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Discussion on 'Tectonic and environmental controls on Palaeozoic fluvial environments: reassessing the impacts of early land plants on sedimentation'. *Journal of the Geological Society,* https://doi.org/10.1144/jgs2016-063.

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The first order importance of tectonic and environmental controls for terrigenous sediment supply has rarely been questioned, but the role of vegetation in the modification of alluvial signatures has been observed since the mid-20th Century (Vogt, 1941). Studies of sparsely vegetated rivers (Schumm, 1968) and alluvial stratigraphic variation (Cotter, 1978; Davies & Gibling, 2010) led to observations of (1) plant modulation of alluvial signatures; and (2) Palaeozoic facies shifts (PFS): unidirectional changes to facies diversity and frequency, in stratigraphic alliance with the plant fossil record. One PFS is the Siluro-Devonian appearance of mud-rich, architecturally complex alluvium, traditionally ascribed to meandering rivers, and sedimentologically distinct from pre-vegetation strata (Davies & Gibling, 2010; Long, 2011). Using selected secondary data, Santos et al. (2017) dispute the correlation of these observations using three key points: 1) The mid-Palaeozoic was typified by orogenic assembly of low-gradient equatorial continents and elevated sea level, which led to tropical weathering (abundant fines) and extensive alluvial plains. This drove the PFS by promoting river meandering independently of vegetation. 2) Meandering does not require vegetation; shown by examples in Precambrian deposits, on other planets, and in "non-vegetated" deserts. Meandering rivers were more abundant than the pre-vegetation rock record suggests, due to selective bypass and deflation of fines. 3) Early Siluro-Devonian (meaning Ludlow-Early Devonian) land plants were too small, their biomass and cover too limited, and their wetland habitat too narrow to have stabilized meandering channels, influencing landscape little more than earlier microbial communities. We contest the conclusions and methodology of the paper, and deal with each point in turn.

1) Palaeogeographic setting – The paper argues that the PFS towards a "fine-grained meandering fluvial-style" was solely due to tectonic and sea-level conditions, but fails to explain how non-unique conditions, cyclic since the Archean, initiated a tangible unidirectional singularity in the stratigraphic rock record. The paper does not explain why similar shifts are not reported from pre-Silurian instances of enhanced chemical weathering (Corcoran and Mueller, 2002), orogenies (e.g., Hudsonian, Grenvillian; Bradley, 2011) or extensive equatorial plains (e.g., in Rodinia; Li et al., 2008), nor other intervals of high sea-level, platforms and mountain-building (e.g., the Cretaceous; Seton et al., 2012). Without quantifying global facies during these intervals for comparison, Santos et al.'s (2017) conclusions rely on limited correlation between partial Palaeozoic sea-level curves and facies data, constructed from non-comparable secondary datasets (their Figures 3-4): the most obvious correlation in these figures remains that between rooting and interpreted meandering style. The claim for identifying a tectonic cause for these shifts is undermined by basing assertions on literature pre-dating the plate tectonics paradigm (i.e., palaeogeographic data from Weller (1898); sediment accumulation within geosynclines).

The implication that this PFS was restricted to equatorial, orogenic Euramerica is untrue (known bias was previously discussed: Davies & Gibling, 2010, p. 182). Siluro-Devonian vegetated muddy overbank deposits are also known from non-orogenic settings such as high-latitude Gondwana (Hunter & Lomas, 2003) and palaeoequatorial South China (Xue et al., 2016).

2) *Meandering without vegetation* – Previous authors have emphasised: (1) a distinction between modern river planform and "fluvial style" in ancient facies; and (2) no physical reasons precluding meandering rivers before vegetation, through stabilizing agents such as clay, mineral cements and ice (Cotter, 1978, p. 362; Davies & Gibling, 2010, p. 184; Long, 2011). However, the PFS is a tangible change to the spectrum of fluvial styles preserved in the rock record; the first widespread appearance of a certain recurring type of meandering-fluvial succession, observable in younger strata of any age, but absent in older strata (and interpretable as fine-grained meandering systems; see Long, 2011). Such heterolithic successions are 10's-100's m-thick, and contain at least 10% mudrock (often >50%) *and* repeated or pervasive outcrop-scale architectural evidence for channel sinuosity *throughout* their stratigraphic thicknesses (see Davies & Gibling, 2010, for associated facies characteristics).

Santos et al. (2017) cite rare Neoproterozoic examples of inclined heterolithic strata (IHS) from the Torridon Group of Scotland (similar to common post-Palaeozoic motifs; their Figure 1) as evidence for long-lived floodplains and meandering channels before vegetation. However, both these IHS are <2 m-thick, are associated with interpreted overbank mudrocks <2 m-thick, and are atypical of the c.190 m-thick Allt na Béiste Member in which they occur (Stewart, 2002); mudrock accounts for c.0.2% of Torridon Group alluvium as a whole, otherwise dominated by archetypal pre-vegetation sandstone strata (based on estimated thicknesses of alluvial formations in Owen & Santos (2014), less if Stewart's (2002) estimates are used). Flow resistance is fundamental for channel sinuosity (Lazarus & Constantine, 2013); in modern rivers resistance may involve vegetation or not, but fewer causes existed prior to vegetation and thus evidence for solely abiotic resistance promoting sinuous channels is as rare as these examples. A literature survey reveals 366 sand-dominated Precambrian and Cambrian formations where abundant mudstone and IHS are apparently absent (see Supplementary Material). By contrast, ~40% of all Earth's recorded Upper Devonian fluvial formations have been attributed to meandering rivers by virtue of containing such facies signatures throughout their stratigraphic thicknesses (Davies et al., 2011).

Santos et al. (2017) miscite Long (2011) in suggesting that silt-grade sediment is common in pre-vegetational systems: it is not. Our original data confirm that only 3% of Archean-Cambrian alluvial successions contain >10% fines, compared to 74% in the Silurian-Devonian (Figure 1; Davies & Gibling, 2010). The paper infers bypassing and deflation could account for the scarcity of IHS in pre-vegetation settings. Although undoubtedly significant, these processes are unlikely to have selectively removed heterolithic lateral-accretion deposits with sand and mud layers.

Santos et al.'s (2017) use of satellite imagery to justify pre-vegetation rivers on Earth is inappropriate, not least because it conflates plan-view imagery of channels as synonymous to vertical facies signatures in the pre-vegetation rock record. The "non-vegetated" channel images (their Figure 2) lack ground-truthing of bank stability controls and, magnified, observably host shrubs and trees (images lack resolution to determine smaller plants). Figure 2A is particularly inappropriate as it displays relict channels feeding Lake Chad that were last active before desertification, when vegetation canopy cover and number of plant species were far greater (Drake et al., 2011). The Martian analogues are eroded >3 Ga inverted channel-belt deposits. Because Martian inverted channel-belts have not been investigated by rovers, our understanding of these features is limited to orbital observations, with few constraints on their sedimentology. We consider it dangerous to use Martian analogues that have not been investigated in situ and for which we have a very poor understanding of formative conditions to make interpretations of terrestrial systems. Martian planetary conditions suggest that their formation may anyway have been less reliant on bank cohesion (Matsubara et al., 2015). The scale (100's m-width) and compound nature of these geomorphic features also means that they are fundamentally different geological phenomena to IHS in the Torridonian (outcrop-scale vertical sections of rock, revealing deposits of small single channels) (*contra* Santos et al., 2017). Titan analogues of methane-ethane rivers are irrelevant as all controls are radically different to those of Earth (e.g., Gilliam & Lerman, 2016).

Santos et al. (2017) also support their hypothesis by citing modelling studies that have experimentally created meandering channels in the absence of vegetation (e.g., using mud, Peakall et al., 2007). However, when considering the greening of the continents, the pertinent question is not "can meandering channels be made in an unvegetated flume tank?" (evidently yes, in certain circumstances), but rather "what happens when plants are introduced to an unvegetated flume tank?". Studies that have considered this latter question show a strong influence of vegetation in promoting and sustaining meandering channels (e.g., Tal & Paola, 2007; Braudrick et al., 2009; albeit using small angiosperms in the experiments, due to scaling issues).

3) Early terrestrial life – The paper equates the earliest vegetation as having similar sedimentological effects to pre-existing microbial mats, but this is unfounded: the latter are mechanically different biotic components of fluvial systems (surficial, elastic features: see McMahon et al., 2017). The paper raises the valid point that it is presently uncertain exactly *how* primitive land-plants, with apparently only limited root-like organs, forced the PFS (compare Lenton et al., 2012; Quirk et al., 2015; Xue et al., 2016). Although far less effective than later trees in modulating surface processes, testable hypotheses are known by which the earliest plants *could have* forced the PFS: (1) plants acted alone: resistance to shear in even the earliest root-like organs, whatever their extent, was sufficient to bind floodplains; or (2) plants acted vicariously through fine-grained sediment which was potentially (a) increasingly baffled against winnowing/bypass due to the reduction of near-surface flow velocity by above-ground plant structures (e.g., see Moor et al., 2017, for modern analogues), or (b) produced in increasing amounts by the earliest plants (+/- symbiotic interaction with existing microbial communities). While, at present, the relative role of these remain speculative, what is geologically certain is the observable global facies difference between alluvium deposited when only microbial life was present (pre-Ordovician) and that deposited when both microbiota and primitive land plants were present (post-Silurian).

The paper's palaeobotany section also contains numerous errors and contradiction, arising from selective reading of secondary literature: as examples, (1) there is insufficient data on the precise palaeogeographic aspects of early land plant radiation (Wellman et al., 2013); (2) isotopic data and early coals suggest a considerable Early Devonian plant cover (Małkowski and Racki, 2009; Kennedy et al., 2013); (3) Middle Devonian cladoxylopsid and archaeopterid roots include large systems in soils other than swamps (e.g., Morris et al., 2015). Furthermore, the paper also overlooks the fact that, through a combination of sediment baffling and adventitious recruitment, plants build-up cumulative soil profiles, rich in root biomass, far thicker than the product of a single cohort. The papers compilation of root depth evolution (their Figure 3), based on a selective reading of literature that intermixes single-cohort and multi-cohort palaeosol profiles, is inaccurate.

Additionally, just because the first plant *fossils* occur within sediments deposited in wet, muddy settings (i.e., depositional/preservational not erosional) does not preclude the existence of earlier/other plants in non-preserved environments - as attested by the palynological record (Wellman & Strother, 2015) and exceptionally preserved intramontane floras (e.g., the Rhynie Chert). The well-documented taphonomic megabias against Palaeozoic dryland plants (Falcon-Lang et al., 2009) is especially pertinent because dryland ecosystems show generally deeper rooting and a greater proportion of below-ground biomass (Jackson et al., 1996).

Santos et al. (2017) propose tectonics/sea-level forced changes to fluvial systems and acted as a catalyst for the evolution of terrestrial flora. The adaptive radiation of land plants, however, requires no such geological trigger. If the primary barrier to terrestrial vegetation was environmental we could expect a polyphyletic radiation of plant-like photosynthetic terrestrial organisms once the requisite conditions were met. The monophyly of land plants (e.g. Karol et al., 2001) attests against this, instead suggesting that the limiting factors were intrinsic, i.e. acquisition of novel developmental pathways involved in embryogenesis/organogenesis. Furthermore, claims that (often braided) rivers operating before the PFS were sub-optimal for initial land plant terrestrialization are unfounded: the very first land plants pre-date the PFS by c. 50 Ma.

In summary, robust observations of sedimentary rock characteristics are distinct from subsequent abstract steps of interpretation (e.g., of meandering). An observable, singular and unidirectional facies shift occurs in the global rock record in close stratigraphic alliance with evolutionary developments in the palaeobotanic record. Observations from modern plant-river interactions lend credence to the notion that this alliance is not coincidental (Corenblit et al., 2014) and that it represents a permanent increase in the global abundance of small (outcrop-scale), muddy meandering channels. Unidirectional, irreversible changes to the rock record must reflect unidirectional changes to the Earth system: they cannot be explained by cyclic phenomena such as plate tectonics or sea-level.

References

Bradley, D.C., 2011, Secular trends in the geologic record and the supercontinent cycle. Earth-Science Reviews, 108, 16-33.

Braudrick, C.A., Dietrich, W.E., Leverich, G.T., Sklar, L.S., 2009. Experimental evidence for the conditions necessary to sustain meandering in coarse-bedded rivers. Proceedings of the National Academy of Sciences of the United States of America, 106, 16936–16941.

Corcoran, P.L., Mueller, W.U., 2002. The effects of weathering, sorting and source composition in Archean high-relief basins: examples from the Slave Province, Northwest Territories, Canada. In: Altermann, W. and Corcoran P.L. (Eds.), Precambrian Sedimentary Environments: a modern approach to ancient depositional systems, International Association of Sedimentologists Special Publication 33: 183-211.

Corenblit, D., Davies, N.S., Steiger, J., Gibling, M.R. & Bornette, G., 2014, Considering river structure and stability in the light of evolution: feedbacks between riparian vegetation and hydrogeomorphology. Earth Surface Processes and Landforms, 40, 189-207.

Cotter, E., 1978. The evolution of fluvial style, with special reference to the central Appalachian Paleozoic. In: Miall, A.D., (Editor), Fluvial Sedimentology. Canadian Society of Petroleum Geologists Memoir 5: 361-383.

Davies, N.S., Gibling, M.R., 2010, Cambrian to Devonian evolution of alluvial systems: The sedimentological impact of the earliest land plants. Earth Science-Reviews, 98, 171-200.

Davies, N.S., Gibling, M.R., Rygel, M.C., 2011, Alluvial facies during the Palaeozoic greening of the land: case studies, conceptual models and modern analogues. Sedimentology, 58, 220-258.

Drake, N.A., Blench, R.M., Armitage, S.J., Bristow, C.S., White, K.H., 2011, Ancient watercourses and biogeography of the Sahara explain the peopling of the desert. Proceedings of the National Academy of Sciences of the United States of America, 108, 458-462.

Falcon-Lang, H.J., Pendleton, J., Wellman, C.H., 2011. Dryland plant communities in the Pennsylvanian (mid- to late Bolsovian) Winterbourne Formation of Bristol, southern Britain: further evidence for taphonomic megabias. Review of Palaeobotany and Palynology, 166, 268-285.

Gilliam, A.E., Lerman, A., 2016, Formation mechanisms of channels on Titan through dissolution by ammonium sulfate and erosion by liquid ammonia and ethane. Planetary and Space Science, 132, 13-22.

Hunter, M.A., Lomas, S.A., 2003, Reconstructing the Siluro-Devonian coastline of Gondwana; insights from the sedimentology of the Port Stephens Formation, Falkland Islands. Journal of the Geological Society of London, 160, 459-476.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996, A global analysis of root distributions for terrestrial biomes. Oecologia, 108, 389-411.

Karol, K.G., McCourt, R.M., Cemino, M.T., Delwiche, C.F., 2001, The closest living relatives of land plants. Science, 294, 2351.

Kennedy, K.L., Gibling, M.R., Eble, C.F., Gastaldo, R.A., Gensel, P.G., Werner-Zwanziger, U., Wilson, R.A., 2013. Lower Devonian coaly shales of northern New Brunswick, Canada: plant accumulations in the early stages of terrestrial colonization. Journal of Sedimentary Research, 83, 1202-1215.

Lazarus, E.D., Constantine, J.A., 2013, Generic theory for channel sinuosity. Proceedings of the National Academy of Sciences of the United States of America, 110, 8447–8452.

Lenton, T.M., Crouch, M., Johnson, M., Pires, N., Dolan, L., 2012. First plants cooled the Ordovician. Nature Geoscience, 5, 86-89.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernste, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkocha, D.P., Jacobs, J., Karlstrom, K.E., Lul, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis. Precambrian Research, 160, 179-210.

Long, D.G.F., 2011. Architecture and depositional style of fluvial systems before land plants: a comparison of Precambrian, early Paleozoic and modern river deposits. In: S. Davidson, S. Leleu and C.P. North (Editors), From River to Rock Record: The Preservation of Fluvial Sediments and their subsequent Interpretation. SEPM, pp. 37-61.

Małkowski, K., Racki, G., 2009. A global biogeochemical perturbation across the Silurian-Devonian boundary: ocean-continent-biosphere feedbacks. Palaeogeography, Palaeoclimatology, Palaeoecology 276, 244–254.

Matsubara, Y., Howard, A.D., Burr, D.M., Williams, R.M.E., Dietrich, W.E., Moore, J.M., 2015, River meandering on Earth and Mars: A comparative study of Aeolis Dorsa meanders, Mars and possible terrestrial analogs of the Usuktuk River, AK, and the Quinn River, NV. Geomorphology, 240, 102–120.

McMahon, W.J., Davies, N.S., Went, D.J., 2017 In Press, Negligible microbial matground influence on pre-vegetation river functioning: evidence from the Ediacaran-Lower Cambrian Series Rouge, France. Precambrian Research. doi: 10.1016/j.precamres.2017.01.020

Moor, H., Rydin, H., Hylander, K., Nilsson, M.B., Lindborg, R., Norberg, J., 2017, Towards a trait-based ecology of wetland vegetation. The Journal of Ecology, doi: 10.1111/1365-2745.12734.

Morris, J., Leake, J.R., Stein, W.E., Berry, C.M., Marshall, J.E.A., Wellman, C.H., Milton, J.A., Hillier, S., Mannolini, F., Quirk, J., Beerling, D.J., 2015, Investigating Devonian trees as geo-engineers of past climates: Linking palaeosols to palaeobotany and experimental geobiology. Palaeontology, 58, 787-801.

Owen, G., Santos, M.G.M., 2014, Soft-sediment deformation in a pre-vegetation river system: the Neoproterozoic Torridonian of NW Scotland. Proceedings of the Geologists' Association, 125, 511-523.

Peakall, J., Ashworth, P.J., Best, J.L., 2007, Meander-bend evolution, alluvial architecture, and the role of cohesion in sinuous river channels: a flume study. Journal of Sedimentary Research, 77, 197–212.

Quirk, J., Leake, J.R., Johnson, D.A., Taylor, L.L., Saccone, L., Beerling, D.J., 2015, Constraining the role of early land plants in Palaeozoic weathering and global cooling. Proceedings of the Royal Society of London, Series B, 282, 20151115.

Schumm, S.A., 1968, Speculations Concerning Paleohydraulic Controls of Terrestrial Sedimentation. Geological Society of America Bulletin, 79, 1573-1588.

Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T.H., Shephard, G., Talsma, A., Gurnis, M. Turner, M., Chandler, M., 2012, Global continental and ocean basin reconstructions since 200 Ma. Earth-Science Reviews, 113, 212–270.

Stewart, A.D., 2002, The later Proterozoic Torridonian rocks of Scotland: their sedimentology, geochemistry and origin. Geological Society of London Memoir 24, 130 pp.

Tal, M., Paola, C., 2007. Dynamic single-thread channels maintained by the interaction of flow and vegetation. Geology, 35, 347-350.

Vogt, T., 1941, Geology of a Middle Devonian cannel coal from Spitsbergen. Norsk Geologisk Tidsskrift, 21, 1–12.

Weller, S. 1898, The Silurian fauna interpreted on the epicontinental basis. Journal of Geology, 6, 692–703.

Wellman, C.H., Steemans, P., Vecoli, M., 2013, Palaeophytogeography of Ordovician-Silurian land plants. Geological Society, London, Memoir 38, 461-476.

Wellman, C.H., Strother, P.K., 2015, The terrestrial biota prior to the origin of land plants (embryophytes): a review of the evidence. Palaeontology, 58, 601-627.

Xue, J., Deng, Z., Huang, P., Huang, K., Benton, M. J., Cui, Y., Wang, D., Liu, J., Shen, B., Basinger, J.F., Hao, S., 2016, Belowground rhizomes in paleosols: The hidden half of an Early Devonian vascular plant. Proceedings of the National Academy of Sciences of the United States of America, 113, 9451-9456.

Figure Caption

Figure 1 – Percentage of worldwide Archean- to Devonian-aged alluvial formations for which mudrock strata make up >10% of their total stratigraphic thickness, primarily constructed using published data (mudrock thickness determined as recorded by original authors, estimated from illustrated stratigraphic sections, or estimated during original field visits). Archean to Neoproterozoic data drawn from an original literature survey (see Supplementary Material). Cambrian to Devonian data from Davies and Gibling (2010) (and subdivided using their 'vegetation stages' VS2 - VS6). Data from formations whose age crosses stratigraphic boundaries are processed in accordance with methodology outlined in Davies and Gibling (2010). Archean: n=45, Paleoproterozoic: n=98, Mesoproterozoic: n=58, Neoproterozoic: n=94, VS2: n=16, VS3: n=8, VS4: n=10, VS5: n=14, VS6: n=16; x-axis scaled to Ma duration.

Figure 1

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