

RE-EVALUATION OF PRECAMBRIAN “FUCOIDS,” MICROBially INDUCED SEDIMENTARY STRUCTURES IN THE PROTEROZOIC DOX FORMATION, GRAND CANYON NATIONAL PARK, ARIZONA

JUSTIN S. TWEET¹ and SPENCER G. LUCAS²

¹National Park Service, 9149 79th Street S., Cottage Grove, MN, 55016, justin_tweet@nps.gov;

²New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, NM, 87104, spencer.lucas@state.nm.us

Abstract—Two rock surfaces (part and counterpart) in the Mesoproterozoic Dox Formation, collected and reported by Edwin D. McKee in the early 1930s, preserve a polygonal pattern of spindle-shaped, sediment-filled fractures. They are remarkably similar to microbially-mediated shrinkage cracks filled with petees *sensu lato* documented from other Proterozoic and some geologically younger stratigraphic units worldwide. McKee’s specimens are likely to be microbially induced sedimentary structures (MISS) and, together with records of stromatolites from the Dox Formation, indicate that this stratigraphic unit is likely to contain a significant record of MISS that merits further exploration and study.

INTRODUCTION

The Mesoproterozoic Unkar Group has yielded the oldest evidence of life in the Grand Canyon (Tweet, 2020). To date, this early fossil record is in the form of stromatolites and similar microbial structures, for example the stromatolites preserved in the Bass Limestone (Beus et al., 1974; Ford and Breed, 1977) and the Dox Formation (Stevenson and Beus, 1982; Timmons et al., 2012). However, the paleontology of the Unkar Group is poorly known. One reason for this is because a variety of features originally reported as Unkar Group invertebrate body or trace fossils are now regarded as pseudofossils or dubiofossils (Seilacher, 1956; Alf, 1959; Cloud, 1968; Glaessner, 1969; Ford and Breed, 1977). In addition, the discovery of diverse and abundant microfossils in the overlying Neoproterozoic Chuar Group has focused the attention of Precambrian paleontologists on these rocks. These factors have left a variety of enigmatic specimens from the Unkar Group that would benefit from further study using modern techniques and the advantage of several decades of research on early life. Among these poorly known specimens are Dox Formation “fucoids” collected by Grand Canyon National Park (GRCA) naturalist and geologist Edwin D. McKee in 1930 and briefly discussed in 1932. The purpose of this study is to review McKee’s specimens in the light of more recent discoveries about microbially induced sedimentary structures (MISS). MISS, representing interactions of microbes with their environment, would not be described until decades after McKee’s report, and thus were not available to McKee as a potential interpretation.

HISTORY OF SPECIMENS

Per GRCA Museum Collection records, McKee collected the four specimens described herein (GRCA 2052, 11442, 11443, and 20048) and an additional 20 catalogued specimens (GRCA 2035–2039, 2042–2051, and 11437–11441) from the Dox Formation opposite the mouth of Chuar Creek in May 1930. On modern topographic maps, Chuar Creek is a tributary of Lava Creek, but at the time of McKee’s work in the 1930s the name “Chuar Creek” was used for Lava Creek. This can be seen, for example, on a map included with Bailey (1931), documenting a trip on the Tanner Trail that McKee participated in. Coincidentally, in the same month that McKee was collecting the “fucoid” specimens, Charles Resser and A. A. Stoyanow were searching for fossils in the overlying Neoproterozoic rocks of the Chuar Group in the Nankoweap Basin, 16 km (10 miles) to the northeast; McKee was not part of this expedition (Anonymous, 1930; Resser, 1930). McKee discussed the “fucoid” specimens

in an issue of “Grand Canyon Nature Notes,” a park publication series issued from 1926 to 1935 as a way to briefly document various aspects of the park’s natural resources. The report, “Some Fucoides from Grand Canyon” (McKee, 1932), included a photo (unnumbered, include here in Fig. 1) and this description of the specimens:

“Some of the most interesting but least understood of the fucoides found in Grand Canyon come from the bright red shales of the Dox formation (Algonkian age).

As with most fucoides they represent the natural casts of depressions occurring [sic] on the old mud surfaces. They average about one inch in length, taper to a point at each end and curve, often in two directions. They are found associated with the casts of ripple marks, the square moulds of salt crystals and the casts of shrinkage cracks in mud. Because of the possibility that they may be of organic origin and because of the remarkable scarcity of fossil plant life together with the entire lack of traces of animal life in rocks of Algonkian age, they are of especial interest. Possibly, however, they formed from the impressions of some mineral crystals. Our commonest mineral, ice, is known to leave such impressions (though not curving) and certain fucoides found in the Portage shale of New York state are believed* to have been formed in that manner. Further investigation may disclose some valuable information regarding these peculiar and somewhat similar structures of the ancient Algonkian age.

*Clark, J. M., New York State Museum Bul. 196.”

In McKee’s usage, “fucoides” were “peculiar worm-like ridges of varying shapes and sizes” with no reference to origin: “The term now serves admirably for a ‘loop-hole’ in referring to any structure of that general nature regardless of its origin” (McKee, 1932). The word “fucoid” (from the Greek *fykos*, seaweed) was introduced by paleontologists in the 1800s to refer to what were thought to be algal structures and continued to be used well into the 1900s, as McKee’s use of the term illustrates (Osgood, 1975). Many structures originally called “fucoids” are now known to be trace fossils. Although he noted that the Dox Formation specimens were worth further study, McKee did not return to them in his long geological career.

During a visit to the Grand Canyon National Park paleontological collections in September 2019, the lead author of this report, who had prepared an overview of the Precambrian paleontology of the park (Tweet, 2020), was reminded of McKee’s specimens and photograph, prompting a search for

the specimens. Both of McKee's photographed specimens were located in GRCA collections (Fig. 1). One of these has been broken into two pieces, which are cataloged as GRCA 2052 and GRCA 20048, and the other is GRCA 11442. GRCA 11443, a previously unreported specimen that fits to GRCA 11442, was also found (Fig. 2). It is not known why GRCA 11443 was not included in the 1932 photo.

Because of the composition of the 1932 photo (Fig. 1), it is not immediately obvious that the left and right specimens are part and counterpart. The features on the left specimen are preserved in negative (concave) relief, whereas those on the right are preserved in positive (convex) relief, and a large redox spot visible on GRCA 2052 and 11442 provides a landmark to line up the specimens (Fig. 1). Thus, the four specimens together make one large slab (Fig 2).

The current GRCA catalog numbers, which use the formula "GRCA [XXXX]," were most likely assigned in the late 1950s (K. Besom and C. Hyde, pers. commun., June 2020), after the 1932 photo was taken. Small light patches near the upper ends of the two specimens in the photo (Fig. 1) are backgrounds for the original number, "Fa-40," which have been struck out since that time. "F" denotes "fossil" and "a" denotes "Algonkian," in reference to the age of the rock. The four specimens all originally shared the designation Fa-40 and were only given separate numbers when the current numbering system was adopted. GRCA collection notes give the longest dimension of GRCA 2052 as 360 mm, but GRCA 2052 currently does not exceed 265 mm in any dimension, and the longest dimension of GRCA 20048 is 155 mm. Allowing for overlap along the broken edge, and not

knowing how the measurement that produced the 360 mm figure was obtained, it seems most likely that this figure also includes what is now GRCA 20048. At some point, GRCA 20048 was broken into three main pieces and reassembled. In comparison to the 1932 photo, a few surficial fragments and bits of the lower margin have been lost from GRCA 20048. It is not clear if this damage happened before or after GRCA 20048 detached from GRCA 2052, but it seems most likely that the two large pieces separated before the more thorough breakage of GRCA 20048, or GRCA 2052 would also have broken into several pieces. Curiously, GRCA 20048 seems to have "usurped" its number from the original GRCA 20048, which, according to collection notes, is a much smaller specimen collected by Raymond Alf in 1958, probably from the Hakatai Shale. The original "usurped" GRCA 20048 was not observed in September 2019.

GEOLOGY

The Dox Formation, also known as the Dox Sandstone, is part of the Unkar Group (Grand Canyon Supergroup) (Timmons et al., 2012). It is the thickest of the Unkar Group formations (at least 950 m thick) and generally crops out as red-brown slopes. This formation is only known to crop out within eastern and central GRCA (Stevenson and Beus, 1982). It was named in Noble (1914) for a "series of micaceous shaly sandstones of uniform character, varying only in color and bearing marks of shallow-water origin throughout" (Noble, 1914, p. 53). Stevenson and Beus (1982) made a detailed reevaluation of the unit, which they divided into four members. In ascending order, these members are the Escalante Creek Member, Solomon

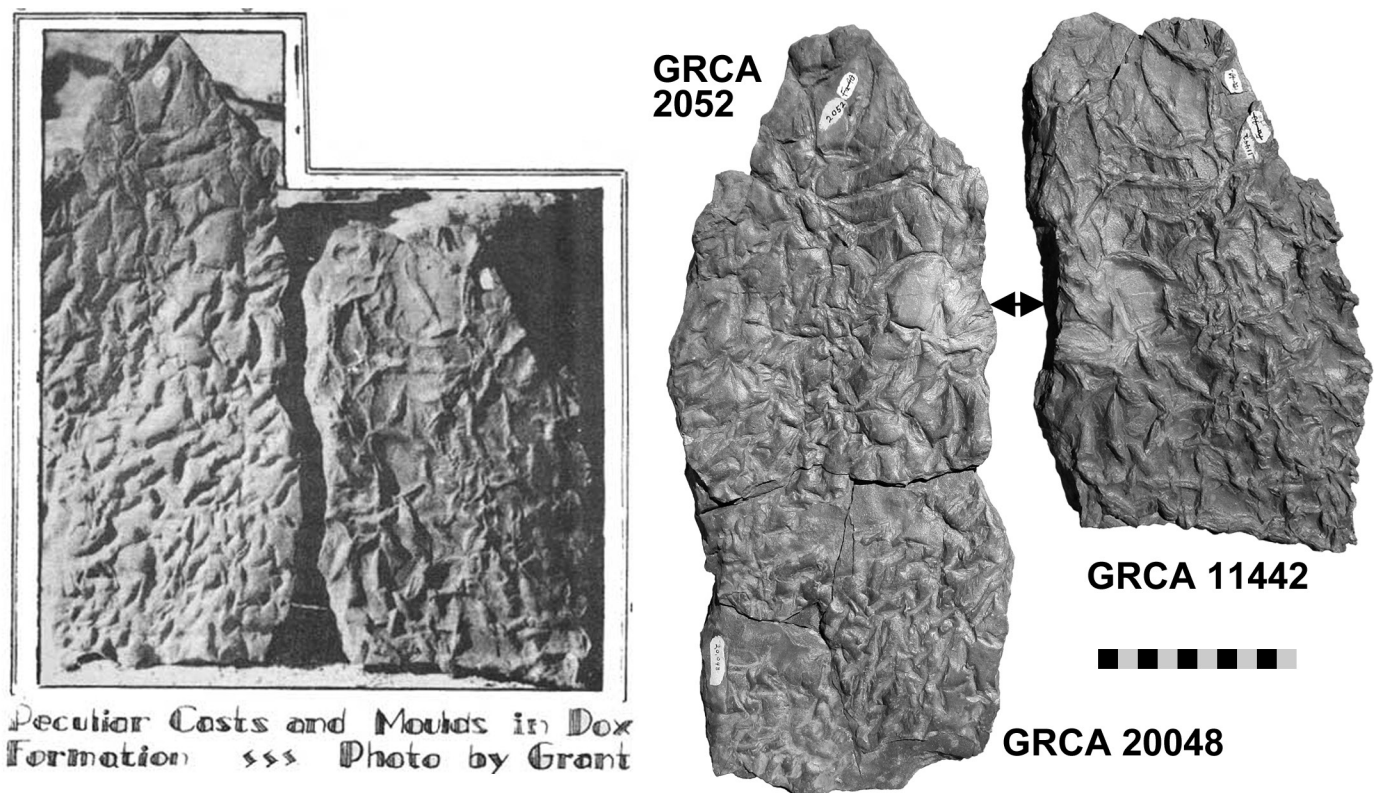


FIGURE 1. Original figure of "fucoid" specimens as depicted in McKee (1932) compared to their condition in 2019 (scale is 10 cm, each box representing 1 cm) (Justin Tweet). "Grant" is noted NPS photographer George A. Grant. In Grant's photo, the specimens appear to be propped against concrete or stone blocks, perhaps part of a stair or low wall. For the 2019 photo, GRCA 11442 is positioned higher relative to the other specimens to more closely approximate where the two surfaces correlate. A black double-headed arrow indicates the approximate location of a large redox spot part/counterpart, which is more obvious under different lighting and in color. A faint trough approximately following the long axis of GRCA 2052 and a corresponding rise on GRCA 11442 may be evidence of a bedform.

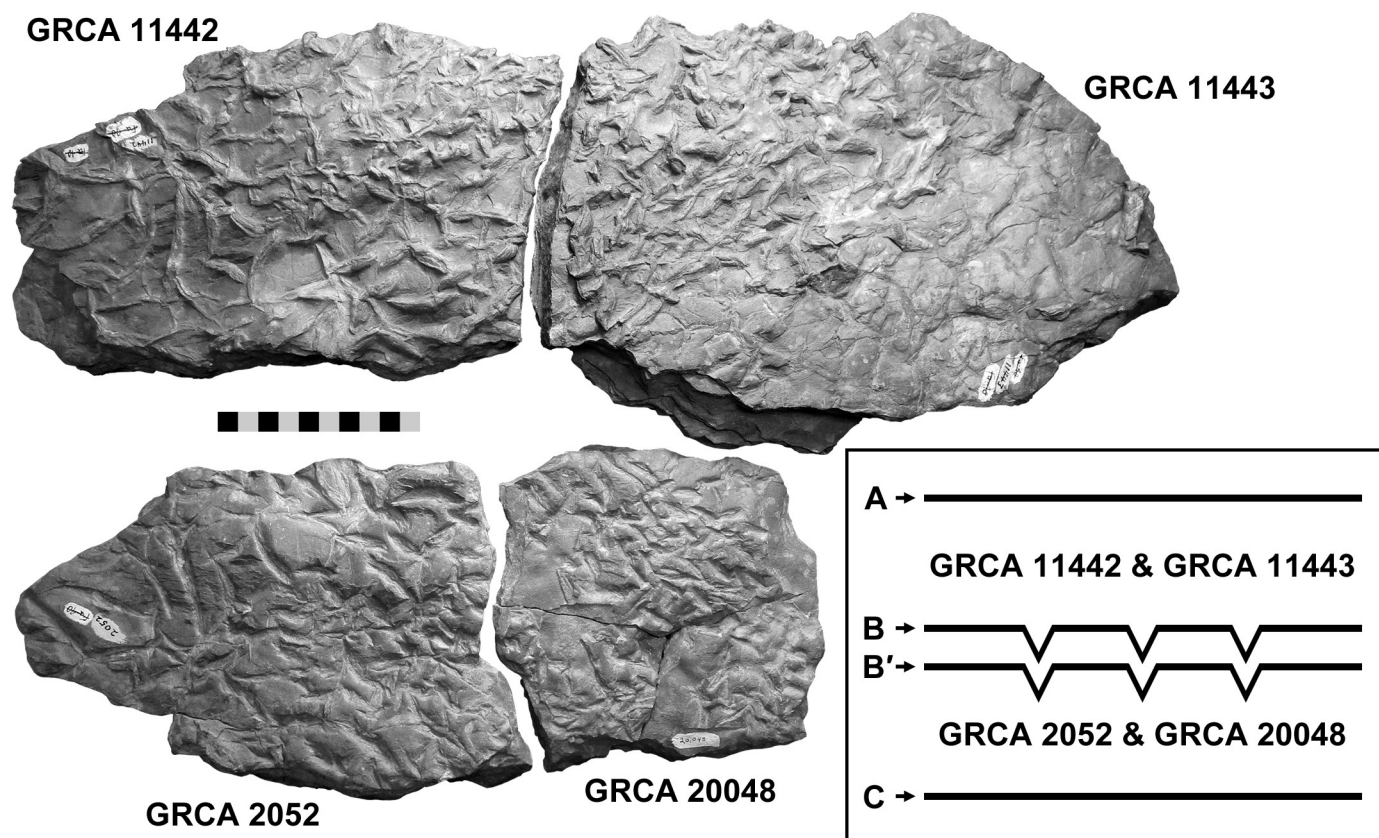


FIGURE 2. The four associated pieces collected by McKee are arranged here in two left-right pairs according to the fit of broken margins (Justin Tweet). The two pairs are also part-counterpart. The scale is 10 cm, with 1 cm boxes. The inset diagram depicts a cross-section through the stack of pieces, showing the identifications used for the surfaces. The downward triangles represent the spindles, which are positive on the B surfaces of GRCA 11442 and 11443, and are negative on the facing B' surfaces of GRCA 2052 and 20048. The vertical order of the specimens is arbitrary. Applying this terminology to the photographed specimens, the upper pair are showing B surfaces and the lower pair are showing B' surfaces.

Temple Member, Comanche Point Member, and Ochoa Point Member. Overall, these units have fairly similar lithologies except for the Escalante Creek Member, which is more heterogeneous and features black, green, gray, tan, white, and brown beds, unlike the dominantly red-brown rocks of the other members. The Solomon Temple Member is primarily composed of red siltstone and sandstone, with a slope-forming lower interval leading into an upper interval of channel sandstone. The Comanche Point Member is a slope-forming unit dominated by cyclic red siltstone and thin interbedded quartz sandstone, interrupted by occasional marker units of white, greenish-white, and lavender sandstone and mudstone. A dolomitic stromatolite bed is frequently present just below the lowest marker unit. The Ochoa Point Member is dominated by massive or poorly bedded mudstone and siltstone, with increasingly thick sandstone interbeds up-section until the conformable contact with the overlying Cardenas Basalt (Stevenson and Beus, 1982).

The Dox Formation has long been interpreted as a record of deposition in shallow water, going back to Noble's 1914 description. The Escalante Creek and Solomon Temple members have been interpreted to represent fluvial and deltaic deposition, whereas the overlying Comanche Point and Ochoa Point members have been interpreted to represent deposition in nearshore marine, mudflat, and possibly intertidal settings (Timmons et al., 2012). Sedimentary structures such as ripples and shrinkage cracks are common, especially in the Comanche Point Member and lower Ochoa Point Member (Stevenson and Beus 1982). Deposition of the Dox Formation occurred between approximately 1140 and 1104 Ma (Timmons et al., 2012; Mulder et al., 2017).

At this time, no detailed information has been located that could refine the stratigraphic horizon of the four specimens described and illustrated here beyond "Dox Formation." Three of the four members of the Dox Formation are mapped in the area across from the mouth of "Chuar Creek" (Lava Creek) as depicted in Stevenson and Beus (1982, fig. 2) and Timmons et al. (2012, pl. 1): the Escalante Creek Member (north of the Palisades Fault), Comanche Point Member, and Ochoa Point Member. However, Quaternary deposits are more immediately across from the mouth of the creek. Potentially, McKee collected at least some of the two dozen specimens from May 1930 as float eroded from adjacent Dox Formation outcrops. If nothing else, the color and lithology of the specimens are more typical of the Comanche Point and Ochoa Point members than the Escalante Creek Member.

DESCRIPTION OF SPECIMENS

Together, GRCA 2052, 11442, 11443, and 20048 make a flattened, slightly bilobed block of micaceous fine-grained sandstone approximately 53 cm long by 19 cm wide by 6 cm thick (Fig. 2). This block was split into two halves along a bedding plane, one half in negative relief and the other with positive relief. The specimens are reddish- to orangish-brown except for greenish-gray redox spots, which are found on all surfaces but are particularly abundant on the surfaces opposite the part-counterpart surfaces. The original way-up orientation of the specimens has been lost, if it was ever known. For convenience, we have described the stack as having the negative features oriented down, which makes GRCA 11442 & 11443 the upper part of the stack and GRCA 2052 & 20048 the lower part

of the stack. We can then designate the surfaces as follows (Fig. 2 inset): the upper surface of GRCA 11442 & 11443 is A; the lower surface of GRCA 11442 & 11443, with positive “fucoids” is B; the facing surface of GRCA 2052 & 20048, with negative “fucoids,” is B’; and the opposite surface of GRCA 2052 & 20048 is C. Positive features are found on both the A surface and C surface, so they do not constrain the up orientation.

The B and B’ surfaces of the four specimens feature

abundant, spindle-shaped ridges (B; Figs. 3A, 3C) or valleys (B’; Figs. 3B, 3D) of sandstone, wider in spindle centers than at their terminations, and more U-shaped in cross-section than V-shaped. They are straight to gently curved and do not form obvious networks or show predominant orientation(s). Instead, they are densely crowded, often overlap, and occasionally appear to be radiating from a point (Figs. 3C, 3D). Overall, they form an irregular polygonal pattern. Most of the spindles are

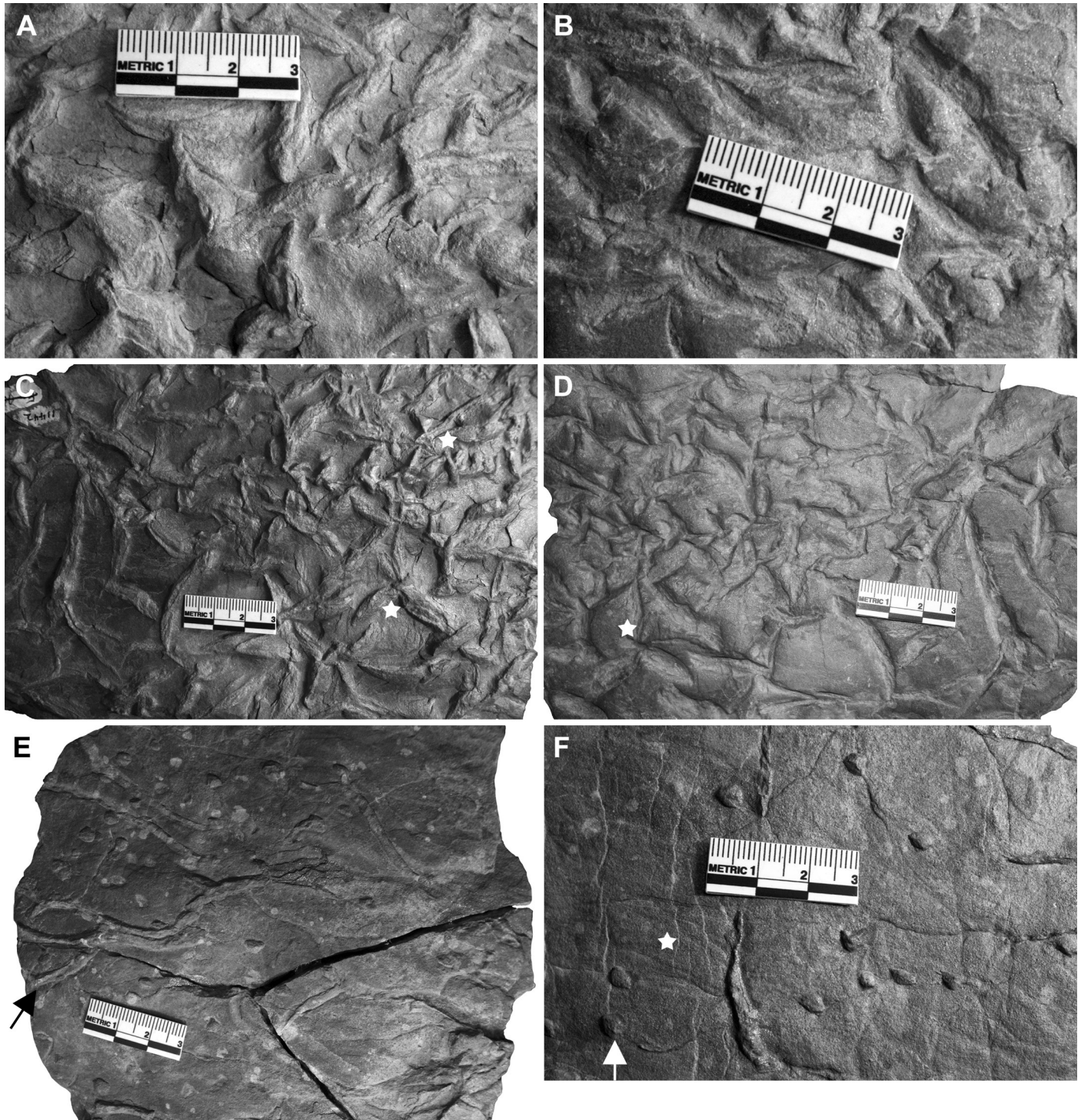


FIGURE 3. Detail photographs of various features (Spencer Lucas). **A**, Ridge-like positive spindles on the B surface of GRCA 11443. **B**, Valley-like negative spindles on the B’ surface of GRCA 20048. **C**, Positive spindles on the B’ surface of GRCA 11442, including radiating spindles (two examples are indicated with white stars). **D**, Negative spindles on the B’ surface of GRCA 2052; another point of radiation is indicated by a white star. **E**, Several “burrow”-like features on the C surface of GRCA 20048, including examples that parallel each other for several cm (part of this set is indicated by a black arrow). **F**, Several blebs (an example is indicated by a white arrow), a spindle feature, and fine wrinkles (a patch is indicated by a white star) are visible on the C surface of GRCA 2052.

between approximately 20 and 50 mm long and approximately 5 mm in width, with much less variation in width than length, and with vertical relief of less than 5 mm. These are the features that McKee described in 1932; as he noted, they are distinct from classic mud cracks, which can also be found in the Dox Formation (“They are found associated with the casts of ripple marks, the square moulds of salt crystals *and the casts of shrinkage cracks in mud;*” from 1932 description quoted above, with emphasis added). In certain lighting conditions the B and B’ surfaces appear to exhibit gentle warping roughly parallel to length, as if subtle, broad ripples have been overprinted by the spindle-shaped features (Fig. 1).

The B surface of GRCA 11443 is noticeably different, distant from the join with GRCA 11442: the positive spindles disappear, with simpler linear markings on the order of 1 to 2 mm across and 20 to 30 mm long present instead (Fig. 4). What appears to be the edge of a spalling or flaking front can be identified in places near the farthest extent of the spindles, so it seems that the B surface has been eroded or otherwise damaged in the spindle-free areas. These may represent two closely spaced generations of cracks. There is no corresponding B’ on GRCA 20048 to check, because it only replicates about half of GRCA 11443.

The A surfaces of GRCA 11442 & 11443 and the C surfaces of GRCA 2052 & 20048 are distinct from the B/B’ surfaces and each other. The A surface of GRCA 11442 & 11443 (Fig. 5A) is the least marked of the surfaces, aside from abundant redox spots generally 1–10 mm in diameter. The A surface cuts through bedding and includes part of another bed, which conceals the main surface on GRCA 11443. There are hints of ripples on both

levels; the two potential generations of ripples are perpendicular (Fig. 5A). If they are ripples, they imply that the A surface is the stratigraphically topmost surface. Although approximately perpendicular, they would not represent true interference ripples because they are found on different horizons. There are a few example of spindle-shaped features near the break of the two specimens similar to those on the B/B’ surfaces (including a negative feature on GRCA 11442 adjacent to a positive feature on GRCA 11443), and rare longer features that resemble burrow-like features on the C surface of GRCA 2052 & 20048. A note associated with GRCA 11442 mentions the ichnogenus *Teichichnus*. It is not obvious why this ichnogenus has been invoked, because *Teichichnus* does not strongly resemble any of the types of features found on GRCA 11442, or for that matter the other three specimens (compare for example to Häntzschel, 1975 or Knaust, 2018).

The C surface of GRCA 2052 & 20048 has a small number of linear to sinuous features (Fig. 5B). These can be distinguished from the spindle-shaped features of B and B’ by their greater lengths (generally between 50 and 100 mm), narrower widths (generally 3 to 4 mm), and parallel sides; in some ways they resemble invertebrate burrows (Fig. 3E). In some places, two or more of these features appear to merge (with the features preserving their distinct identity, like lanes of traffic) or branch (Fig. 3E). The C surface also has a small number of equant, ovoid, or triangular positive nodular features of undetermined origin, generally 4 to 6 mm long and with up to about half that much vertical relief (Fig. 3F). None were found on an edge, so it is not known if they are “rooted” in the slab or are surficial blebs. Uncommon pockmarks of about the same size may represent



FIGURE 4. The B surface of GRCA 11443 appears to have been eroded or otherwise damaged on the left, where simple, thinner linear features are present instead of positive spindles. Scale is 10 cm (1 cm boxes) (Justin Tweet).

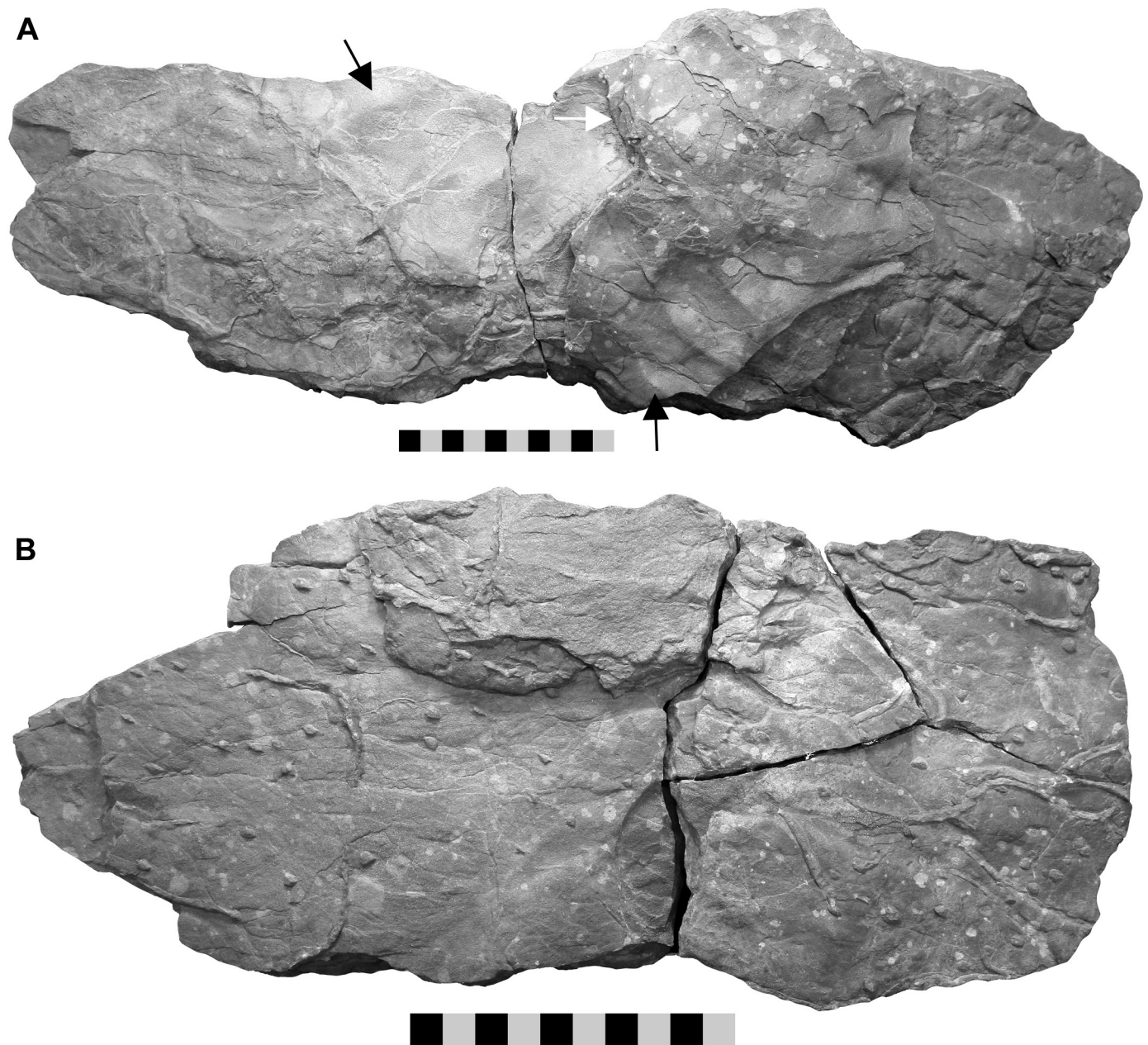


FIGURE 5. Wider views of the opposing surfaces of the two pairs (Justin Tweet). **5A**, The A surface of GRCA 11442 (left) and 11443 (right); GRCA 11443 also includes part of a different bed, which conceals the main A surface. Black arrows indicate two potential generations of ripples, roughly perpendicular to each other. A white arrow points out the edge of the covering bed. **5B**, The C surface of GRCA 2052 (left) and GRCA 20048 (right), showing a scattering of blebs, spindles, longer features resembling burrows, and redox spots. Scale bars for both are 10 cm (1 cm boxes)

nodular features that have been detached, or impressions of nodular features that were attached to the now-missing opposite surface. Other features on the C surface include numerous redox spots 1–10 mm in diameter and areas of what appear to be fine, roughly parallel wrinkles (the latter especially on GRCA 2052) (Fig. 3F). Close inspection suggests that these might be tiny steps in bed partings.

IDENTIFICATION

We view most of the features on the Dox Formation surfaces, particularly the negative and positive spindles on B and B', as good examples of shrinkage crack features, either the cracks themselves or crack fill (petee ridges, filled sand cracks), almost certainly mediated by microbial activity. Admittedly, it is not

possible at this time to rigorously evaluate many aspects of these specimens. However, the positive and negative spindle-shaped “fucoids” are morphologically the same as known sediment shrinkage crack features (e.g., Donaldson, 1967; Seilacher, 2007; Eriksson et al., 2007; Buatois et al., 2013; Banerjee et al., 2014; Hargitai et al., 2014; Sarkar et al., 2014), and can be analyzed in terms of such features.

Cracks may result from subaerial desiccation (the classic polygonal mud crack) or may occur in submerged sediments, either at the sediment-water interface or within the sediment (Plummer and Gostin, 1981; Hargitai et al., 2014); those cracks that form beneath water are commonly called syn(a)eresis cracks, although they are often not due to syneresis (Davies et al., 2016). The following concise summary is drawn from

Eriksson et al. (2007).

Features related to sediment cracking can be negative (e.g., either the negative space of cracks themselves, or molds of positive features) or positive (e.g., petee ridges, filled sand cracks, and so forth). Separated from the original geological context, it can be very difficult to distinguish one type from another, although sedimentological analysis can provide some constraint. Although it may intuitively seem that cracks should be preserved as negative features with fill descending from above, positive features are common. In the case of microbial settings they result from the removal of the mat by decay or other processes, leaving behind the crack fill. The crack fill itself may be from above (resulting in filled sand cracks, which usually have a different composition than the underlying rock), or from below due to environmental pressures (resulting in petee ridges *sensu lato* as described in Eriksson et al., 2007). There appears to be a restricted environmental signal as well: shrinkage cracks and petee ridges interpreted as MISS are largely confined to upper intertidal to supratidal zones (Bose and Chafetz, 2012; Banerjee et al., 2014; Sarkar et al., 2014).

Shrinkage crack features in sandstone are often seen as likely MISS, because sand accommodates contraction by grains sliding rather than cohesive cracking unless there is a binding agent, such as a microbial mat (Seilacher, 1999). It should be noted, though, that the presence of mud can also lead to sand shrinkage cracks, so both lower and upper beds of a surface with shrinkage features need to be known to be sure that mudstone was not present (Eriksson et al., 2007). In this case, we have both the upper and lower beds for the B and B' surfaces, and there is no indication of intervening mudstone. Regardless, it can be difficult to distinguish biotic cracks and ridges from abiotic (Noffke, 2010; Eriksson et al., 2007; Hargitai et al., 2014; Davies et al., 2016). Further work to locate additional specimens in the field and document their geologic context and sedimentological characteristics should clarify those questions that cannot be answered from the existing specimens.

Interpretation of such Proterozoic shrinkage features has a complex history, with initial workers identifying them as algal structures, burrows possibly made by an animal similar to annelids, or even body fossils (e.g., White, 1928; Endo, 1933; Lee, 1939; Hofmann, 1967). Under these interpretations, certain shrinkage features from the Proterozoic received the taxonomic names *Manchuriophycus* Endo, 1933 ("burrows") and *Rhysonetron* Hofmann, 1967 ("body fossils"). However, Häntzschel (1949, 1962, 1975) concluded that these features were mudcracks of inorganic origin and therefore pseudofossils. Notably, Hofmann (1971) revised his 1967 interpretation, concluding that "*Rhysonetron*" represented shrinkage fractures filled with sediment. Nevertheless, in a remarkably prescient paper, Donaldson (1967) argued, based on actualistic data, that such Proterozoic structures were made by the desiccation of algal mats, which is similar to the current interpretation of these structures.

Current interpretation of features like those from the Dox Formation (e.g., Eriksson et al., 2007; Hargitai et al., 2014, and references cited therein) is that they were created as a result of shrinkage, either subaerially or by syneresis, which is the dewatering of gel-like sediments that occurs at the sediment-water interface or within the sediment, not subaerially (Plummer and Gostin, 1981; Seilacher, 1999). The explanation of the fractal pattern of spindle-shaped ridges seen on sand surfaces like those from the Dox Formation is that a microbial community provided cohesion to the sand, but this cohesion also induced shrinkage and cracking that would not otherwise be produced in sand. Sediment then entered the fractures (from above or below) and formed spindle-shaped sand ridges. Thus, the spindles reflect a microbially mediated fracturing and subsequent filling of the fractures, so they are a kind of MISS.

Other features on the blocks may be examples of other kinds of MISS. In particular, the elongate and vaguely burrow-like features on the C surface (Fig. 3E), some of which run in parallel for short distances, have some similarities to rolled-up mat fragments as described by Donaldson (1967) and Eriksson et al. (2007).

SIGNIFICANCE

This appears to be the first report to consider features in the Precambrian rocks of the Grand Canyon in terms of MISS, which is probably a function of the relative newness of the study of MISS and the lack of interest in the canyon's Precambrian "fucoids" after they were dismissed as burrows (Cloud, 1968; Glaessner, 1969). The likely presence of MISS in the Dox Formation is not unprecedented, given that the presence of stromatolites in the Comanche Point Member (Stevenson and Beus, 1982; Timmons et al., 2012) establishes that mat-producing microbial organisms were present during deposition. Beyond the Dox Formation, other formations of the Grand Canyon have great potential for further exploration and research. For example, various "fucoids" and other putative trace fossils have been reported from all of the units of the Unkar Group except for the Cardenas Basalt (see Tweet, 2020 for more information and references), as well as the overlying Nankoweap Formation of the Chuar Group. Most of these formations are siliciclastic and are interpreted as representing deposition in shallow water. In the case of the Nankoweap Formation, Ford (1990) noted the presence of sinuous putative trace fossils, which he interpreted as more likely to be truncated mud cracks. Another intriguing report comes from White (1929a), who noted "several forms of small, slightly crooked, fusiform remains, which appear fairly certainly organic [p. 392]" in the Bass-Hakatai transitional interval. For that matter, the specimen chosen to represent the Dox Formation on GRCA's "Trail of Time" features a "fucoidal" surface (Fig. 6).

Stromatolites are not only present in the Dox Formation, they are well-known in the Bass Formation, the lowest formation of the Unkar Group (White, 1928; Nitecki, 1971; Beus et al., 1974; Ford and Breed, 1977; Timmons et al., 2012), and there is no reason to think that mat-producing microbiota were not present



FIGURE 6. Tens of thousands of visitors to Grand Canyon National Park have passed this "fucoidal" sample of the Dox Formation on the Trail of Time (Justin Tweet).

throughout the deposition of the Unkar Group. Stromatolites are the only well-documented fossils in the Unkar Group at this time; investigation of these formations for MISS could greatly expand our knowledge of life outside of the carbonate rocks, which are a minority of the Unkar Group. As noted above, certain MISS such as features related to shrinkage cracks can also provide information on paleoenvironments.

Potential MISS are also known from Paleozoic units within the park, such as “*Rivularites permiensis*” of White (1929b) and Supai Group records of “*Rivularites*” (McKee 1982), although these reports have not been formally evaluated specifically in terms of MISS. As with the Precambrian rocks, investigation of the Paleozoic formations for potential MISS would doubtless turn up additional examples.

CONCLUSIONS

The likely presence of MISS in the Dox Formation sheds new light on a variety of enigmatic features in the Precambrian rocks of the Grand Canyon, often previously interpreted as trace fossils and then discounted as pseudofossils. Although the existence of MISS had not been postulated when Edwin D. McKee collected and reported his “fucoids” in the early 1930s, his curiosity has paid unexpected dividends, potentially illustrating ancient life in a form not understood at the time. McKee’s “fucoids” serve as an incentive for further research into potential MISS in the Precambrian of the Grand Canyon beyond the limited scope of this present study. Locating additional examples in the field and applying techniques and technology such as those described in Noffke (2010) would provide a much better understanding of these features. Features suggestive of MISS have been reported anecdotally from several formations of the Grand Canyon Supergroup, indicating that they may be widespread.

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