doi:10.1130/G33346Y.1

Early Cambrian metazoans in fluvial environments, evidence of the non-marine Cambrian radiation

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Davies and Gibling (2012) raise concerns that sediments hosting trace fossils in the early Cambrian middle member of the Wood Canyon Formation, which we have interpreted as fluvial, may be marine in origin. They suggest that in the absence of body fossils or specific minerals, it may not be possible to separate marine and fluvial sediments. They point out that there is no single diagnostic sedimentary structure unique to fluvial environments, and that the presence of mudstones and the trace fossils themselves are sufficient evidence for interpreting a marine environment for the middle member of the Wood Canyon Formation. In a second comment, McIlroy (2012) suggests that while the morphology of the trace fossils is different from those recognized in marine members of the Wood Canyon Formation, they are consistent with juvenile traces and those occurring in stressed environments in younger marine sediments, and thus do not uniquely identify a fluvial environment.

A fluvial origin for the trace fossils we reported in the middle member of the Wood Canyon Formation (Kennedy and Droser, 2011) is significant and worthy of careful consideration because it implies that the Cambrian radiation extended beyond the marine realm to the terrestrial, and there was a sufficient terrestrially derived food supply to support metazoan activity in rivers. We feel that the depositional environment encompassing these trace fossils should be established with evidence that is independent of the trace fossils themselves, particularly as we have little knowledge of what early Cambrian fluvial trace fossils should look like. We also feel that, while single sedimentary features may occur in both marine and fluvial environments, the combined evidence speaks strongly for a fluvial environment.

Evidence supporting a fluvial environment of deposition for the interval hosting the trace fossils at our study sites does not stand on a single piece of evidence, but rather includes (1) gritty, unsorted, and immature arkosic sandstone and trough-cross bedded cobble conglomerate in wedge-shaped channel deposits, unidirectional paleocurrent, gravel bars, and silty, mudcracked mudstones defining fining-upward cycles that are truncated by channelized arkosic sandbodies with abundant mud chips; (2) a strong lithological contrast with the lower member (interpreted as marine) that contains supermature quartz arenite, carbonate beds, wave ripples, planar, herringbone (bi-directional), and hummocky cross-stratification; and (3) separation of these two units by a sequence boundary/unconformity. This surface is variously interpreted as an angular unconformity that forms the base of the Sauk Sequence (a cratonwide sequence boundary; Fedo and Cooper, 2001), or a lower-order sequence boundary (Hogan et al., 2011). At our study sites, there is an abrupt and erosive contact with no interbedding between the lower and middle Members, and no return to sediments with arenite composition, wave ripples, hummocky cross-stratification, carbonate beds, or evidence of tidal influence until the transition to the Upper member >50 m upsection. The composition of the middle member is uninterrupted immature and gritty arkosic sand and conglomerate, with no evidence for marine incursion(s) such as better sorting of sediment, changes in sediment composition, wave reworking, reversals of paleocurrents, or shoreface erosion. These features are apparent, however, where interbedding between the middle and upper member occur as a transitional contact toward the top of the formation. While meter-scale trough-crossbedded cobble conglomerates may occur in high-energy beach environments or tidal channels, as Davis and Gibling point out, the examples they provide are compositionally more mature and associated with shore-face or tidal features.

The middle member of the Wood Canyon Formation has been used as an example of early Cambrian fluvial sedimentation by several studies (e.g., Fedo and Cooper, 1990), including a study by Davies et al. (2011) who assigned a sheet-braided fluvial environment to the middle member. The representative outcrop photo of the middle member Davies et al. (2011) present in their figures 4A and 4B is the same trough-crossbedded arkosic facies with thin muddy intervals we present in figure 1 of our paper (Kennedy and Droser, 2011). This facies occurs at both our study sites (separated by ~40 km), and in both locations, trace fossils were present within it. We are thus confident we are referring to a similar interval that Davies et al. (2011) also consider fluvial, when trace fossils are not included in their interpretation.

Davies and Gibling question the origin of muddy sediments we interpreted as overbank deposits on the basis that such deposits have low preservation potential in early Cambrian fluvial environments relative to vegetation-stabilized landscapes. These deposits are silt to fine sand, and gritty in texture, arkosic in composition, and red/gray and oxidized in appearance. They form thin beds (5–20 cm) that are truncated by arkosic sand and conglomerate-filled channels, and are rarely more than 10 m in lateral persistence. Upward, channelized sands form an increasing proportion of the succession until they are fully amalgamated, leaving no bedded fines preserved, though mud chips of this same material are common through the middle member. Davies et al. (2011, p. 229) identify this same lithology in their figures 4A and 4B and refer to it as "sheet-like fluvial sandstone strata exhibiting rare dark mudstone layer." These mudstones are distinctly different than the laminated, laterally continuous siltstones comprised of quartz arenite present in the lower member.

Our findings support Davies and Gibling's conclusion that this landscape was unstable in the absence of vegetation-stabilizing channels. However, we disagree with their interpretation that habitats were too ephemeral to host metazoan life; rather, evidence from the middle member of the Wood Canyon Formation indicates low preservation potential of channel tops where animals burrowed. Given the poor preservation potential of shallow burrows in a landscape characterized by channel migration and erosion, and the default interpretation that trace fossils are indicative of a marine environment offered by Davies and Gibling, it is unlikely that fluvial trace fossils should be commonly reported.

McIlroy (2012) suggests the trace fossils we report (Kennedy and Droser, 2011) are consistent with forms observed in marine environments, including those of juveniles or those formed in stressed environments. He suggests that the trace fossils we describe are not sufficiently different to support an interpretation of a fluvial depositional environment. We did not, however, consider the trace fossil morphology in our interpretation of the environment of deposition; we only noted its difference from standard marine forms was consistent with later examples reported from fluvial environments. We feel that it is premature to interpret a depositional environment from the morphology of these trace fossils, as they presently represent the only fluvial examples reported from the lower Cambrian.

McIlroy suggests that had other studies noted the trace fossils we report, they would have considered the middle member marine. This argument is both speculative and circular. The trace fossils should not contribute to the interpretation of the depositional environment in this particular case, as their origin is the issue at stake. McIlroy further proposes that a braided delta interpretation is supported by trace fossil occurrence in fine-grained distributary channel sediments with evidence of tidal currents in the form of herringbone cross-stratification. He has confused what we reported, however, which was that herringbone cross-stratification is found only in the marine lower member, and the trace fossils do not occur in the mudstones themselves. Trace fossils originate at channel tops and pipe downward into coarse-grained sediments filling the channels beneath the mudstones (Kennedy and Droser, 2011). The mudstones are significant because they indicate a relatively complete fining cycle and mark preserved channel tops.

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