens of microns size range, separated by organic matter. That is the reason why this material weathers recessive, and it is these recessive intervals of the

Woodford that were sampled by McGlannan et al. 2022 and subsequently by us to make sure we don't engage into an "apples" vs "oranges" discussion.

In their reply, McGlannan et al. (2024) try to invalidate this point by stating that they "preferentially avoided silica-rich facies and predominantly sampled laminated shale facies", implying that we had not done so and that our observations regarding petrography in some way "missed the mark". We take exception to that, because we were very much cognizant of this issue and that is exactly why we went to the very outcrops that were sampled by McGlannan et al. (2022) and did indeed sample the softer intervals between chert ledges of the Woodford Shale. Although these recessive interbeds are softer than the chert beds, abundant diagenetic silica still dominates the fabric and detrital quartz grains invariably are overgrown by secondary quartz.

In our extensive experience with mudstone petrography, the detrital vs. authigenic nature of silt-size quartz grains cannot be determined (as the authors did) via inspection of "smear slides of residues" with a petrographic microscope. To make that determination requires the resolution offered by scanning electron microscopes (SEM). Fig. 3 shows our Woodford samples from the perspective of scanned cathodoluminescence, illustrating the type and size range of detrital quartz. The dominant reddish-orange colors of quartz grains suggest derivation from the same low-grade metamorphic source, the Acadian orogeny, presumed for Late Devonian black shales farther east (Schieber , 2016). The general abundance and size range of detrital quartz from the Woodford is in essence the same as that observed in Upper Devonian black shales of the Illinois Basin ca. 500 km to the east, and in the Williston Basin ca. 900 km to the north (Fig. 3), plausibly suggesting that all three locales received clastics from the Acadian orogen in the east (Schieber, 2016). The lacking differences in size range and source characteristics of detrital quartz (Fig. 3) between samples from Oklahoma and those of time-equivalent Devonian black shales from the Illinois and Williston basins (both far offshore the Acadian source region) supports strong dilution of clastics by early diagenetic silica in the case of the Woodford samples. No principal difference is observed between these locales. The randomly oriented phyllosilicate platelets (cardhouse fabric) observed in these rocks (Figs. 1 and 4), shielded from compaction by early diagenetic silica cements (Figs. 1 and 2), strongly suggests that the detrital component of these shales arrived via bedload transport of flocculated muds, and is quite similar to uncompacted fabrics seen in flume experiments that simulated accumulation of muds from bottom current transported floccules (Schieber et al., 2007; Schieber, 2011). Settling of airborne dust through the water column should produce an entirely different fabric with largely bedding-aligned phyllosilicates (O'Brien and Slatt, 1990).

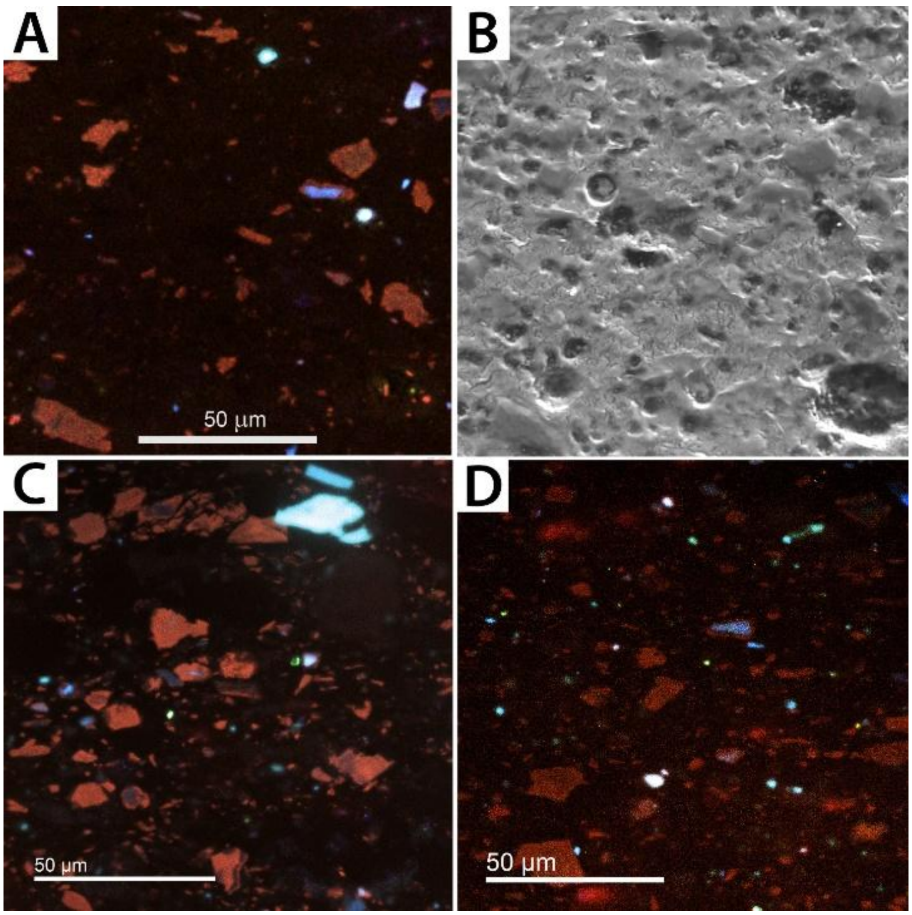

Figure 3: *Scanned CL-appearance and size range of detrital quartz in the Woodford compared with other Devonian black shales across the United States. A) Scanned cathodoluminescence image where detrital quartz shows as reddish and reddish-blue particles (bright bluish-green particles are K-feldspar), whereas the diagenetic matrix silica is largely non-luminescent. B) The same field of view (secondary electron image), detrital quartz grains appear as medium-gray objects, whereas the fine crystalline matrix quartz appears light gray and has a fine*

granular texture. C) CL images of the New Albany Shale in the Illinois Basin, and D) of the Bakken Shale of the Williston Basin for comparison. There is no significant difference in type and size range of detrital quartz grains between the Woodford, New Albany, and Bakken. The main difference is that the Woodford shows substantially more dilution by diagenetic silica. The Cl images were acquired several years apart with somewhat different instrument settings and image resolution, but they are displayed at the same magnification. The image in Part C was collected with substantially higher beam dwell time than images in Parts A and D, resulting in a "crisper" looking image.

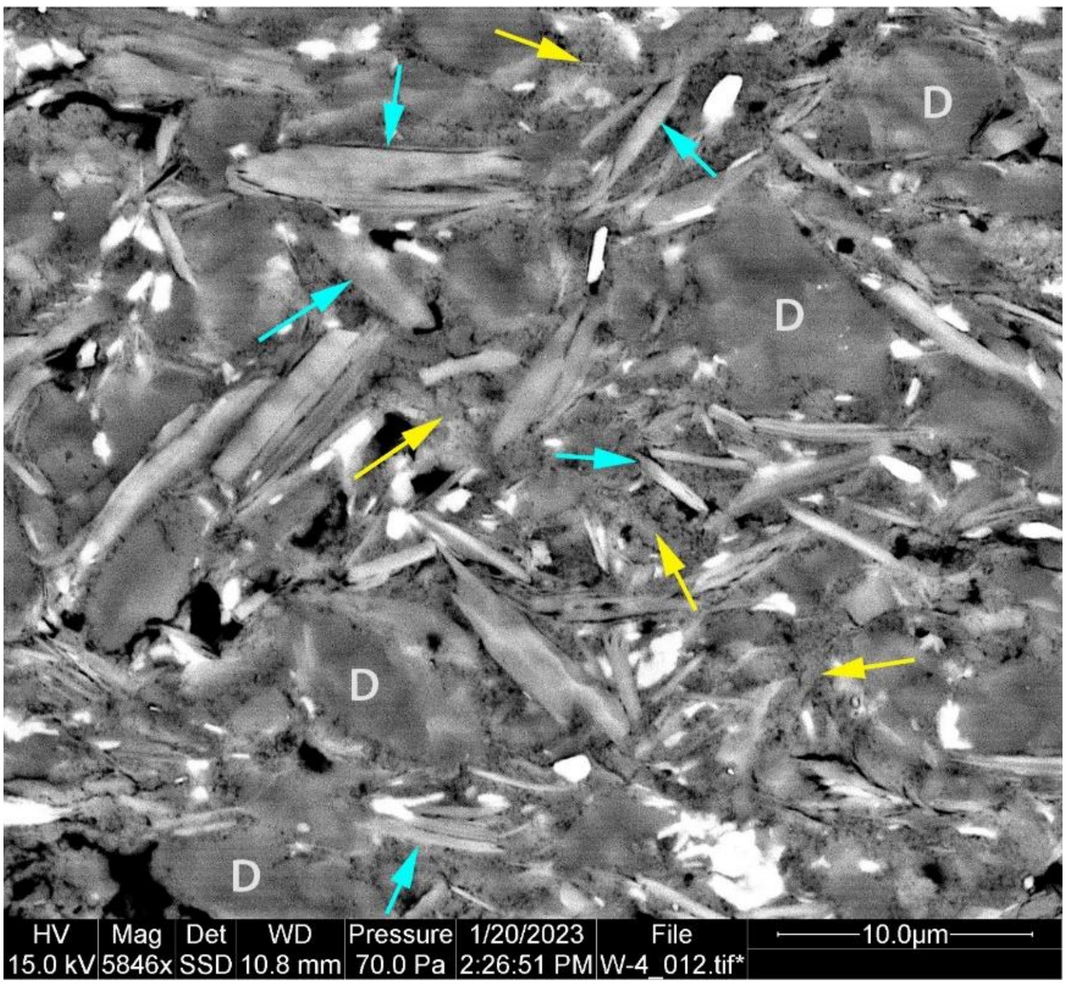

Figure 4: *Shale fabric with randomly oriented clay and mica flakes (blue arrows), scattered small detrital quartz grains (marked D), and a fine crystalline matrix of early diagenetic silica (yellow arrows).*

Second, when examined in detail, stratigraphic relationships in Devonian organic-rich mudstone successions show rapid shifts of depocenters in response to basin–dynamics (e.g., basement fault reactivation; Jacobi and Fountain, 2002; Wilson et al., 2022) as well as accommodation change due to subsidence (tectonic) and sea-level fluctuations. In the Late Devonian, regional unconformities (sequence boundaries) and their correlative conformities have been recognized and correlated across the United States by various authors (Brett et al., 2011; Lazar and Schieber, 2022; Wilson et al., 2022). Yet, these erosional contacts (and implicit hiatuses) are absent from Fig. 2 of McGlannan et al. (2022), greatly oversimplifying the existing stratigraphic complexities. Stratigraphic analysis shows that in the Appalachian Basin (Smith et al., 2019; Wilson et al., 2022), the Illinois Basin (Lazar and Schieber, 2022), and in central Oklahoma (Infante Paez et al., 2017), Devonian black shale successions invariably onlap onto structural highs (Cincinnati Arch, Nemaha Ridge). Such distal responses to shoreline progradation and retrogradation imply lateral sediment supply (for example by wind-driven bottom current systems) from a distal source and require shoreline-attached sediment dispersal systems. Had eolian sediment dispersal indeed been the key control in the distal realm, stratal units should be expected to drape across positive elements, rather than terminate against them.

McGlannan's reply is very supportive and aligned with a dynamic hydrodynamic system proposed by numerous authors cited in our text, however, this (now stated) sentiment is **not aligned with the original McGlannan article** wherein it is stated "we propose that eolian delivery is an additional and simpler explanation that avoids the need to call upon unknown and unusually powerful storms or tides, as well as flocculation, which is inconsistent with the minimal clay-mineral content of the study units." As demonstrated in our discussion, sedimentary structures (including evidence for flocculation) that suggest significant lateral transport via bottom currents are abundantly observed in the Woodford.

The most pervasive chert deposits associated with Late Devonian black shales occur in southern Laurentia, where a proximity to deep ocean waters and a combination of SE tradewinds with the Ekman spiral provide ideal conditions for upwelling of nutrient-rich waters onto the flooded North American craton (e.g., Parrish, 1982; Schopf, 1983; Parrish and Barron, 1986; Comer, 1991). Whereas the influence of this nutrient source likely diminishes away from the cratonic edge (Murphy et al., 2000a, 2000b), it is a highly plausible scenario for driving marine productivity in the Anadarko–Arkoma and Permian Basins and the Woodford Shale sections sampled by McGlannan et al. (2022).

Third, due to the Devonian-age colonization of land masses by trees and other land plants, nutrient supply to shelf and epicontinental seas increased so dramatically (Algeo et al., 1995; Algeo and Scheckler, 1998) that eolian sourced nutrients, had they existed, would not have made any difference with regard to the available nutrient supply. Also, as mentioned above, the very likely existence of upwelling of nutrient-rich deep-sea waters along the southern margin of the Late Devonian inland sea is a much more plausible nutrient source (rather than eolian input) for that part of the Late Devonian black-shale system. Fundamentally, there is no need, nor any justification, to call upon input of eolian clastics as a critical factor for the formation of any of the Late Devonian black-shale successions in North America. Several studies of geochemical proxies and organic petrography have shown marine-terrestrial co-dependencies linking rapid expansion of land plants, enhanced continental weathering, terrestrial runoff, and nutrient supply from the Acadian borderlands to enhanced primary productivity in the Devonian inland sea (Maynard, 1981; Algeo et al., 1995; Algeo and Scheckler, 1998; Berner, 2005; Wilson and Schieber, 2017; Song et al. 2021). Collectively these studies evoke a mental image of coastal plains with thriving forests, unlikely to have facilitated widespread deflation and lofting of siliciclastic fines as postulated by McGlannan et al. (2022). Furthermore, generating copious quantities of dust to fertilize the Devonian inland sea for several millions of years by way of deflation implies a commensurate concentration of sand and formation of eolian dunes (Kocurek, 1996). Yet, in spite of a long history of research into Devonian nearshore and onshore deposits of the Appalachian Basin (e.g., Bridge and Willis, 1991; 1994; Walker and Harms, 1975; Slingerland and Loule, 1988) no eolian deposits have ever been documented.

McGlannan et al., 2024, disagree with our argument on the requirement for "a commensurate concentration of sand and formation of eolian dunes" to generate "copious quantities of dust." Yet, in our critique we do not assume (as McGlannan et al., 2024 imply) that dust is generated by "grinding down" sand grains. We operate from an understanding that fines (mud, silt) are the most abundant product of weathering, and that in order to generate large quantities of dust, a substantial pile of sand is being "left behind". And it is that sand that concerns us, because we don't see it in the Devonian rock record. The Copper River deltaic system is called upon as an analog by McGlannan et al., 2022, and it so happens that the Copper River delta shows abundant eolian sand dunes (longitudinal ridges as much as 150 feet high) nourished by sustained, unidirectional, high-velocity winds that blow down the Copper River Canyon. If we accept the Copper River Delta as an analog for dust sourcing to the Late Devonian mudstone-dominated depositional system of the North American craton, spanning 10's of millions of years of (supposedly) eolian dust generation, we would expect to see ample evidence of eolian dunes (the sand that was left behind) forming in coastal areas of this supposed source region of eolian dust, especially given the vast expanse of Late Devonian shales across Laurentia and the high volume of dust that would be required to form them.

In summary, the confluence of petrographic constraints, stratigraphic relationships, and global controls thoroughly invalidates the premise of McGlannan et al. (2022). The considered evidence shows a striking mismatch between well documented geologic realities and the "eolian supply" vision proposed by McGlannan et al. (2022).

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