

## Petrological evidence supports the death mask model for the preservation of Ediacaran soft-bodied organisms in South Australia

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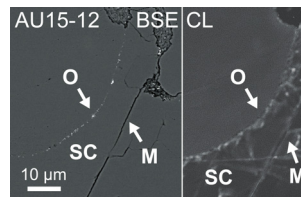
We gratefully acknowledge the Comment by Tarhan et al. (2019) in response to our paper (Liu et al., 2019) discussing preservation of Ediacara Member fossils. We agree that the mere presence of pyrite or iron oxides in these rocks does not establish either that pyrite was an agent of fossilization, or that authigenic marine silica was not. However, our observations were important in demonstrating both that early diagenetic pyrite cementation remains a plausible taphonomic mechanism in the Ediacara Member, and that the early silicification taphonomic model (Tarhan et al., 2016) is undermined by available petrological and geochemical data.

We documented thin veneers of hematite occurring in abundance as grain coatings, together with clay minerals, along discrete horizons (i.e., not scattered), including fossiliferous bedding planes. The presence of framboidal aggregates within these Ediacara Member horizons implies that the observed hematite is likely to have replaced pyrite, which, as Tarhan et al. (2019) correctly note, is a common marine cement and microbial byproduct, and is thus not unexpected as an original mineralogical constituent. These observations are consistent with a potential role for pyrite as a cementing agent on these surfaces.

Tarhan and colleagues convincingly establish that some iron oxides have been redistributed along exposed bedding surfaces in the Ediacara Member, forming as late-stage precipitates introduced by groundwater (Tarhan et al., 2018), including along microfractures (Tarhan et al., 2019, their figure 1). As we reported, iron oxides do occur at present-day grain boundaries (i.e., outside silica overgrowths) where microporosity has probably facilitated redistribution (e.g., Liu et al., 2019, our figures DR2D and DR2E; bright, non-arrowed patches). However, abundant hematite and some framboids are observed to directly abut original, rounded grain boundaries, and are encased wholly within syntaxial, grain-mantling silica, with little or no associated porosity (Fig. 1; our figure DR2). The observed silica cements must post-date these iron oxides. Furthermore, several of the observed hematite-rich horizons have never been exposed at the surface, and we interpret both their clays and the original iron minerals coating primary grain boundaries to be original or early diagenetic features. Even if the silica cement also formed early, it undoubtedly post-dates the clays and iron minerals embedded within it. We acknowledge that the extensive weathering history of the Australian continent could have introduced hematite at a late stage, but the same would then necessarily be true of the surrounding silica cement, critically undermining the petrological evidence offered by Tarhan et al. (2016) in support of their early silicification model.

The suggestion of Tarhan et al. (2019) that a primary silica cement would form only on grain boundaries and exclude organic matter is implausible, and contrary to the evidence of much older silicified sandstones (e.g., Wacey et al., 2011). It represents a departure from the original silicification model of Tarhan et al. (2016, p. 953), which explicitly involved silica nucleation onto organic matter. Moreover, the geochemical evidence presented in that paper remains unconvincing. Al

(ppm) and Ge (ppm) concentrations are weakly positively correlated in the combined data from sampled cements (e.g., Spearman's  $\rho = 0.339$ ; significant at 0.01 level), although this should be interpreted cautiously since the paired ppm values are not strictly mutually independent. The low Ge contents in detrital grains and high Ge contents in silica cements in some samples (e.g., 'Aspidella 33' of Tarhan et al., 2016) do not indicate anactinetic early silicification. High inter-sample variability in cement elemental concentrations, itself more consistent with late alteration than inheritance from Ediacaran seawater, raises further questions.



**Figure 1.** Backscattered electron microscopy (BSE, left) shows hematite (white) embedded in silica cement (SC), where there is no porosity, unlike the modern grain boundary (M). Cathodoluminescence microscopy (CL, right) reveals the original grain boundary (O).

Our paper did not claim to present a mechanistic explanation for the role of pyrite in Ediacara Member preservation; such detailed explanations exist elsewhere (e.g., Gibson et al., 2018). We clearly outlined the future steps required to determine whether there is a systematic association between fossils in the Ediacara Member and continuous pyrite veneers. We agree with Tarhan et al. (2019) that our reliance on externally weathered samples is sub-optimal, but we share this weakness with every other taphonomic study of the Ediacara Member; fresh core material is currently unavailable. We also agree wholeheartedly with those authors that multiple taphonomic pathways operated during the late Ediacaran Period. While we remain open to the possibility that silica could have played a preservational role in the Ediacara Member, for example by favoring clay mineral authigenesis or consolidating pre-existing pyrite cements or rheological boundaries (cf. Bobrovskiy et al., 2019), we do not consider available petrological and geochemical evidence to support the early silicification model as originally articulated.

### REFERENCES CITED

- Bobrovskiy, I., Krasnova, A., Ivantsov, A., Luzhnaya, E., and Brocks, J.J., 2019, Simple sediment rheology explains the Ediacara biota preservation: *Nature Ecology & Evolution*, v. 3, p. 582–589, <https://doi.org/10.1038/s41559-019-0820-7>.
- Gibson, B.M., Schiffbauer, J.D., and Darroch, S.A., 2018, Ediacaran-style decay experiments using mollusks and sea anemones: *Palaos*, v. 33, p. 185–203, <https://doi.org/10.2110/palo.2017.091>.
- Liu, A.G., McMahon, S., Matthews, J.J., Still, J.W., and Brasier, A.T., 2019, Petrological evidence supports the death mask model for the preservation of Ediacaran soft-bodied organisms in South Australia: *Geology*, v. 47, p. 215–218, <https://doi.org/10.1130/G45918.1>.
- Tarhan, L.G., Hood, A.V.S., Droser, M.L., Gehling, J.G., and Briggs, D.E.G., 2016, Exceptional preservation of soft-bodied Ediacara Biota promoted by silica-rich oceans: *Geology*, v. 44, p. 951–954 <https://doi.org/10.1130/G38542.1>, <https://doi.org/10.1130/G38542.1>.
- Tarhan, L.G., Planavsky, N.J., Wang, X., Bellefroid, E.J., Droser, M.L., and Gehling, J.G., 2018, The late-stage “ferruginization” of the Ediacara Member (Rawnsley Quartzite, South Australia): Insights from uranium isotopes: *Geobiology*, v. 16, p. 35–48, <https://doi.org/10.1111/gbi.12262>.
- Tarhan, L.G., Hood, A.V.S., Droser, M.L., Gehling, J.G., Briggs, D.E.G., Gaines, R.R., Robbins, L.J., and Planavsky, N.J., 2019, Petrological evidence supports the death mask model for the preservation of Ediacaran soft-bodied organisms in South Australia: Comment: *Geology*, v. 47, p. exxx, <https://doi.org/10.1130/G46326C.1>.
- Wacey, D., Kilburn, M.R., Saunders, M., Cliff, J., and Brasier, M.D., 2011, Microfossils of sulphur-metabolizing cells in 3.4-billion-year-old rocks of Western Australia: *Nature Geoscience*, v. 4, p. 698–702, <https://doi.org/10.1038/ngeo1238>.