A comment on "Metamorphic origin of anastomosing and wavy laminas overprinting putative microbial deposits from the 3.22 Ga Moodies Group (Barberton Greenstone Belt)"

Martin Homann[1] and Christoph Heubeck[2]

[1] Department of Earth Sciences, University College London, WC1E 6BT London, UK
[2] Department of Geosciences, Friedrich-Schiller-Universität Jena, Germany

Precambrian Research 365 (2021) 106395
https://doi.org/10.1016/j.precamres.2021.106395

Saitoh et al. (Precambrian Research 362, 2021, 106306) challenge the conventional view that crinkly and wavy carbonaceous laminations from shallow-water sandstones of the Moodies Group represent fossilized remnants of microbial mats (Heubeck, 2001; Noffke et al., 2006; Heubeck, 2009; Gamper et al., 2012; Homann et al., 2015, 2016, 2018; Heubeck et al., 2016; Homann, 2019; Köhler and Heubeck, 2019) and suggest a metamorphic origin instead. Although the authors present detailed analytical data, we argue below that their samples are weathered, selectively investigated, and interpreted with scant consideration of their geological context; based on our systematic study of these same structures, we find their main conclusions not warranted. Scrutiny of claims for biogenicity is a most welcome and integral part of early life research, but it deserves to be done systematically and on multiple scales (e.g., Brasier et al., 2006; Rouillard et al., 2021).

Weathered samples invalidate CM data and diagenetic sequence

In a publication intended "*to better constrain the origin of the laminae*" and Archean depositional and diagenetic history, Saitoh et al. (2021) document "*recent oxic rainwater infiltration into the analyzed Moodies sediment*" and iron oxide alteration (p. 14; Figs. 5, 8, S2) of 42 samples, which had been partly used for sulfur isotope analyses (Saitoh et al., 2020) and are now investigated by µm-scale geochemical analyses.

Exposing sedimentary strata deposited under reducing conditions to oxygenated meteoric water severely affects element mobility, with a number of significant consequences for mineral parageneses and abundance. The presence of goethite indicates that reduced mineral species and any primary carbonaceous matter (CM) were likely remobilized. Saitoh et al. (2021) repeatedly state that the Moodies sandstones are depleted in CM; however, TOC values are reported from only 3 of the 42 samples (Supplementary Table 2), averaging 90 ppm. 93% of the samples are not considered, including the intertidal subunit 2 that is particularly rich in microbial mats. Fig. 8 of Saitoh et al. (2021) demonstrates that oxidation of CM indeed occurred: Raman spectra of sample SAD21 show no goethite but CM whereas spectra of sample SAD4 show goethite but no CM. Sample SAG39 (Fig. 9) does contain CM in the laminae and shows an enrichment in Ti oxides (see also Homann et al. 2015, 2018). It is therefore difficult to follow how the authors draw conclusions about Archean depositional environments, the occurrence of microbial mats, and element abundances. In our experience, unweathered microbially laminated Moodies sandstones appear dark grey with nearly black, laminations that are clearly visible under the microscope (Fig. 1 J-L). From those, Homann et al. (2018) documented TOC values of up to 700 ppm (n=18; mean=430 ppm), consistent with measurements from similar lithologies of Archean age.

Diagenetic history

The "*schematic model of the depositional and post-depositional history*" (Fig. 12) shows no depositional processes but begins (Stage 1 "Sedimentation") with a static situation after deposition and shallow burial of a "*fine-grained lamina"* consisting of "*mud matrix / organic matter (microbial mat?)"*. The origin of the organic matter thus remains unresolved. Incongruously with title and abstract, the authors state that sedimentary conditions "*may also have been favorable for potential biofilm installation*" (p. 12).

Stage 2 shows pore space filled by quartz cement supplied by pressure solution under burial conditions; the mud matrix is slightly (ca. -15%) compacted. Had initial cementation occurred only under conditions of quartz pressure solution, the undeformed, three-dimensional preservation of the mats, trapped gas bubbles (Homann et al., 2015; Homann, 2019), delicate onlap structures, cm-scale microrelief (Heubeck, 2009), and cavities with microstromatolites (Homann et al., 2016) would have been impossible.

Stage 3 "Sericite cementation" shows the mud matrix disappeared, replaced by "sericite cement". The precipitation of sericite from solution into fluid-filled pores is rather rare; much more common is its origin during low-grade metamorphism of clays at around 300°C. Its origin in Moodies sandstones as an alteration product of metastable volcanic rock fragments, shale clasts and sedimentary (pseudo-)matrix is extensively documented (Heubeck and Lowe, 1999; Sleep and Hessler, 2006; Heubeck, 2019; Reimann et al., 2021).

Stage 4 shows the unexplained reappearance of the "mud matrix/organic matter (microbial mat?)" while Stage 5 documents that studied samples are weathered.

The authors suggest that laminae resulted from metamorphic overprint of a clay matrix. Although they do not support this claim ("*such original clay matrix is not petrographically observed in the present rocks*"), they argue that it is "*commonly recognized in other Moodies localities (e.g., Eriksson and Simpson, 2000; Homann et al., 2018)*". Although mudstone drapes are common in the Moodies rocks, being the result of suspension settling in tidal environments, they are easily distinguishable morphologically from carbonaceous laminations of fossilized microbial mats, e.g., by their micaceous sheen, desiccation cracks, or the conformable draping of ripples.

Mesoscale geological information

The authors do not present a conclusive alternative for an abiogenic, e.g., metamorphic origin of the carbonaceous laminae and largely disregard published morphological and textural relationships. Along the traverse sampled by Saitoh et al. (2021), abundant and diverse sedimentary structures indicate the syndepositional origin and early diagenetic stiffening of the carbonaceous laminae. Despite a statement to the contrary ("... *little evidence for tearing and transportation of biofilm fragment, along the analyzed Moodies succession*"), the investigated section includes excellent examples of microbial mat chip conglomerates and laminae with substantial microrelief (Fig. 1; all photographs are from the vicinity of the sampled section). Homann et al. (2015; stratigraphic Log 9; Fig. 10D) clearly locates the relevant sites in this section. They were also shown to two of the co-authors of Saitoh et al. (2021) during a field trip in October 2017 and are documented in a detailed field trip handout (see Fig. 5-2 in supplementary information).

The most plausible source of heating, alteration, and near-surface cementation

In searching for a thermal energy source to drive alteration and metamorphism, the authors list (without preference) seven post-Moodies thermal events of the subsequent 1100 Ma, and incorrectly cite a post-Moodies crystallization age ("~3.21 Ga") of the pre-Moodies Kaap Valley Tonalite (3229 Ma; Moyen et al., 2019). A potential driver not mentioned of this heating is the 15 km long and up to 500 m-thick, Moodies-age Lomati River Sill (LRS), stratigraphically about 1 km below the investigated section (Lowe et al. 2012); Heubeck and Lowe 1994). Reimann et al. (2021) documented the consequences of thermal alteration in the LRS halo, including a well-exposed dike stockwork intruding unconsolidated, in part biolaminated Moodies sands in correlative strata only 2.5 km from the section investigated by Saitoh et al. (2021). This stockwork may have its equivalent in a dike network visible on Google Earth images cross-cutting this section. We thus consider the proximity, large size, shallow emplacement depth, Moodies crystallization age, and extensive subvolcanic stockwork of the LRS to have likely been pivotal in preserving this unique Early Archean microbial ecosystem by providing silica-bearing fluids and early-diagenetic thermal energy to the sedimentary environment.

Contradictory statements

Saitoh et al. (2021) extensively state previous observations but comment them ambiguously, largely without providing decisive data. Are the carbonaceous laminations metamorphic in origin (Highlights, Abstract, Title) or biogenic (Title, Conclusions)? Were depositional conditions favorable to microbial mat growth (p. 12) or not (Abstract)? Did OM originate as biofilm (p. 12), have a metamorphic origin (title), settle from suspension (p.16) or does *"microbial mat development and preservation (also see Noffke, 2009) appear questionable"* (p. 16)? Did sericite precipitate as a cement, partly in veins (p. 13) or was *"the original clay matrix in the laminae ... replaced with sericite during low-grade and fluid mediated metamorphism"* (p. 14)? We certainly agree with the concluding statement ("*...we do not exclude that some of the observed Moodies laminae were originally microbial mats*") but note its contradiction by the Highlights ("*Metamorphic origin of the analyzed Moodies laminae*").

Summary

The BGB, the Moodies Group, and its carbonaceous laminae are complexly metamorphosed (e.g., Byerly et al., 2019; Heubeck, 2019; Reimann et al., 2021); in addition, most outcrops are at least surficially weathered. These conditions do not necessarily erase the multiple lines of mesoscale evidence supporting the synsedimentary and biogenic origin of the laminations, well documented in the literature cited by Saitoh et al. (2021). Microbial mats generally represent a well-established morphological fossil throughout much of early Earth history and have also been reported from other sandy deposits of the Kaapval and Pilbara Cratons (e.g., Hickman-Lewis et al., 2018; Noffke et al., 2008; Rasmussen et al., 2009). Carbonaceous laminae of the Moodies Group are not an isolated phenomenon and evidently formed cohesive, sticky, surficial, fluid- and gas-rich layers mm-to-cm thick with a microrelief of a few cm at the sediment-water interface (Fig. 1). They were in places brittily, in other places ductily deformed under (near-)surface conditions and compacted in some places barely, in others early, releasing copious amounts of fluid. The preserved organic matter indicates biogeochemical cycling of carbon and nitrogen (Homann et al., 2018); primary *in situ* morphologies strongly resemble those of modern microbial mats (Homann et al., 2015, Homann, 2019).

Saitoh et al. (2021) conclude that unweathered rock material is required to significantly advance our knowledge on the Moodies Group carbonaceous laminae. This is certainly true. One of the scheduled boreholes of the ICDP BASE project through the Moodies Group (drilling scheduled Oct. 2021- March 2022) is almost entirely dedicated to this purpose. Although the number of analytical techniques employed by Saitoh et al. (2021) on the samples is impressive, they could have been brought to full use had the authors selected unweathered samples, integrated the disparate results, and adequately considered published literature.

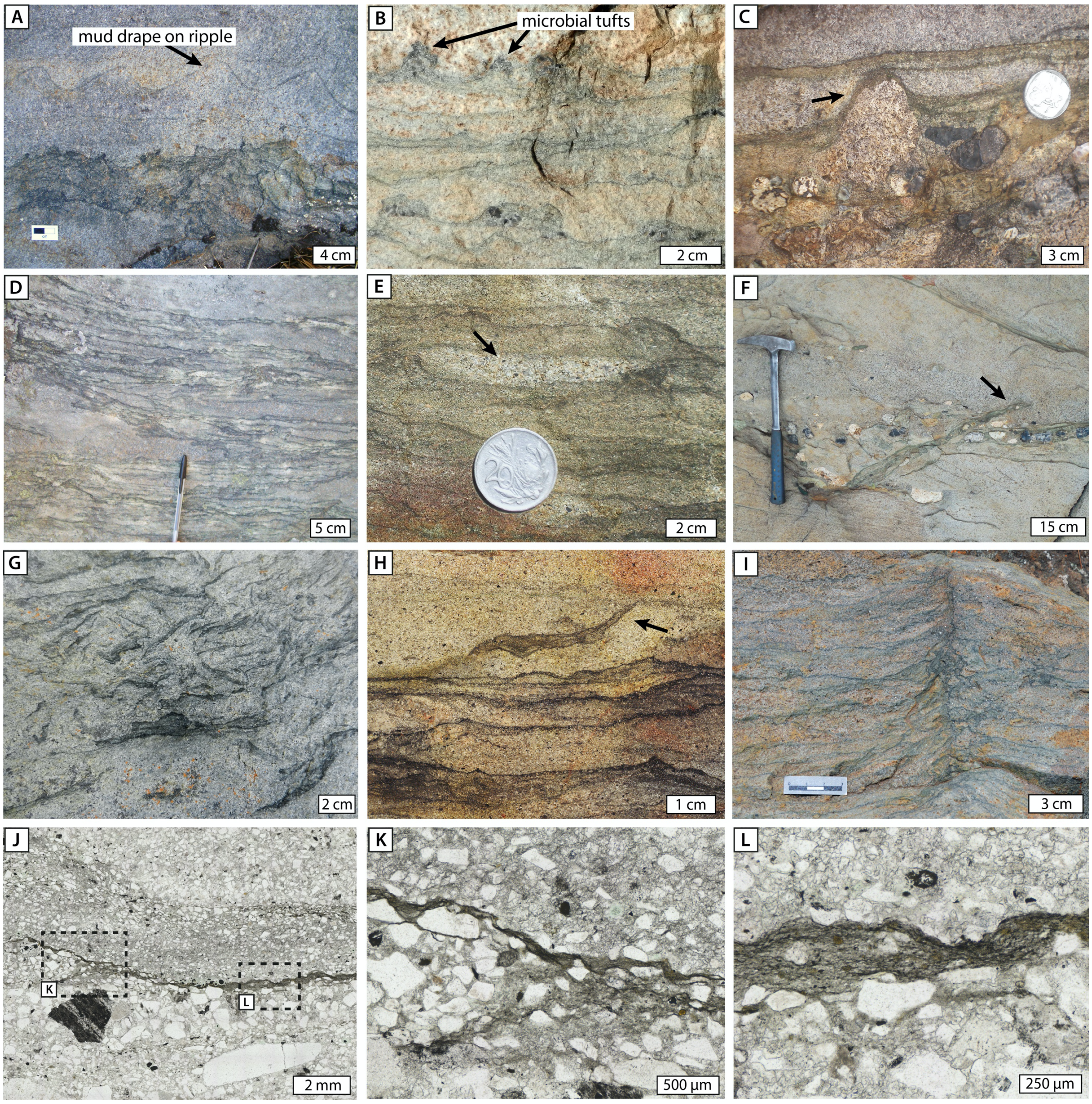

Fig. 1. Field (A-G, I), slabbed and polished hand sample (H), and thin section photographs (J-L) of sedimentary structures in Moodies sandstones from outcrops on and near Stratigraphic Log 9 of Homann et al. (2015), re-examined by Saitoh et al. (2021). This compilation demonstrates the primary, not diagenetic or metamorphic origin of the laminae as benthic microbial mats. (A) Highly oblique (and therefore vertically exaggerated) section through a sandstone slab showing tufted microbial mats (below) overlain by mud-draped rippled sandstone (arrow). Microbial microrelief existed prior to formation of ripples; it did not form during metamorphism. (B) Microbial mats showing tufted to domal morphology and silicified gas bubbles. Stiffening of fabric and cementation of the cavities predated compaction. (C) Microbial mats onlapping and overgrowing emergent conglomerate clast (arrow). Laminae covered topographic relief prior to deposition of overlying sand. (D) Complex onlap of several microbially laminated channel fills (right) onto tidal-channel margin (left). The origin of such depositional pattern by metamorphic processes without compaction and deformation would be highly unlikely. (E) Coarse-sand channel fill (arrow) between microbial domes. Apparently, a

cm-high microbial microrelief existed at a time when sand filled the intervening depression. (F) Microbially stabilized sandstone slab (arrow), tilted into a narrow tidal channel which was subsequently filled by gravelly sandstone. Surficial laminae behaved cohesively and brittily prior to channel filling. (G and H) Microbial mat chips. Stiff and brittle laminae existed at a time when they could be fragmented, eroded, and transported by currents. (I) Fluid-escape structure with central channel. Laminae deformed ductily while sand was unconsolidated and dewatering. (J, K, L) Carbonaceous laminae covering medium-coarse-grained sand. Laminae formation postdates deposition of coarse sand (resulting from maximum tidal current?) but predates deposition of significantly finer-grained deposits from lower-energy currents. Note that the preserved thickness of the laminae can vary laterally. Abundant trapped grains show that cementation predated significant burial and that subsequent compaction was minor.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Keyron Hickman-Lewis for his constructive review. We also would like to thank Gary Byerly and Don Lowe for their comments on an initial draft, but all statements are our own.

References

Brasier, M., McLoughlin, N., Green, O., Wacey, D., 2006. A fresh look at the fossil evidence for early Archaean cellular life. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 361, 887–902. https://doi.org/10.1098/rstb.2006.1835

Byerly, G.R., Lowe, D.R., Heubeck, C., 2019. Geologic Evolution of the Barberton Greenstone Belt—A Unique Record of Crustal Development, Surface Processes, and Early Life 3.55–3.20 Ga, in: Van Kranendonk, M.J., Bennett, V.C., Hoffmann, J.E. (Eds.), Earth’s Oldest Rocks. Elsevier, pp. 569–613.

Gamper, A., Heubeck, C., Demske, D., Hoehse, M., 2012. Composition and Microfacies of Archean Microbial Mats (Moodies Group, ca. 3.22 Ga, South Africa), in: Noffke, N., Chafetz, H.S. (Eds.), Microbial Mats in Silicilastic Depositional Systems Through Time. SEPM (Society for Sedimentary Geology), Tulsa, pp. 65–74. https://doi.org/10.2110/sepmsp.101.065

Heubeck, C., 2019. The Moodies Group — a High-Resolution Archive of Archaean Surface Processes and Basin-Forming Mechanisms, in: Kröner, A., Hofmann, A. (Eds.), The Archaean Geology of the Kaapvaal Craton, Southern Africa. Regional Geology Reviews. Springer Nature, Switzerland, pp. 133–169.

Heubeck, C., 2009. An early ecosystem of Archean tidal microbial mats (Moodies Group, South Africa, ca. 3.2 Ga). Geology 37, 931–934. https://doi.org/10.1130/G30101A.1

Heubeck, C., Bläsing, S., Grund, M., Drabon, N., Homann, M., Nabhan, S., 2016. Geological constraints on Archean (3.22 Ga) coastal-zone processes from the Dycedale Syncline, Barberton Greenstone Belt. South African J. Geol. 119, 495–518. https://doi.org/10.2113/gssajg.119.3.495

Heubeck, C., 2001, Microbial films of the Archean Moodies Group (~3.1 Ga), Barberton Greenstone Belt, South Africa: Fossil and recent biofilms (Microbial Mat Meeting 2), Oldenburg, Feb. 17-21, 2001.

Heubeck, C., Lowe, D.R., 1999. Sedimentary petrography and provenance of the Archean Moodies Group, Barberton Greenstone Belt, in: Lowe, D.R., Byerly, G.R. (Eds.), Geologic Evolution of the Barberton Greenstone Belt, South Africa. Geological Society of America Special Paper 329, pp. 259–286.
Hickman-Lewis, K., Cavalazzi, B., Foucher, F., Westall, F., 2018. Most ancient evidence for life in the Barberton greenstone belt: Microbial mats and biofabrics of the ~3.47 Ga Middle Marker horizon. Precambrian Res. 312, 45–67. https://doi.org/10.1016/j.precamres.2018.04.007
Homann, M., 2019. Earliest life on earth: Evidence from the Barberton Greenstone Belt, South Africa. Earth-Science Rev. 196, 102888. https://doi.org/10.1016/j.earscirev.2019.102888
Homann, M., Heubeck, C., Airo, A., Tice, M.M., 2015. Morphological adaptations of 3.22 Ga-old tufted microbial mats to Archean coastal habitats (Moodies Group, Barberton Greenstone Belt, South Africa). Precambrian Res. 266, 47–64. https://doi.org/10.1016/j.precamres.2015.04.018
Homann, M., Heubeck, C., Bontognali, T.R.R., Bouvier, A.S., Baumgartner, L.P., Airo, A., 2016. Evidence for cavity-dwelling microbial life in 3.22 Ga tidal deposits. Geology 44, 51–54. https://doi.org/10.1130/G37272.1
Homann, M., Sansjofre, P., Van Zuilen, M., Heubeck, C., Gong, J., Killingsworth, B., Foster, I.S., Airo, A., Van Kranendonk, M.J., Ader, M., Lalonde, S. V, 2018. Microbial life and biogeochemical cycling on land 3,220 million years ago. Nat. Geosci. 11, 665–671. https://doi.org/10.1038/s41561-018-0190-9
Köhler, I., Heubeck, C., 2019. Microbial-mat-associated tephra of the Archean Moodies Group, Barberton Greenstone Belt (BGB), South Africa: Resemblance to potential biostructures and ecological implications. South African J. Geol. 122, 221–236. https://doi.org/10.25131/sajg.122.0015
Lowe, D.R., Byerly, G.R., Heubeck, C., 2012. Geologic Map of the west-central Barberton Greenstone Belt, in: South Africa, Scale 1:25,000. Geological Society of America Map and Chart Series No. 103, Boulder. https://doi.org/10.1130/2012. MCH103
Moyen, J.-F., Stevens, G., Kisters, A.F.M., Belcher, R.W., Lemirre, B., 2019. TTG Plutons of the Barberton Granitoid-Greenstone Terrain, South Africa, Earth's Oldest Rocks. Elsevier B.V. https://doi.org/10.1016/b978-0-444-63901-1.00025-3
Noffke, N., Beukes, N., Bower, D., Hazen, R.M., Swift, D.J.P., 2008. An actualistic perspective into Archean worlds - (cyano-)bacterially induced sedimentary structures in the siliciclastic Nhlazatse Section, 2.9 Ga Pongola Supergroup, South Africa. Geobiology 6, 5–20. https://doi.org/10.1111/j.1472-4669.2007.00118.x
Noffke, N., Eriksson, K.A., Hazen, R.M., Simpson, E.L., 2006. A new window into Early Archean life: Microbial mats in Earth's oldest siliciclastic tidal deposits (3.2 Ga Moodies Group, South Africa). Geology 34, 253. https://doi.org/10.1130/G22246.1
Rasmussen, B., Blake, T.S., Fletcher, I.R., Kilburn, M.R., 2009. Evidence for microbial life in synsedimentary cavities from 2.75 Ga terrestrial environments. Geology 37, 423–426. https://doi.org/10.1130/G25300A.1
Reimann, S, Heubeck, C.E., Fugmann, P., Janse van Rensburg, D.J., Zametzer, A., Serre, S.H., Thomsen, T.B., 2021. Syndepositional hydrothermalism selectively preserves records of one of the earliest benthic ecosystems, Moodies Group (3.22 Ga), Barberton Greenstone Belt, South Africa. South African J. Geol. 124, 253–278. https://doi.org/10.25131/sajg.124.0012
Rouillard, J., Van Zuilen, M., Pisapia, C., Garcia-Ruiz, J.M., 2021. An Alternative Approach for Assessing Biogenicity. Astrobiology 21, 151–164. https://doi.org/10.1089/ast.2020.2282

Saitoh, M., Nabhan, S., Thomazo, C., Olivier, N., Moyen, J.-F., Ueno, Y., Marin-Carbonne, J., 2020. Multiple Sulfur Isotope Records of the 3.22 Ga Moodies Group, Barberton Greenstone Belt. Geosciences 10, 145. https://doi.org/10.3390/geosciences10040145

Saitoh, M., Olivier, N., Garçon, M., Boyet, M., Thomazo, C., Alleon, J., Moyen, J., Mottoros, V., Marin-carbonne, J., 2021. Metamorphic origin of anastomosing and wavy laminas overprinting putative microbial deposits from the 3 . 22 Ga Moodies Group (Barberton Greenstone Belt). Precambrian Res. 362, 106306. https://doi.org/10.1016/j.precamres.2021.106306

Sleep, N.H., Hessler, A.M., 2006. Weathering of quartz as an Archean climatic indicator. Earth Planet. Sci. Lett. 241, 594–602. https://doi.org/10.1016/j.epsl.2005.11.020