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Discussion

Reply to comment on the paper by Davies et al. "Resolving MISS conceptions and misconceptions: A geological approach to sedimentary surface textures generated by microbial and abiotic processes" (Earth Science Reviews, 154 (2016), 210–246)

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1. Introduction

We thank Noffke (2017) for her comment and for providing an opportunity to clarify our classification of "sedimentary surface textures". We accord great credit to Dr. Noffke and other dedicated researchers whose detailed work has brought microbially induced sedimentary structures (MISS) to the widespread attention of geoscientists. However, we stand by our assertion that attributing structures observed in practical field and laboratory studies to processes of formation is much more problematic than Noffke (2017) indicates. Indeed, points in the Comment confirm the need for a classification system that categorises the degree of certainty attributed to a given interpretation. We stress that our paper was not designed as a critique of previous studies of MISS but rather was designed to encourage a reasonable assessment of uncertainty in assigning sedimentary surface textures to physical processes or to MISS.

While the contribution of Noffke (2017) raises valid points of discussion, to which we respond below, we first emphasise that in several places the Comment inaccurately reflects the conclusions of Davies et al. (2016). Furthermore, Noffke (2017) attributes to us a large number of statements and assumptions that do not appear in the original paper (e.g., "the paper by Davies et al. regards microbial mats simply as coherent layers that develop at random atop of clastic deposits", "Davies et al. article assumes that stages of mat development were never considered in MISS research", "Davies et al.'s statement that crinkled surfaces are now 'routineously [sic] described as wrinkle structures' is therefore incorrect"; "they are not interference ripple marks, as the article of Davies et al. assumes"; "The unusual statement by Davies et al. that Noffke (2014) [sic] claims to have detected fossil life on Mars is a misrepresentation of the conclusions presented"; plus other instances). In these and other respects, the Comment published by Noffke (2017) is an erroneous precis of Davies et al. (2016), and we make no attempt here to argue against statements in which our conclusions have been misrepresented.

2. The classification of sedimentary surface textures

We maintain that classifying sedimentary surface textures as 'A' where they are known to be abiotic in origin, 'B' where they are known to be microbial in origin, 'ab' where there is uncertainty, and 'Ab' or 'Ba' where there is uncertainty but one interpretation is favoured, provides a pragmatic solution to the inherent uncertainty involved in ascertaining the origin of sedimentary surface textures. We emphasise that such a scheme: 1) minimises the risk of over- or misinterpretation that is pervasive to geological investigations (which must rely on abductive reasoning to interpret the formative causes of ancient geological structures); and 2) provides a flexible classification scheme (i.e., a given structure may be classified as 'ab' in the field, or in a paper in which the main aim was not the identification of MISS, but further investigation of the same structure may lead to its reclassification).

In justification of this, it is important to recognise that MISS have many manifestations. Noffke (2017) illustrates 17 main sedimentary features that she classifies as MISS (her figure 2), and the variety of forms may be even greater if alternative classification schemes are considered (e.g., TOS: Gehling and Droser, 2009; MRS: Eriksson et al., 2010). However, a key issue is the enormous range of possible abiotic processes that may generate MISS-like features. Although we illustrated a suite of such processes known to us, it is not possible to set down all possible processes in a simple classification of a few types, as Noffke (2017) seems to suggest. Nor is it currently possible to set up rigorous criteria for identifying all of these processes, in addition to evaluating the many diagenetic and other effects that modify the structures. For this reason we introduced the term "sedimentary surface textures" to cover features generated by a very wide range of processes, known and in many cases unknown. The term "surface" was used because most studies start with what is observed on a bed surface (the issue of the

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original position of MISS on or within the sediment is a different question).

In her Comment, Noffke sets out a protocol for MISS studies that involves a) detection in outcrop, b) identification of a candidate structure, c) confirmation of a candidate structure (petrological study), and d) differentiation from abiotic sedimentary structures. This implies that a rigorous scientific approach can usually allow confirmation of the abiotic or biotic origin of structures. Such an approach has yielded good results in some cases. However, in numerous places in the Comment, Noffke assumes that this protocol will work routinely to establish a degree of certainty. The Comment includes statements such as "this non-genetic descriptive framework eases a geologist's reconnaissance of such structures, and does not require knowledge of formation history"; "there is no problem to determine formative mechanisms and abiotic structures in the field"; "a geologist can readily differ between mud and mat, modern or fossil, based solely on a close-up view with a hand held lens or standard microscope."

Our practical experience differs strongly from this point of view. Our paper arose from many years of wrestling with the interpretation of problematic sedimentary surface textures, and the identification of MISS, in natural rock outcrops. On many field occasions, we have been confronted with structures that were highly problematic and required lengthy discussion about possible origins. A single stratigraphic section may contain hundreds of such problematic cases and an individual judgement call is required for each of them – certainty in one case does not translate into certainty in other cases. It is only possible to bring back a modest number of samples and, even then, laboratory-based imaging and petrographic work frequently fails to resolve the question. The examples have often been subject to the distorting effects of *syn*-sedimentary or later tectonic deformation, and petrographic analysis is often hampered by a profound degree of diagenesis. Thus, although the protocol presented by Noffke (2017) might ideally be expected to resolve the problem, our experience indicates that in reality, such resolution is not commonplace. If in the judgement of the researcher the analysis has not allowed certainty (i.e., 'ab', 'Ab', 'Ba' textures), this does not mean that a microbial origin is ruled out. Noffke's statement that "No paper of quality would provide a statement of absoluteness" supports our view that introducing more rigour in assessing uncertainty, as set out in our classification system, has considerable merit.

Discussions with many researchers have suggested that discriminating between biotic and abiotic processes is a widespread practical issue. With the rise in criteria for recognising MISS, and the potential palaeoenvironmental implications of their positive identification, researchers increasingly need to consider MISS as a possible origin for observed features on bedding planes. However, in many instances 1) researchers do not have the time or facilities to make a full assessment of each of potentially hundreds of examples encountered in many field programmes, for which the study of MISS may only be a minor component; and 2) non-specialist researchers may not be up to date with the full (and growing) archive of MISS-related literature to be able to make judgements on structures with any certainty. Our scheme is aimed to be of as equal benefit to such researchers as it is to the "MISS community", and a number of papers, published since that of Davies et al. (2016), demonstrate how our scheme may be usefully employed across a variety of such situations (McMahon et al., 2017; Sciscio et al., 2016; Chu et al., 2017; McMahon and Davies, 2017; Shillito and Davies, 2017; Grosjean et al., 2018).

We agree with Noffke (2017) that precise hypotheses and criteria for evaluating origins should be developed where possible, encouraging a rigorous and fully quantitative analysis. However, it is crucially important to recognise that many datasets are not amenable to this approach. That is the case for most field studies, during which the researcher is faced with the inherent variability of MISS and a wide range of possible abiotic processes. Some candidate abiotic processes may come immediately to the researcher's mind, whereas others may be overlooked or not known to the researcher. For this reason the approach used here has utility in explicitly recognising this uncertainty. On the face of it, Noffke's approach might seem to bring an "empirical" understanding to the problem, but many real cases preclude this approach.

A case in point is Noffke's (2017) hypothetical example of distinguishing MISS from a sand volcano in her Step 4. She presents the case of a structure resembling a microbial "gas dome", which may resemble an abiotic "sand volcano" in macroscopic examination. Her approach is to consider the context of other structures and then to carry out petrographic analysis to look for features that might accord with a sand volcano (in her example, she cites distorted layers) or a gas dome (e.g., mat fabrics). At first sight, this approach seems reasonable. However, in this example, the researcher has fixed (possibly erroneously) on a single alternative abiotic mechanism, without considering the many other possible processes, not known or not thought about, with or without diagnostic criteria available. Thus, any conclusion would represent a limited consideration of the large range of possible abiotic processes that could mimic gas domes (some of which are illustrated in our paper). Although it is perhaps unfair to critique this hypothetical example, the case study points clearly to the problem of using a seemingly rigorous but actually flawed approach in discriminating between MISS and physical processes.

3. Interpreting features on the surface of Mars

A final case study illustrating the merit of our approach can be found in the Martian features re-illustrated by Noffke (2017) in her comment. As stated by Davies et al. (2016), Noffke (2015) hypothesized that these features may be MISS. The necessary data to support a conclusive diagnosis of these features as MISS are currently uncollected from these Martian outcrops; such interpretations are presently reliant on imagery alone (Coates et al., 2017). Noffke (2017) implies that, in such instances of incomplete sampling, all of her additional criteria necessary for the confirmation of MISS may be disregarded, and the features may be hypothesized as MISS until those additional criteria are addressed with further data. This is argued to be good practice, in that future Martian ventures may focus on such localities in a search for ancient extraterrestrial life. However, as with the sand volcano case above, this testable hypothesis is flawed by uneven consideration in favour of MISS. While MISS are considered in detail, with comparative imagery of modern microbial mats, an abiotic erosive origin is considered only from a partial theoretical understanding of erosional processes. In other words, other possible processes, not known or not thought about, are given limited consideration. This approach is especially undesirable for detecting evidence of Martian MISS: the profound importance of such an observation means that the onus is on researchers to directly prove biogenicity.

In Fig. 1, we illustrate three unexceptional outcrops of the Tumblagooda Sandstone in Western Australia. In these accessible outcrops, a microbial origin for the outcrop morphology can be ruled out. The eroded forms reflect the balance between recent wind and water erosion and rock properties, largely determined during post-depositional cementation and diagenesis. The morphologies show little or no correlation with the form that the beds had at the time of deposition, as revealed by their discordance with primary sedimentary structures and grain-size patterns. No other accessory evidence is known that would support a microbial origin for these features; they are simply eroded remnants of Silurian sandstone with limited evidence of the depositional setting. Yet each of these outcrops shares morphological characteristics, at a similar scale, to the Martian outcrops illustrated by Noffke (2015, 2017).

Fully testing Noffke's (2015) hypothesis requires the return of specimens from Mars. However, had the same Martian features been studied by a researcher employing our classification scheme, they could have initially classified the features as 'Ba' or 'ab'. Subsequent like-for-like comparison of rocks on Earth and Mars (Fig. 1), would reveal to the

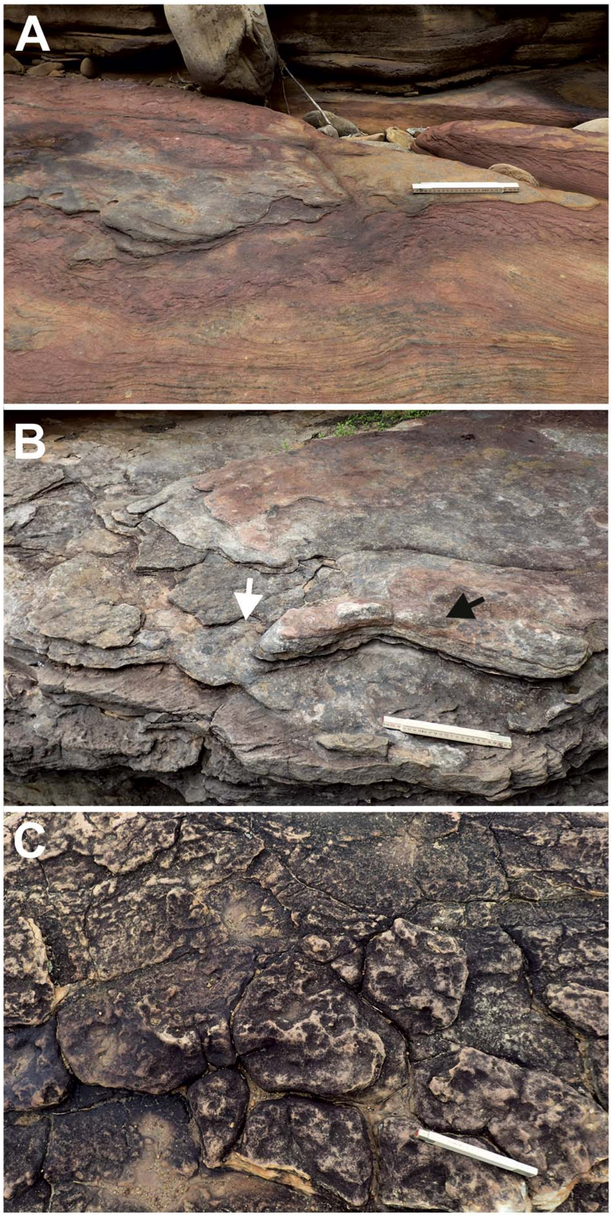

Fig. 1. Abiotically eroded appearance of unexceptional outcrop of the Silurian Tumblagooda Sandstone, Western Australia. A) 'Mesa' with serrated margin ('triangular structures'), formed by preferential erosion of a lower cross-laminated sandstone layer, underlying an amalgamated surface of multiple lamination surfaces within a more resistant sandstone stratum. Water-worn outcrop situated above present day normal high-water level on the bank of an incisive stream. Compare with Fig. 7A of Noffke (2017). B) Curved ridge of more resistant sandstone (black arrow), comprising multiple depositional laminae, adjacent to an 'eroded pocket' (white arrow) into underlying layers. Same location as Fig. 1A. Compare with Fig. 8A of Noffke (2017). C) Fractured surface of an outcrop, cross-cutting depositional laminae within sandstone, exhibiting superficially polygonal clusters of 'holes'. Outcrop situated at top of gorge in a semi-arid climate: holes likely produced by a combination of aeolian grain attrition and salt crystallization (i.e., degraded honeycomb weathering). Compare with Fig. 9A of Noffke (2017). All images taken at Z Bend, Kalbarri National Park, Western Australia. Folding ruler (20 cm in length) for scale.

researcher that abiotic processes can sculpt rock outcrops with superficial similarity to living microbial mats. The pragmatic flexibility of our scheme (Davies et al., 2016) means that they would now be able to classify these particular Martian features as 'Ab', or even 'A'.

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