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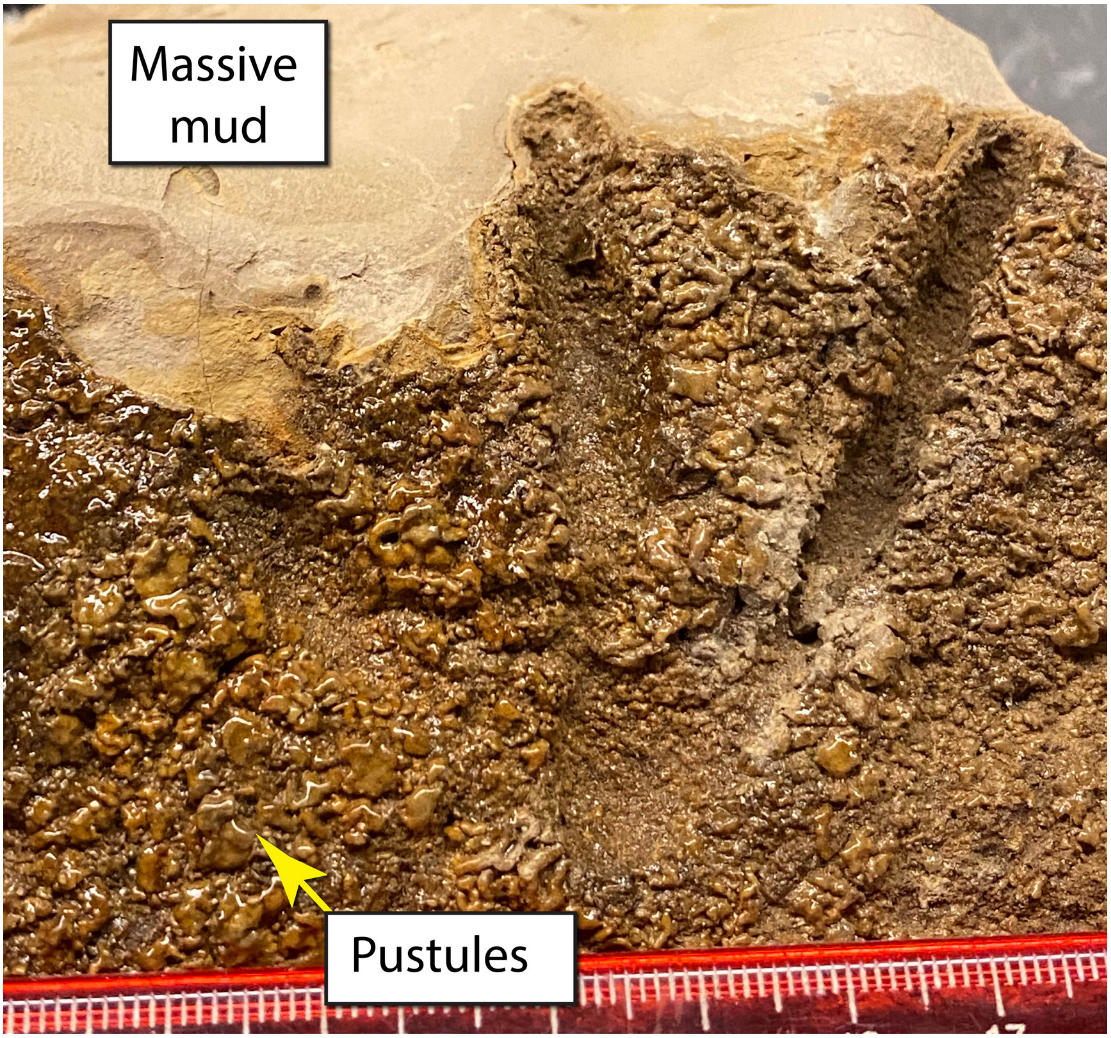
MICROBIALLY INDUCED SEDIMENTARY STRUCTURES AND THE PRESERVATION OF VERTEBRATE TRACKS ON THE COLORADO RIVER DELTA IN LAKE POWELL, HITE, UTAH

Edward L. Simpson, Michael C. Wizevich, Dakota Pittinger, Garrett Rogers, and Kayla Lazer



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Cover

Photograph of preserved Canada goose track preserved in pustular mat. The upper surface is treated with polyurethane (shiny coating on surface) applied in order to facilitate sample extraction. The polyurethane shrank the pustules. Note the massive mud below the track. Scale bar in mm.

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Microbially Induced Sedimentary Structures and the Preservation of Vertebrate Tracks on the Colorado River Delta in Lake Powell, Hite, Utah

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ABSTRACT

Microbially induced sedimentary structures (MISS) increase the preservation potential of vertebrate and invertebrate ichnofossils. The Colorado River forms a delta in Lake Powell at Hite, Utah, and the deltaic shoreline provides a natural laboratory to examine the development of MISS and their influence on vertebrate track preservation. Two types of MISS were identified: pustular and blister. Pustular MISS occur in proximity to the June 2020 high water line. The pustular morphology is characterized by mm-scale small mounds, or pimple-like shapes. Field emission scanning electron microscopy (FESEM) examination identified preserved filamentous cyanobacteria intertwined with fine silt- and clay-sized sediment and well-preserved freshwater diatoms. *Branta canadensis* (Canada goose) tracks are well developed and they vary from single tridactyl tracks to trampled horizons. Blister MISS, in contrast to pustular MISS, are present in lower elevations, forming in deeper water, greater than 0.5 m. Blisters are mm- to cm-scale irregular mounds that consist of arching mats that are detached from the underlying sediment creating a pore space. Through time the blister mat mounds are destroyed by fragmentation due to desiccation combined with wind processes. FESEM and energy-dispersive spectroscopy system (EDS) analyses indicate the presence of filamentous cyanobacteria on the exterior and palisade *Bacillus*-type bacteria are in the interior of the blister arch, and gypsum crystals within the mat arch. Freshwater diatoms are present in both mat types. A single human track and multiple trackways of *Canis latrans* (coyote) were identified on the blister mats. Weakly impressed Canada goose tracks are present. Tracks cross cutting or modifying the pustular MISS have preserved MISS surface textures except in the heavily trampled areas, whereas tracks linked to the blister mat typically do not have preserved mat texture, and usually contain fragmented mat within the impression. Because of fluctuating lake levels and desiccation, these track types had a limited temporal window where they may be produced when moisture conditions permitted MISS development, about two months. Any vertebrates through the area out of the "track window" were not recorded in sediment and mat modification. Tracks imprinted on pustular MISS in lacustrine environments will have a high preservation potential if there are annual fluctuations in lake levels.

Citation for this article.
Simpson, E.L., Wizevich, M.C., Pittinger, D., Rogers, G, and Lazer, K., 2022, Microbially induced sedimentary structures and the preservation of vertebrate tracks on the Colorado River delta in Lake Powell, Hite, Utah: Geology of the Intermountain West, v. 9, p. 131–151, https://doi.org/10.31711/giw.v9.pp131-151.

INTRODUCTION

The preservation potential of vertebrate tracks has been scrutinized for well over seven decades. Numerous studies have demonstrated that the preserved morphology of vertebrate tracks is a function of the producer's anatomy and behavior, coupled with the substrate condition at the time of imprinting, and any modification by post-imprint processes (Peabody 1947, 1948; Lockley, 1986, 1987, 1991a, 1991b; Lockley and Conrad, 1991; Marchetti and others, 2019a, 2019b, 2020; Cuadrado and others, 2021). The fidelity of tracks as a direct function of grain size, moisture variability, and rheology is well documented (Allen, 1989; Manning, 2004; Milań and others, 2004; Milań and Bromley, 2006; Milań and Loope, 2007; Dalman and Weems, 2013; Falkingham and Gatesy, 2014; Belvedere and others, 2017; Gatesy and Falkingham, 2017; Szewcyk and others, 2020; and many more). Post imprint processes include weathering, erosion, bioturbation, early cementation, and post-depositional deformation (Laporte and Behrensmeyer, 1980; Nadon, 2001).

The presence of microbially induced sedimentary structures (MISS) has been invoked as a condition that increases the preservation probability of vertebrate tracks (Paik and others, 2001; Conti and others, 2005; Marty and others, 2009; Carmona and others, 2011; Carvalho and others, 2013; Dai and others, 2015; Fillmore and others, 2017; Noffke and others, 2019; Carvalho and Leonardi, 2021; Cuadrado and others, 2021). MISS both stabilize the initial track structure and may overgrow impressions protecting them from subsequent erosional processes (Marty and others, 2009). In addition, early mineral precipitation of calcium carbonate ($CaCO_3$) induced by microbial metabolic processes (Chafetz and Buczynski, 1992; Dupraz and others, 2009; Marty and others, 2009; Cuadrado and others, 2011; Carvalho and others, 2013; Xing and others, 2015a, 2015b, 2015c) and evaporites in arid environments (Lockely and Rodríguez-de la Rosa, 2009) may form during the initial stages of lithification and promote track preservation.

The occurrence of vertebrate tracks associated with MISS is documented from modern and ancient tidal flats (Avanzini and others, 1997; Marty and others, 2009; Cuadrado and others, 2011; Noffke and others, 2019). In continental settings, track preservation associated with MISS has been documented from alluvial fan to fluvial systems (Carvalho and others, 2013), but rarely lacustrine settings (Lockley and Rodríguez-de la Rosa, 2009; Moratalla and others, 2017). Tracks and associated MISS in modern lacustrine systems have not been scrutinized extensively. Delta-top deposits in Lake Powell, a reservoir within the Glen Canyon National Recreation Area, Utah and Arizona, provide an opportunity to examine the vertical distribution of microbial mats on the shoreline, track generation linked to MISS type, and potential destruction of MISS and tracks over time (figure 1).

GEOLOGIC SETTING OF LAKE POWELL

After the 1963 completion of the Glen Canyon Dam (figure 1), Lake Powell levels rose until reaching a maximum pool height of 1127 m elevation above sea level in 1983. This was followed by a long-term decline caused by superimposed annual drawdowns and diminished recharges from spring snowmelt combined with summer monsoonal precipitation (figures 2 and 3). With the development of Lake Powell, a delta formed near the confluence of the Colorado and Dirty Devil Rivers at Hite, Utah (Pratson and others, 2008; Anderson and others, 2010; Netoff and others, 2010). Lake-level fluctuations over the last several years has led to repeated flooding and exposure of the delta top at Hite as well as channel incision by the Colorado River.

The Hite delta has been subject to increased scrutiny because of the focused emission of greenhouse-related biological methane (CH_4) (Malenda and others, 2020; Waldo and others, 2021). The release of fluid and gas (CH_4, carbon dioxide [CO_2], and air) produces soft-sediment deformation escape features including domes, pockmarks, water-filled (salsas) and dry craters, sediment-filled craters, mud and sand volcanoes, clastic dike systems, and small-scale gas fractures (figure 4; Netoff and others, 2010; Livingston and others, 2015; Sherrod and others, 2016; Miller and others, 2018; Malenda and others, 2020).

The uppermost 2 m of the delta consists typically of different proportions of clay, silt, and fine-sand deposits

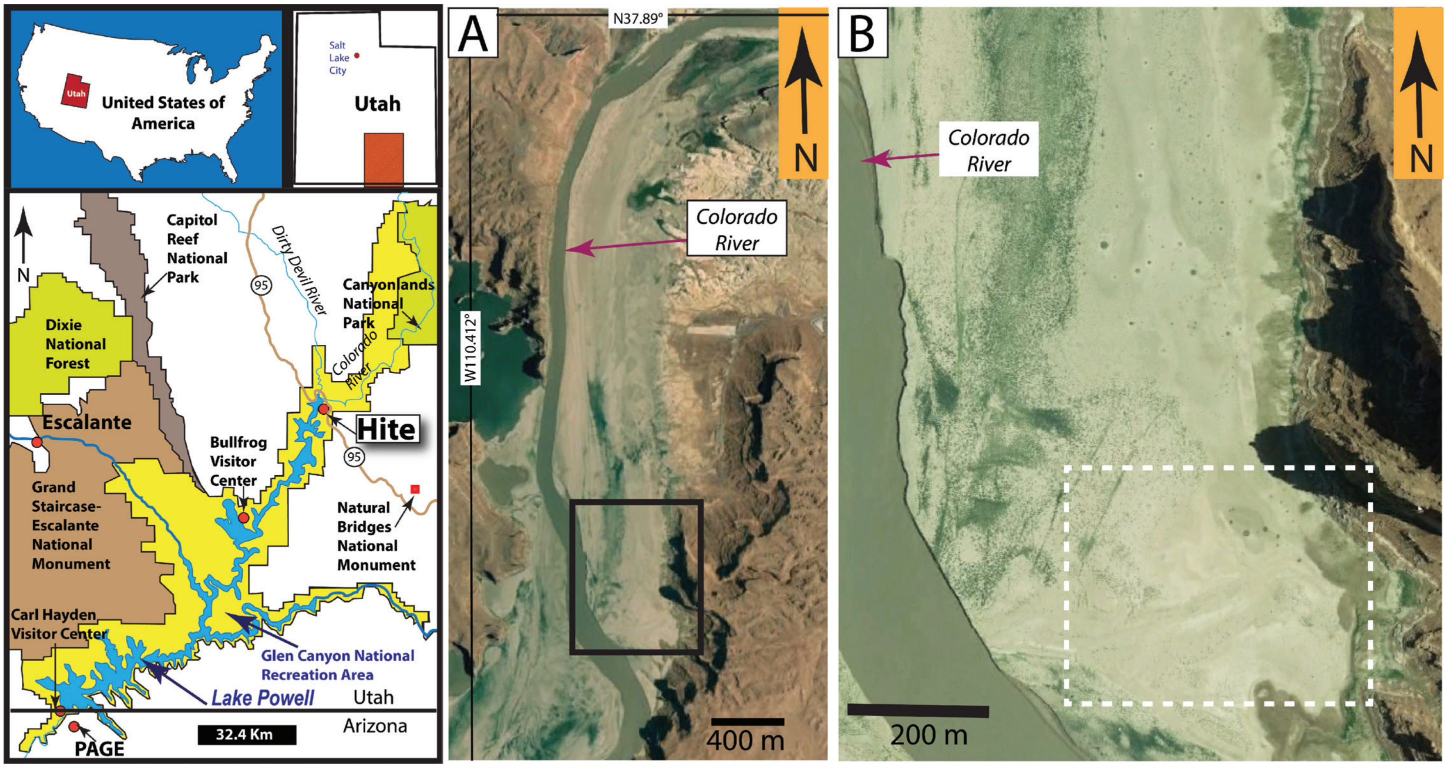


Figure 1. Location map of Lake Powell, Glen Canyon National Recreation Area, Utah and Arizona. The study area is near Hite. (A) Google Earth image of the Hite delta exposed at low water during September 2013. Box denotes study area, and enlarged in (B). Dashed-line box in (B) is approximate location of figure 2.

that formed from surface runoff and/or lake-rise flooding (Willis, 2012; Sherrod and others, 2016). At the southern end of the Hite delta top, a topographic low is present that was periodically inundated as lake level rose during spring snow melt and spring and summer precipitation (figures 2 and 3). The ephemeral nature of the flooded area permits examination of the surface features on the delta top and enables an understanding of the sequential history of MISS and vertebrate track development (figure 3). The study area was inundated sometime in June–July 2020 (figure 3), based on the Lake Powell hydrograph and the elevation of the study area, with a gradual decline in water level that continued through January 2022.

METHODS

The study area is located in the southern part of the exposed delta and was imaged via an unmanned aerial vehicle (drone). Using MetashapePro™, the photographic images were compiled into a three-dimensional model of the study area (figure 2). The area examined was relatively vegetation free. Field observations of the MISS were during early June and early August of 2021. Samples of pustular mats were stabilized with polyurethane during June 2021 to protect them from damage. Samples of surface fragments collected in August 2021were scraped off the top of blister sediment surface MISS. Both types were later analyzed in the Field Emission Scanning Electron Microscope (FESEM) at Kutztown University without additional preparation such as coating. Energy-dispersive spectroscopy system (EDS) examination determined elemental composition. Spectra were taken at 5kv and weight percent (wt.%) are adjusted using 5kv standards in the Aztec Cambridge software.

DESCRIPTION OF LAKE POWELL MATS AND VERTEBRATE TRACKS

Two end-member MISS morphologies were distinguished on microbial mat cover surfaces in the study

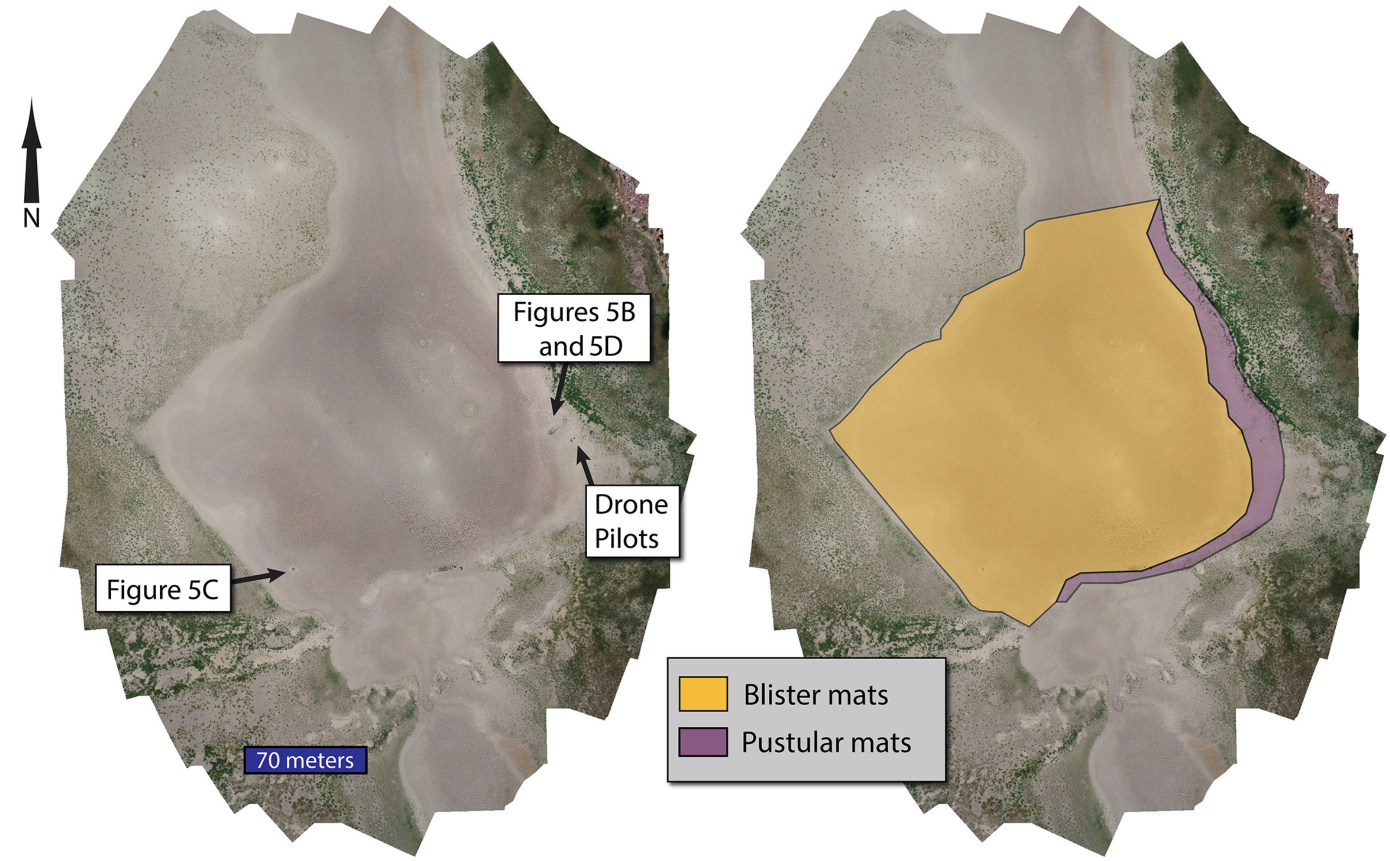


Figure 2. Orthographic model of the study area generated from aerial drone images taken June 3, 2021. Color banding on the left model reflects surface features and probably differences in moisture content. Highlighted colors on the right model equate to the distribution of mat types. See scale on left-side model.

area, blister and pustular. Pustular MISS are present in the high elevations along the upper shoreline zone along the eastern margin of the ponded area, abutting vegetated zones (figure 2). The blister MISS are located at lower elevations (relatively deeper water) relative to the pustular mat (figure 4), continue to the west, and abut a thickly vegetated zone that does not contain microbial mats. No other variety of MISS morphology was recognized. Both MISS types were dry and the uppermost half meter of deltaic sediment is cut by deep desiccation cracks in the montmorillonite-rich clay (figure 4; Netoff and others, 2010). In the pustular MISS area, desiccation cracks are about 20 cm significantly shallower than in the blister mat area.

Description of Pustular MISS

The pustular MISS morphology is characterized by mm-scale small mounds, or pimple-like shapes, forming a single head on the surface (figure 5). Pustules are randomly distributed with no apparent patterning or size difference across the surface and are symmetrical to nearly symmetrical in plan view (figure 5). An individual pustule surface is rough and irregular textured (figure 6). Smaller forms may be superimposed on larger forms resulting in a structure that resembles a small cauliflower curd (figure 5). In cross section, pustular mats are less than 1 mm thick and cored with clay- to silt-size sediment (figure 6). White evaporite crusts are restricted to the margins of the cross-cutting desiccation cracks. No morphological differences in the pustular mats were observed between June and August 2021.

FESEM examination of the pustular MISS documents the presence of preserved flattened filaments (figures 7A through 7D) and diatoms (figures 7E through

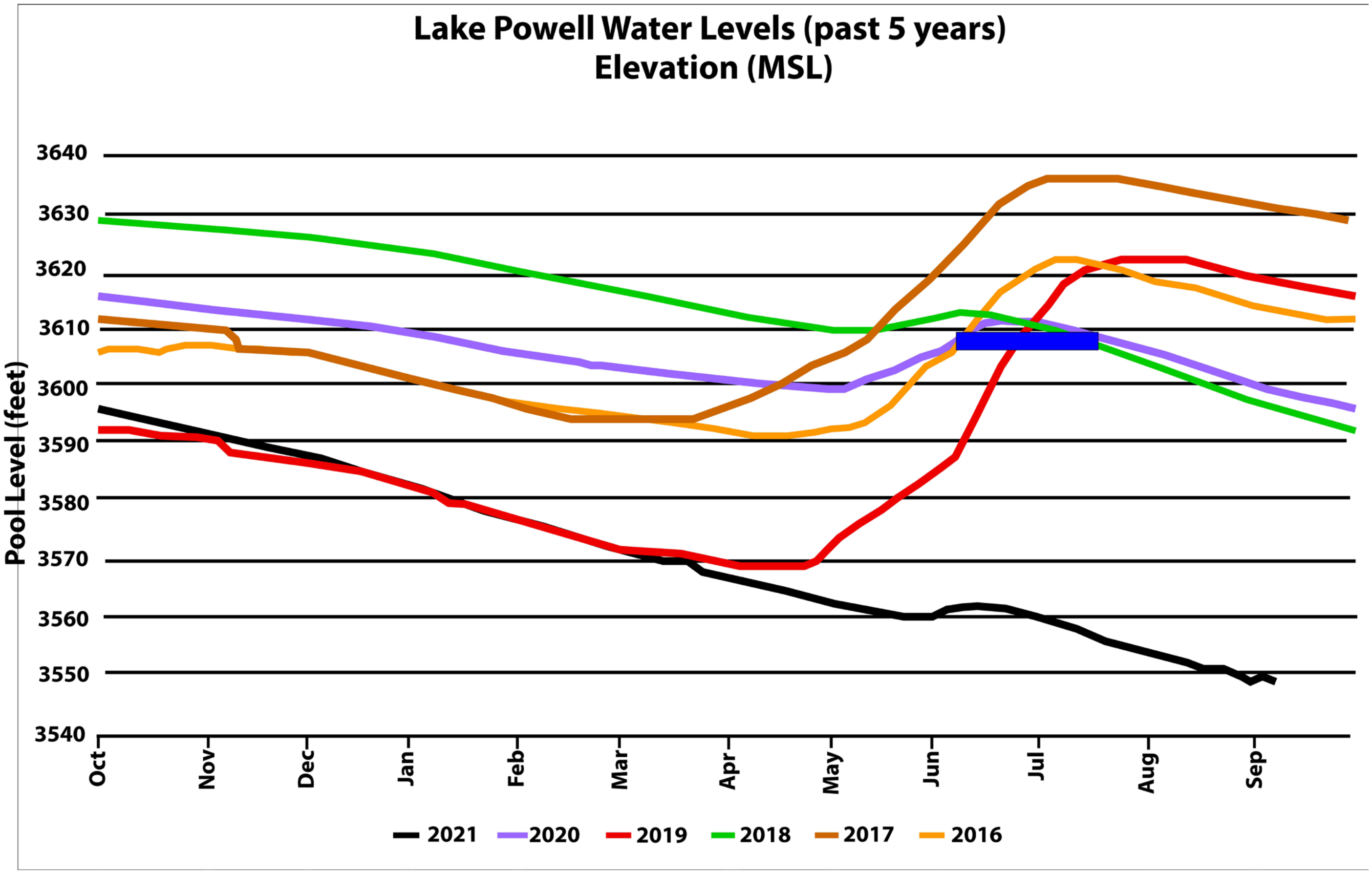


Figure 3. Lake Powell pool level over the past five years. Blue bar, set at study area elevation of the delta top, denotes time period that the lake level was most recently above the area. Note the 2021 reduction in water level, especially the absence of inundation of the study area that typically occurs from June through November. Data from lakepowell.water-data.com/lakepowell/; MSL = mean sea level.

7G). Flat filaments are twisted and entangled around silt- to clay-size particles (figures 7A and 7B). Filaments have lengths of over 100 µm and widths of approximately 2 to 3 mm. Clay particles are adhered to the filament surface. Structureless organic masses are recognizable on the filament surfaces (figure 7C). Complete to nearly complete diatoms are present and have frustule shapes varying from cylindrical, pennate, to fusiform (figures 7E through 7F).

Canada goose (*Branta canadensis*) tracks are preserved cross cutting the pustular MISS (figures 5 and 6). These tridactyl tracks range from single distinct tracks to heavy trampling (sensu Richter and Böhme, 2016). The pustular texture is reduced in size within the true tracks than the surrounding MISS. Tracks depress the underlying sediment surface, but under-track deformational structures are not apparent due to the structureless nature of the underlying mudstone and siltstone (figure 6).

Description of Blister MISS

During the June 2021 observation, the surface expression of the blister MISS was represented by mm- to cm-scale irregular mounds with maximum length of about 3 cm and widths of about 1.5 cm (figure 8). Thickness of crust was less than 1 mm. The blister mounds were randomly distributed with no apparent patterning across the surface (figure 8). These positive structures were slightly asymmetrical with no apparent preferred orientation and arcuate to straight in planform along the crests (figure 8). The surface texture of the blisters was irregular to smooth (figures 8A and 8B). In cross sec-

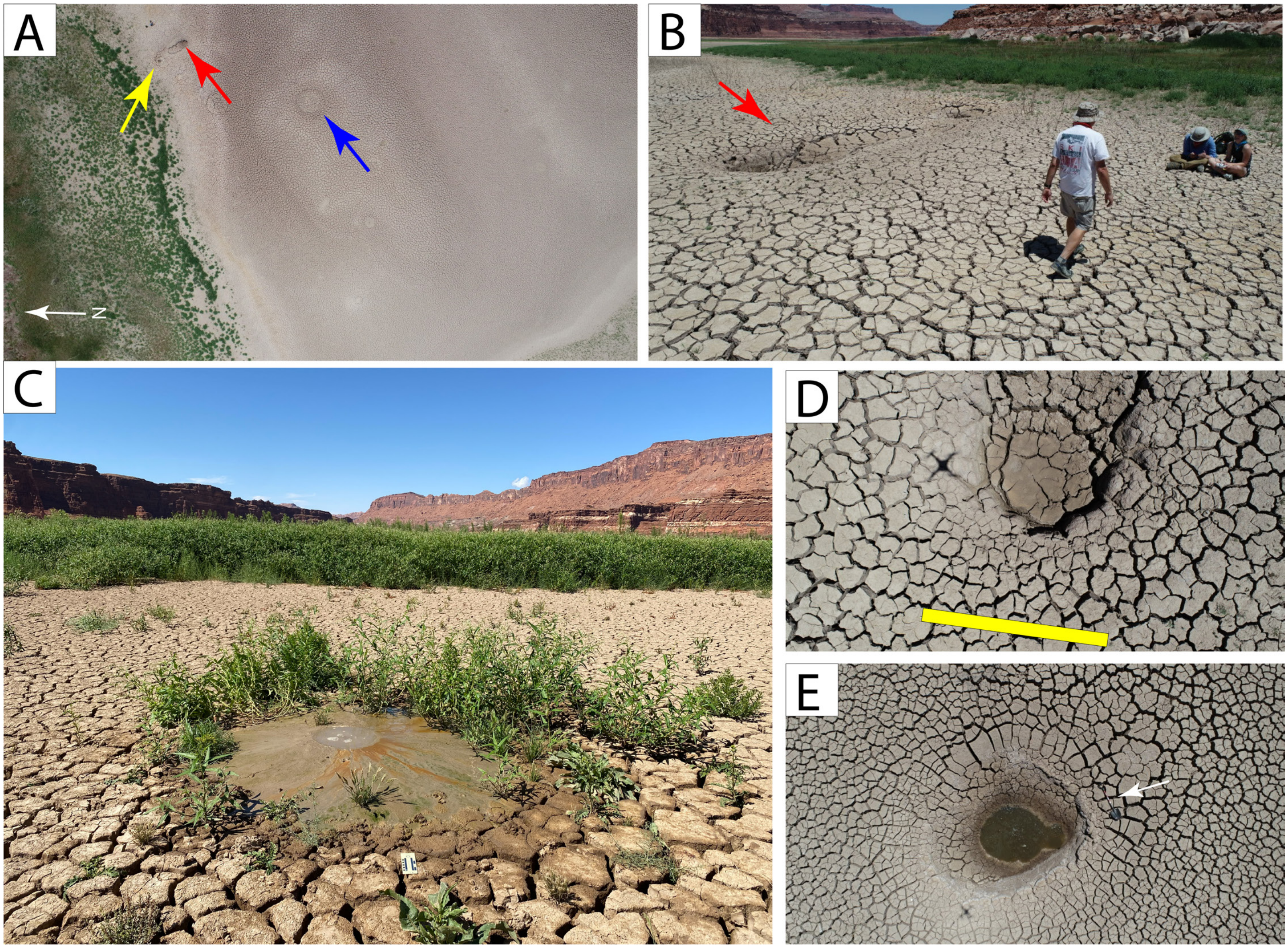


Figure 4. Field photographs of fluid/gas escape structures in the study area. (A) Drone photograph of dried salsa in northern edge of study area. Yellow arrow shows salsa in E. Red arrow marks features that are illustrated in B and D. Blue arrow shows position of filled crater/salsa. (B) Gas escape crater marked with red arrow. (C) Erupting mud volcano. Note the various age flows reflected in the different colors. Scale bar is 16.5 cm. (D) Asymmetrical gas escape crater. Yellow scale bar is 2 m. (E) Salsa with erupting gas contained in the crater. Shovel is 0.7 m (white arrow).

tion, the blisters have a distinct open void beneath the thin mm-thick crusts that corresponds to the overall dimensions of each individual blister. The arch height was up to 5 mm and varies with blister size. In June 2021, numerous crusts were breached with linear and irregular desiccation cracks, illustrating their void-like nature (figures 4, 5, 8, 9, and 10). The brittle, rigid nature of the microbial mat is displayed by crust fragments overhanging the mud cracks (figure 8C). The overhanging blister MISS pieces matched across the fractured surfaces of the desiccation cracks. Some pieces appeared to show a lineation perpendicular to the desiccation crack, suggesting ductile behavior of the mat in the early stages of desiccation (figure 8C). FESEM coupled with EDS examination determined the presence of gypsum crystals within the crusts by crystal morphology and elemental composition (figure 11).

During the August 2021 observation period, the destruction was ubiquitous when nearly all the blisters overhanging voids were reduced to small fragments

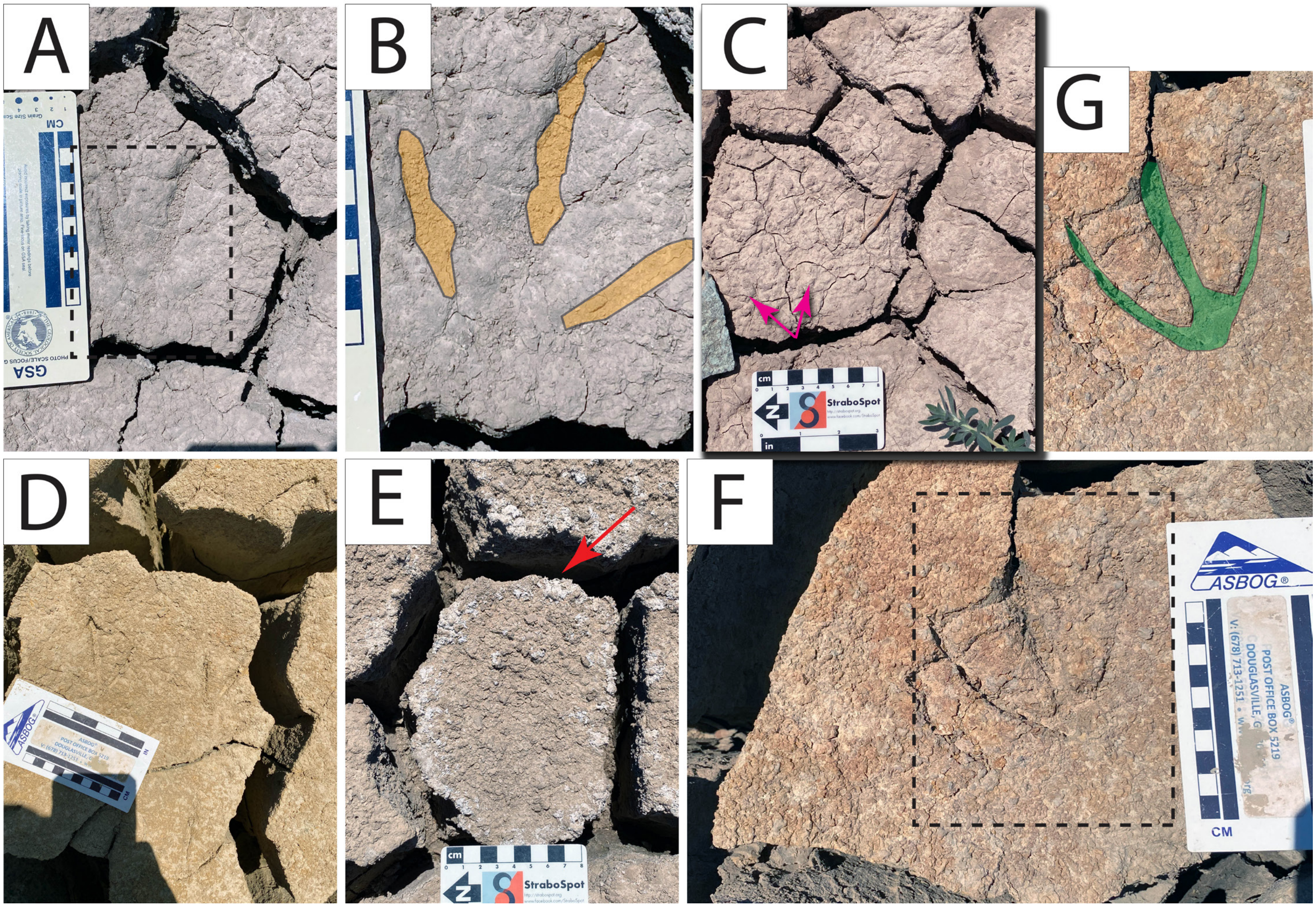


Figure 5. Field photographs of pustular MISS. (A) Pustular MISS with Canada goose track. (B) Enlargement and delineation by orange shading of track in A. (C) Pustular MISS. Note the size of the pustules highlighted by arrows. (D) Multiple Canada goose tracks on pustular mat. (E) Pustular MISS. Note the subcentimeter size of the pustules and white gypsum (arrow). (F) Pustular MISS cross cut by goose track. (G) Enlargement and delineation by green shading of Canada goose track in F. Use scale bar in F. Note the destruction of pustules in the track.

(compare figure 12 with figure 8). The blister mat fragments that originally overhung the desiccation cracks were absent (figure 12).

In blister mat samples, three groupings of microfossils were observed under the FESEM: rods capsules, flat fibers, and diatoms (figure 13). Capsule dimensions are approximately 300 mm in length with widths of 75 mm. Capsules are clustered and commonly tightly packed with long axes nearly perpendicular to the sediment surface forming a palisade-like arrangement. Some capsules have up to four, node-like features (figure 13A). Rods are encrusted with sediment (figure 13B). Flat filaments and diatoms are noticeably less common than in the pustular MISS (compare figures 7A and 7B to figure 13G). Filaments are twisted and entangled around silt and clay particles (figure 13C). Filament lengths vary up 20 mm with widths of approximately 0.5 mm (figure 13C). Diatoms are fragmented with long axes of fragments in the 2 to 15 mm range.

Vertebrate tracks are preserved in the blister MISS that include a human shoe print trackway, coyote (*Canis latrans*) tracks and trackways, and Canada goose prints (figures 14A and 14B). All trackways are linear and cross-cut the blister mat. Within individual tracks, the mat texture is destroyed and in some the track tops are covered with fractured pieces of MISS indicating

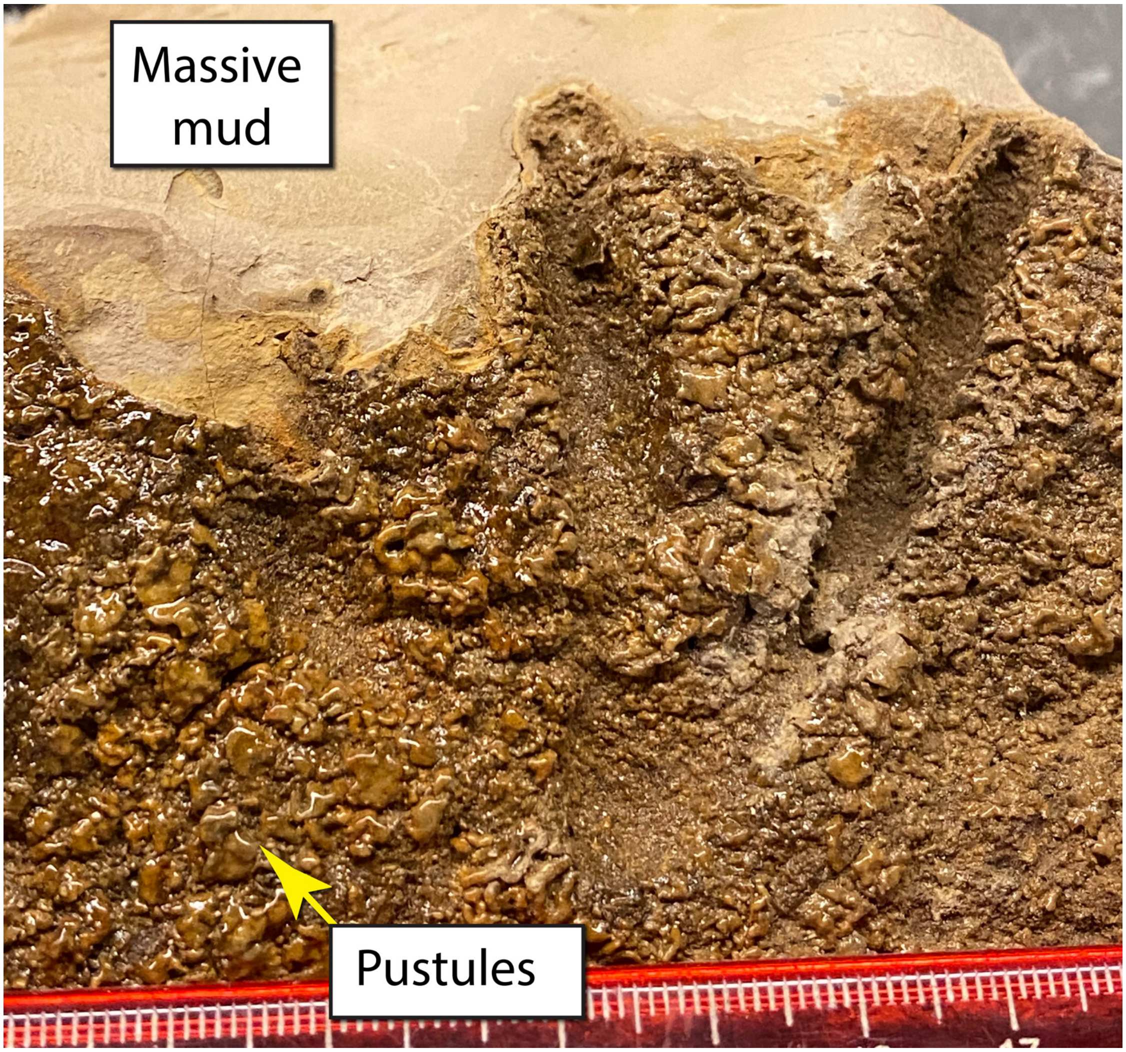


Figure 6. Photograph of preserved Canada goose track preserved in pustular mat. The upper surface is treated with polyurethane (shiny coating on surface) applied in order to facilitate sample extraction. The polyurethane shrank the pustules. Note the massive mud below the track. Scale bar in mm.

brittle deformation of the blister MISS surface. In August 2021 fragments on the mat surface and in tracks continued to be reduced in size. All tracks on the blister mat are impressed in the underlying sediment, indicating the pliable character of the underlying sediment when tracks were imprinted as opposed to the brittle nature of the mats.

INTERPRETATION OF PUSTULAR AND BLISTER MISS

Preservation of filamentous bacteria intertwined with sediment is consistent with a MISS attribution for both the pustular and blister structures (Chafetz and Buczynski, 1992; Noffke 1999, 2009, 2010; Noffke and others, 2001, 2002, 2006; Noffke and Chafetz, 2012).

Cyanobacteria, palisade *Bacillus*, and diatoms are a characteristic freshwater assemblage that can be found inhabiting the photic zones of lacustrine settings (Cohen, 2003). Rods are best interpreted as *Bacillus*-type bacterium that form palisades – large structureless masses identified on FESEM images and are best interpreted as extrapolymeric substance (EPS) biopolymers secreted by microorganisms. Bacterial EPS interactions with clay minerals can develop large structureless features that can be on the scale of 10s of mm to mm

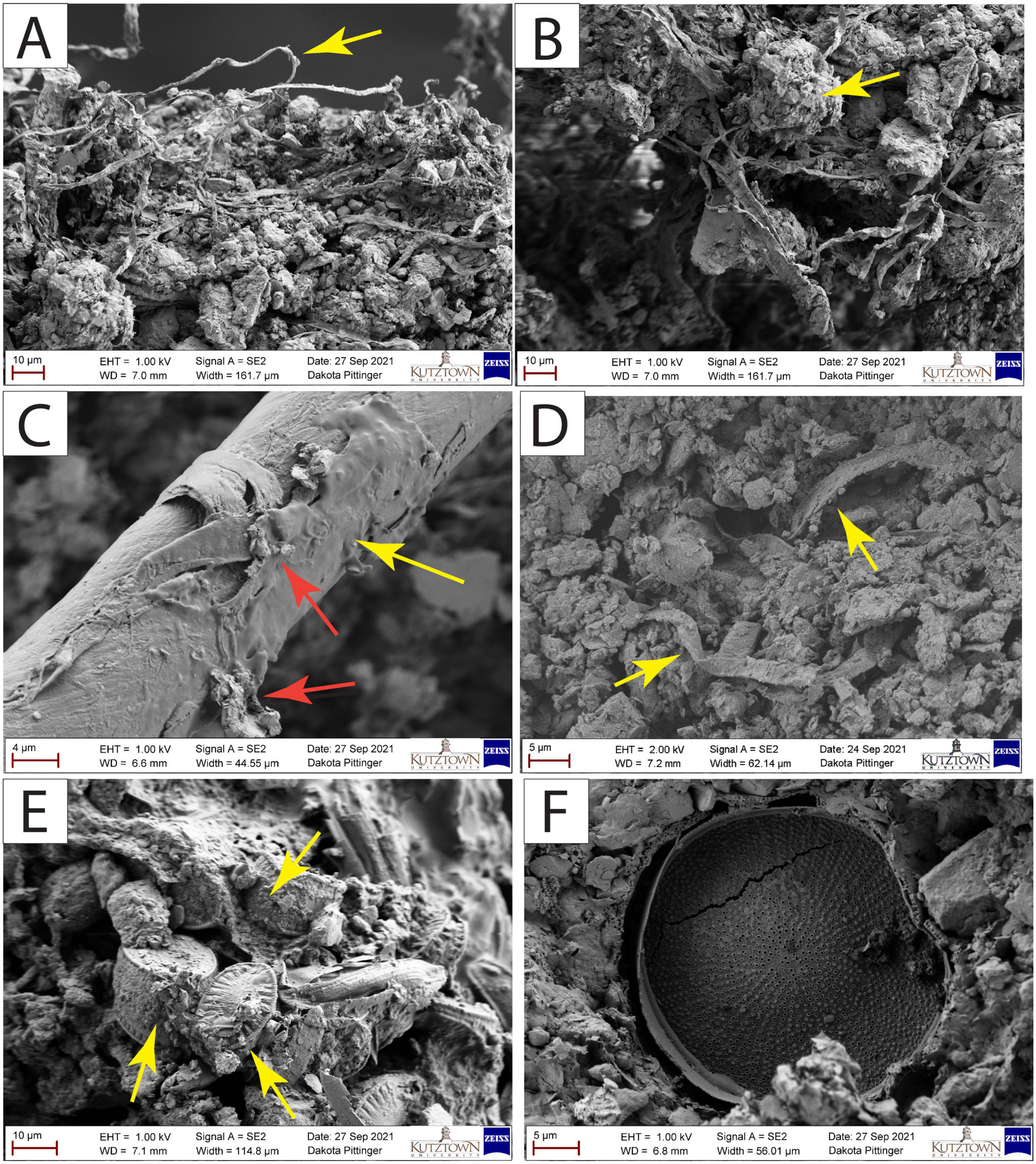


Figure 7. FESEM images of untreated pustular MISS specimens. Scale bars are at left of the bottom data bar for each image. (A) Flat microbial fibers interlaced with silt- and clay-sized particles. Note the twisting of fibers and attached particles (arrow). (B) Twisted flat microbial fibers interlaced with clay agglomerates (arrow). (C) Microbial sheath with extrapolymeric substance (EPS) highlighted with yellow arrow. Note the adhering clay particles highlighted with red arrows. (D) Flat twisted microbial fibers with adhering clay particles (arrows). (E) Cylindric diatoms (arrows). (F) Cylindrical diatom.

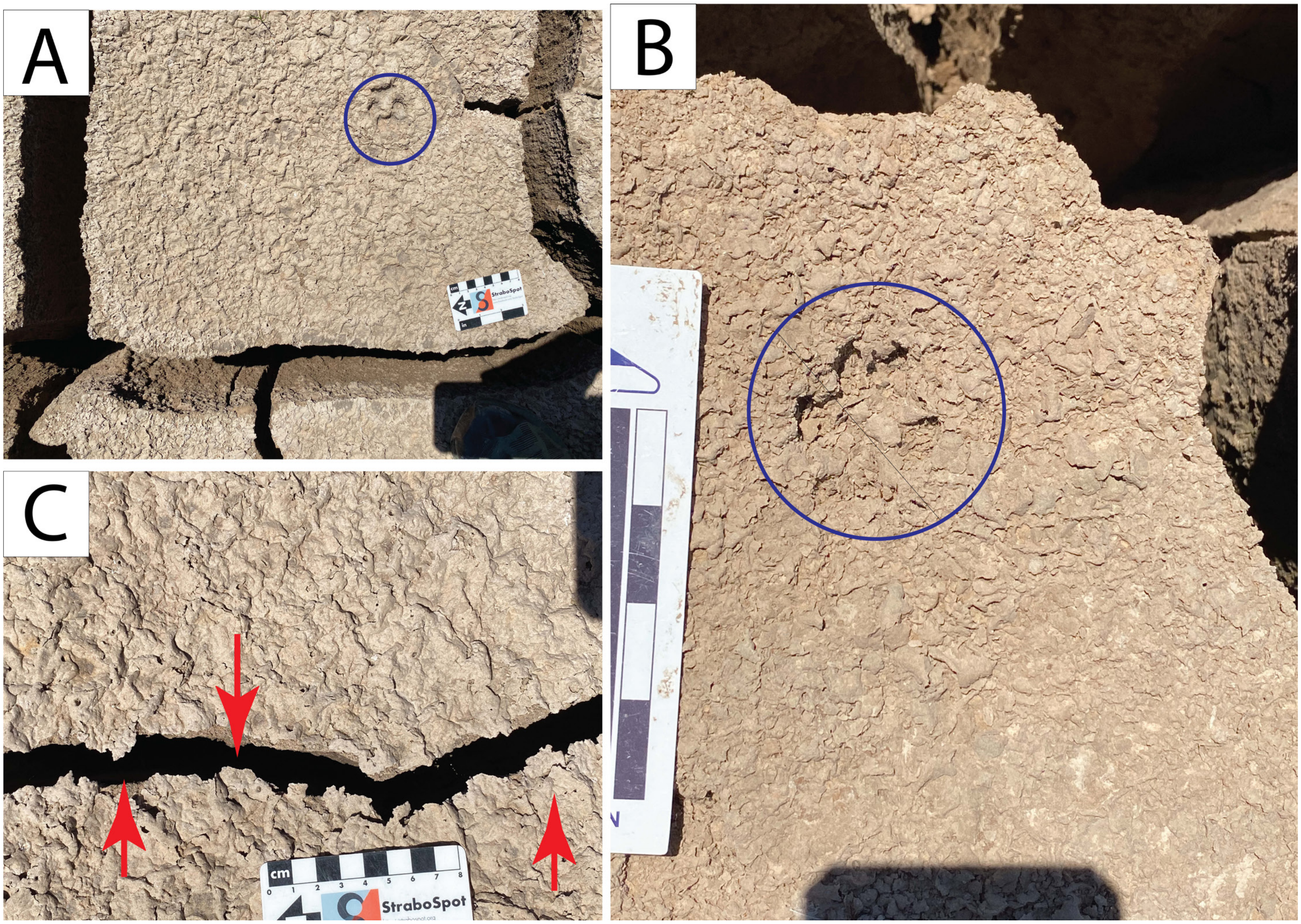


Figure 8. Field photographs of blister MISS. (A) Blister MISS with a coyote track within circle. Scale bar in cm (top) and inches. (B) Blister MISS with coyote track (circled). Scale bar in inches. (C) Blister MISS. Note the crust overhanging the desiccation crack and their adjacent symmetry across the cracks and breaching of crusts over voids highlighted by arrows. Scale bar in cm.

(Alimova and others, 2006). Greater abundance of cyanobacteria in the pustular mats to that of the blister appears to be primarily ecological and may be related to light penetration of the sediment-rich water (Nofke, 2010). Diatoms are more abundant in the pustular MISS also supports ecological partitioning in the microbial mats based on light penetration. Finer pustules in the impressed tracks indicate MISS recovery after imprinting. Upward arching of the sediment surface of the blisters may be the result of gas generation, probably oxygen or decay products by the bacteria being trapped under the less porous microbial mat. Oxygen buildup caused separation of the mat from the sediment surface. This mat-sediment surface separation process is commonplace in modern ephemeral ponds characterized by filamentous bacteria (Simpson and Simpson, 2014). The upward arching permits *Bacillus*-type bacteria to reproduce and grow in the open space, generating the palisade structure, a morphology associated with reproduction.

Adhesion structures produced by saltating sand grains sticking to a sediment surface that is water saturated by capillary action are crudely similar to pustular MISS and can occupy similar marine- or lacustrine-shoreline settings (Hunter, 1973; Kocurek and Fielder, 1982; Dott and others, 1986; Olsen and others, 1989; Koster and others, 1993). However, adhesion ripples are sand deposits. Sand-size grains are absent

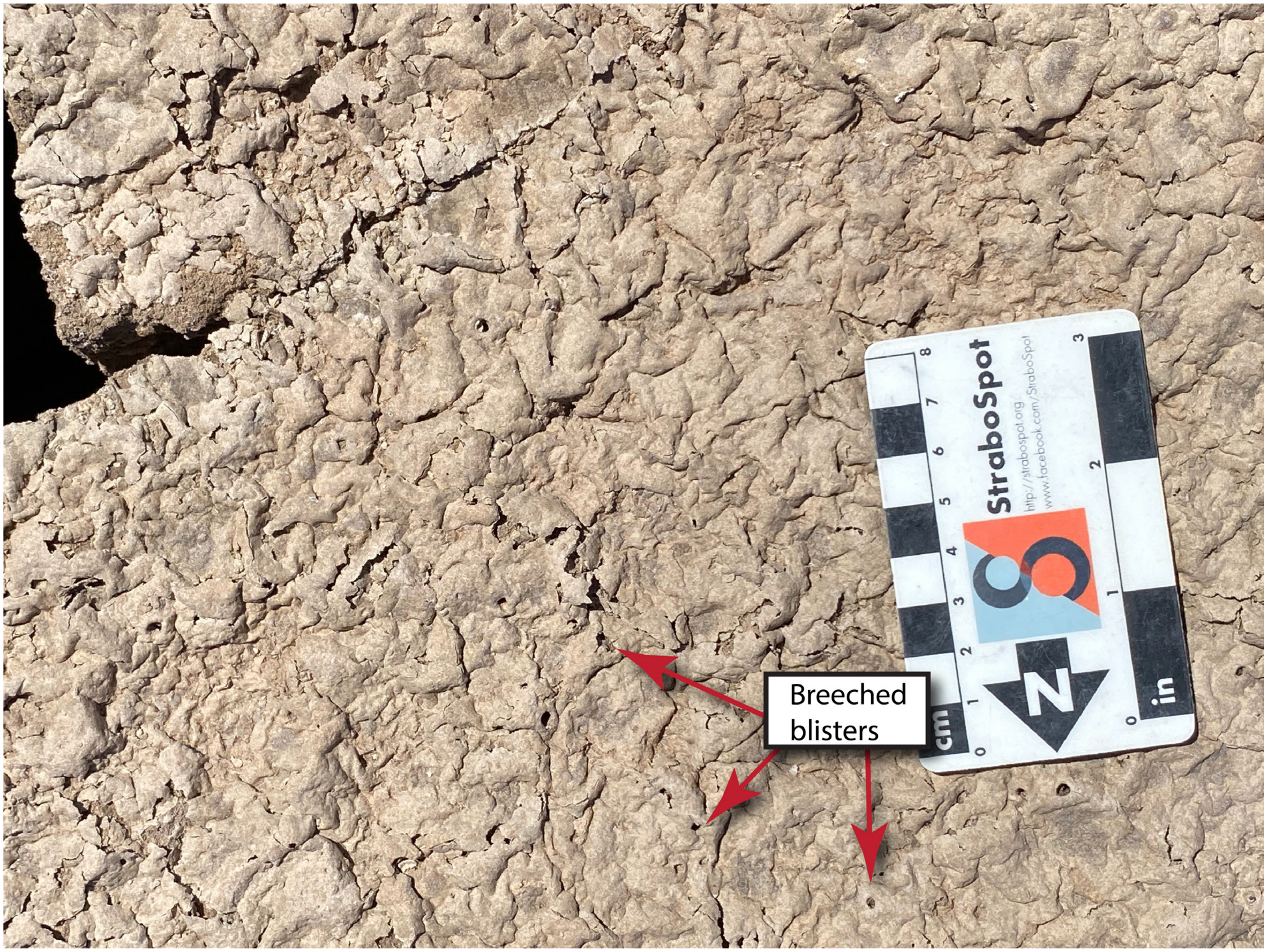


Figure 9. Field photograph of a close-up view of blister surface. Breeches of blister arches are highlighted by arrows.

from the mats. In addition, adhesion structures have a distinctive asymmetrical cross section with internal low-angle pseudo-cross laminations and therefore should not be confused with pustular MISS (Hunter, 1973; Kocurek and Fielder, 1982; Davies and others, 2016). Pustular MISS has been recognized throughout the rock record (Prave, 2002; Bottjer and Hagadorn, 2007; Schieber, 2007; Sheldon, 2012; Zhong-Wu and others, 2013; Kumar and Ahmad, 2014; Wilmeth and others, 2014). Simpson and others (2022) named pustular MISS as a trace fossil ichnospecies *Pustularichnus rebeccahuntfosteri* with the holotype at the Early Cretaceous Mill Canyon Dinosaur Tracksite north of Moab, Utah, USA, where 10 distinctive vertebrate track types are recognized (Lockley and others, 2014a, 2014b).

In contrast to pustular MISS, recognition of blister MISS may be problematic in the rock record as evidenced by the blister destruction documented on the Lake Powell surface supporting their low probability of preservation. A possible equivalent example is termed “cyanobacteria-laden salt ridges” in modern interdune deposits in evaporitic settings (Fryberger and others, 1983, 1988; Simpson, 1983; Simpson and Loope, 1985). These cm-scale modern salt ridges have efflorescent crusts that are separated from the underlying sediment surface with cyanobacteria rimming the arch, gypsum or other types of evaporites present, and limited breeching of the crestline (Fryberger and others, 1983, 1988;

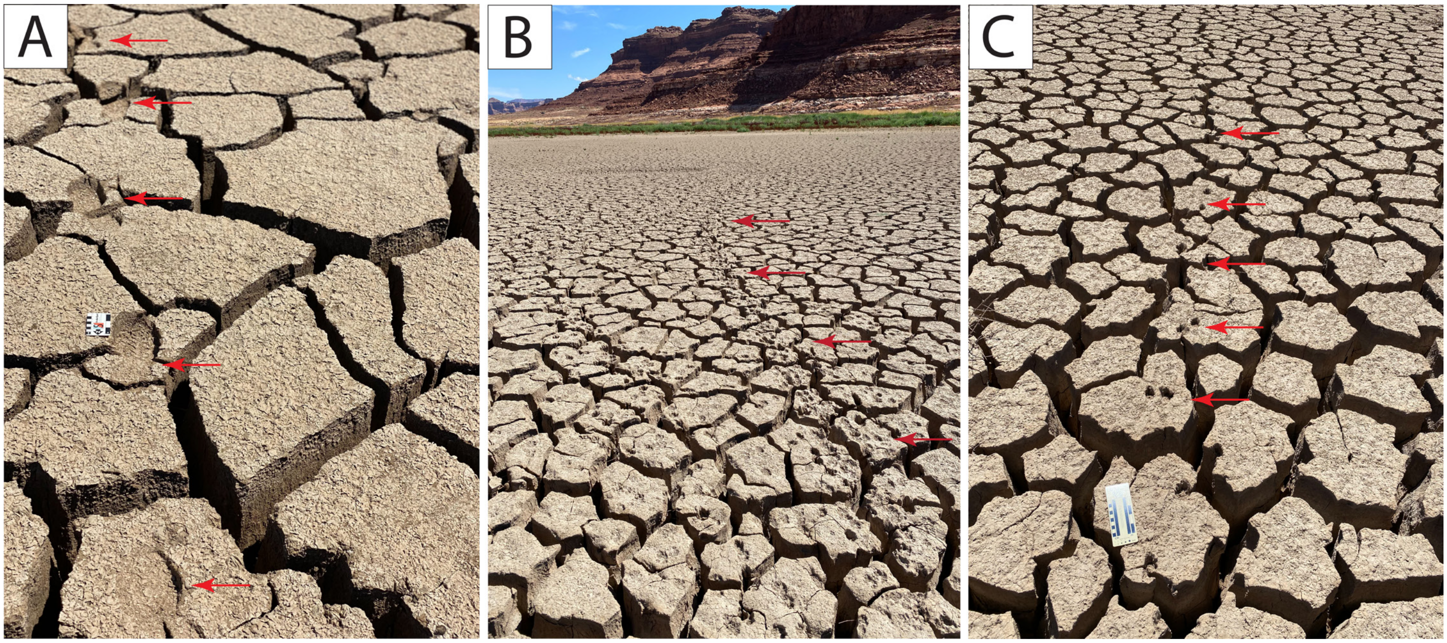


Figure 10. Trackways on blister MISS. Large units on scale bar are in inches. (A) Blister mat with human shoe print trackway (arrows). (B) Multiple superimposed coyote trackways (arrows) across the blistered MISS surface. (C) Isolated coyote trackway (arrows).

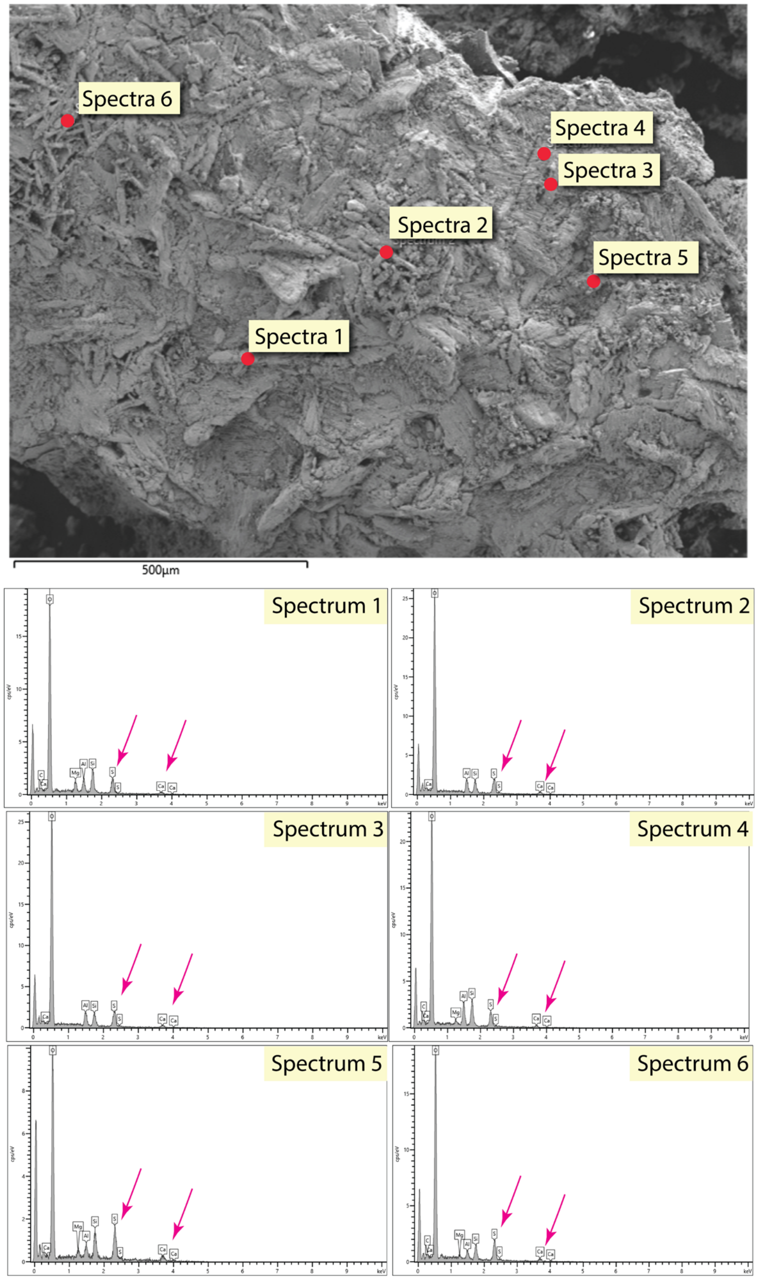
Simpson, 1983; Simpson and Loope, 1985). Differences between the modern salt ridges and the blister MISS include (1) linear ridge morphology with evaporitic interdunal areas for salt ridges versus the nonlinearity shape to the blisters on Lake Powell, and (2) erosion resistance in interdunes versus erosion prone structures on Lake Powell. Simpson (1983) recognized flame-like features in excavated interdune deposits of White Sands National Park, New Mexico. These features were attributed to the burial of salt ridges indicating that longer-term preservation of open structures could mimic flame structures and suggests how the fragile blister MISS may look like if buried before destruction.

Lockley and Rodríquez-de la Rosa (2009) recognized the role of wetting and drying, dissolution, capillary evapotranspiration, and wind deflation in the preservation of human tracks. The destruction of the blister-mat features at Lake Powell is interpreted as prolonged desiccation of the microbial mats inducing reduction in thickness by water loss. The thinning and loss of filament flexibility causes the blister structure to undergo tension on the outer surface leading to crest failure. Once breeched, wind-induced turbulence rapidly enhances arch breakup. Wind destruction of MISS in relation to topography has been documented on tidal flats (Bouougri and Porada, 2012) and ancient tidal flats (Noffke and others, 2019). Our observations on the delta surface indicate these newly formed fragments are mobilized by wind and gradually infill the desiccation cracks leveling the deflation surface. Destruction by wind action of the pustular mat is limited because the interior is filled with sediment as opposed to the void-like nature of blister mats.

DISCUSSION

Tracks in the rock record are more commonly found associated the fine-grained sediments, suggesting that fine-grained sediments provide better footprint preservation. Detailed study of tracks developed in coarser-grained sediment is in its infancy (Carvalho, 2004; Fillmore and others, 2012, 2017; Szewcy and others, 2020). MISS types and associated tracks along the Hite delta shoreline were developed in water-laden fine-grained sediment and indicate a short timeframe where conditions were amenable to track generation and preservation.

In recent sediments, footprint morphology can be



Spectrum Label	Spectrum 1	Spectrum 2	Spectrum 3	Spectrum 4	Spectrum 5	Spectrum 6
C	2.24			1.89		1.22
O	50.67	45.96	44.63	48.65	45.19	48.57
Mg	3.05			0.88	1.09	0.65
Al	4.20	5.25		6.76	2.20	2.48
Si	10.42	6.22		9.43	6.25	6.32
S	13.98	15.68	20.53	12.17	15.78	17.51
Ca	15.45	26.89	34.84	20.23	29.49	23.24
Total	100.00	100.00	100.00	100.00	100.00	100.00

Statistics	C	O	Mg	Al	Si	S	Ca
Max	2.24	50.67	3.05	6.76	10.42	20.53	34.84
Min	1.22	44.63	0.65	2.20	6.22	12.17	15.45
Average		47.28				15.94	25.02
Standard Deviation		2.37				2.89	6.89

Figure 11. EDS spectral analysis of gypsum found in the blister MISS. The six spectral graph locations are shown on the electron image at the top. Note the presence of Ca and S, indicating gypsum. Table results are in weight percent.

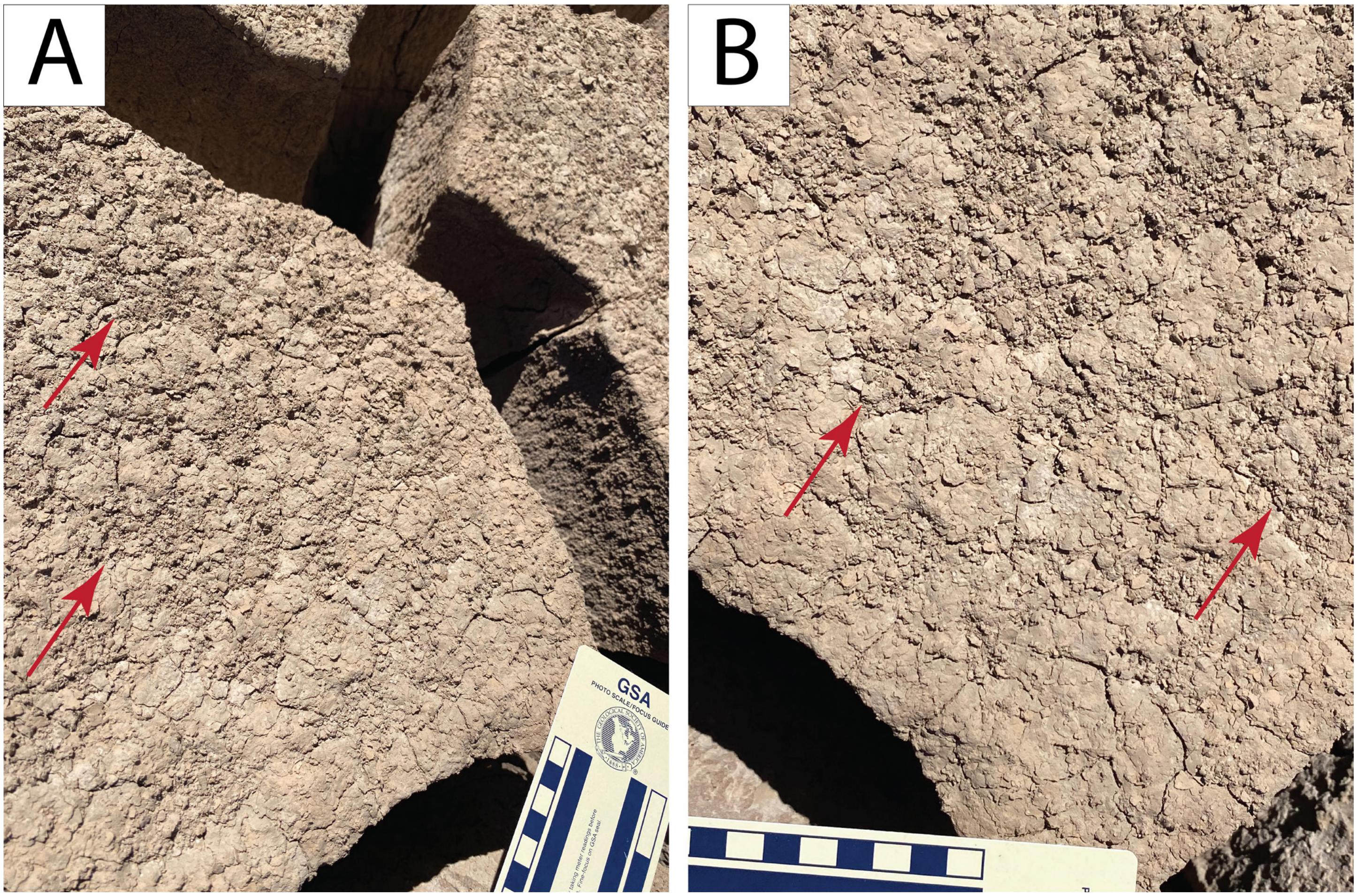


Figure 12. August 2021 field photographs of blister mats after partial destruction. A and B Eroded blistered MISS. Note the sediment “small flakes” of earlier blister structures (arrows) and the absence of crust overhanging the mud cracks. Scale bar in cm.

related the microbial mat thickness and water content of the mat and underlying sediment (Marty and others, 2009). Microbial mats are generally only produced during wet conditions, restricting the timeframe during which footprints are registered/preserved (Marty and others, 2009). Generally, poorly defined footprints or no footprints at all form on dry mats, whereas imprints are sharp in water-saturated mats, and may have associated well-defined displacement rims (Marty and others, 2009). In addition, Cuadrado and others (2011) noted that examining recent tidal flats over a period of time, dried mats only have tracks that were poorly preserved or significantly modified to be unrecognizable. Microbial mats can form a low-permeability layer, which separates the sediment beneath from the atmosphere insulating against water loss; as a result, the sediment below is wet or moist and not necessarily as dry as the overlying mat (Porada and others, 2007).

These observations permit the interpretation of mat and sediment conditions at the time of track imprinting at Lake Powell. Pustular MISS were imprinted with tracks and enough time passed to allow the mat to recover but the underlying sediment remained plastically deformed and hence did not recover to its original shape. In the blister MISS area well-preserved tracks display both a destroyed mat texture and mat fragments resting in the track indicating two different sets of physical conditions for the track generation. Coyote tracks and trackways were generated when both the mat and underlying sediment where wet or moist, allowing for plastic deformation of both the mat and sediment. The human tracks were made during a time period when the blister MISS was dry enough to fracture under the foot pressure and sediment was moist enough to plas-

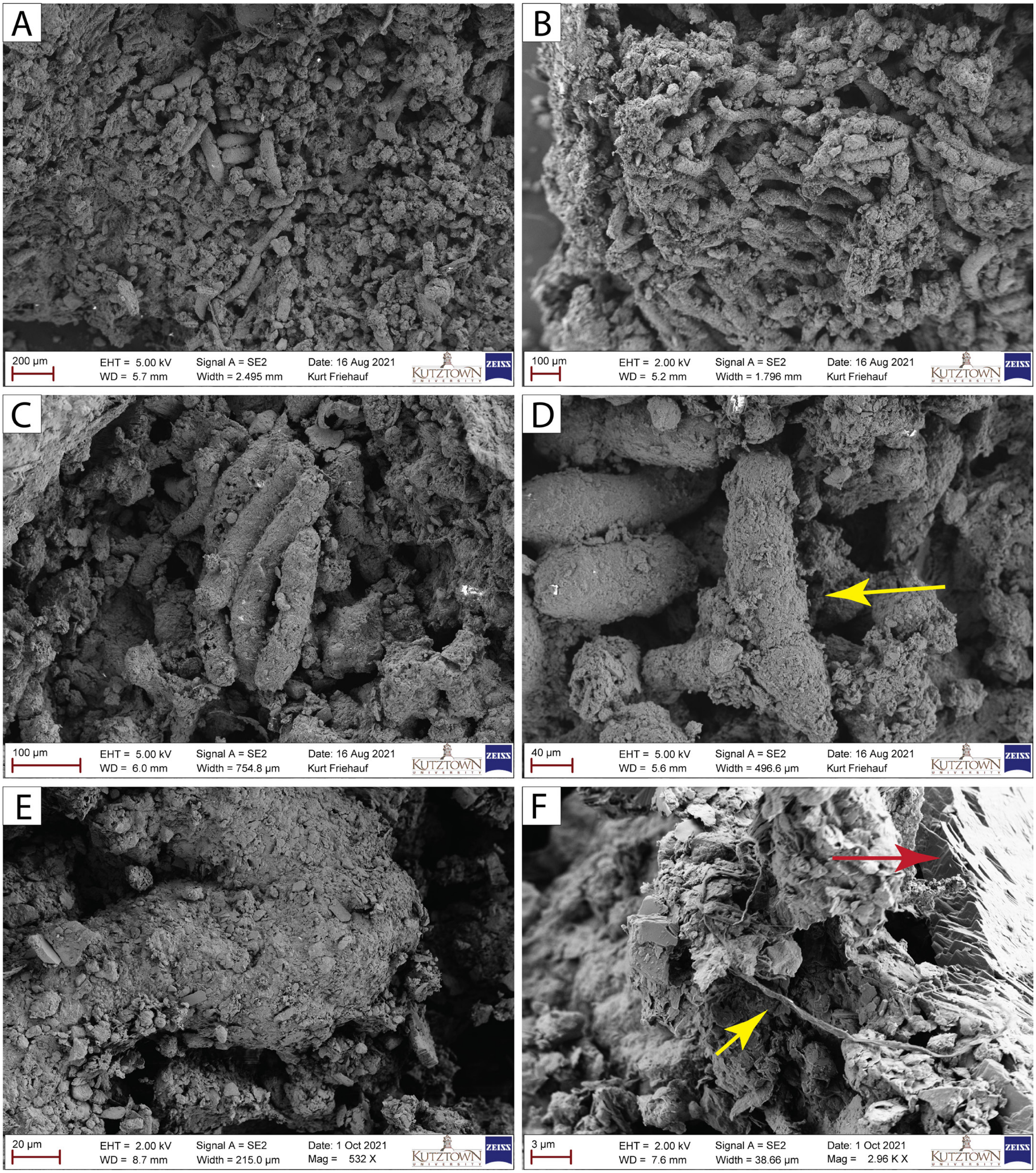


Figure 13. FESEM images of microbes in blister mats. Scale bars are at the left of the bottom data bar for each image. (A) Clustered ovate capsules on the underside of sediment crust. (B) Cross section through blister MISS. Note fine silt and clays attached to the outer surface. Upper surface is to the left. (C) Close-up of aligned capsules in clusters. Note parallel alignment. (D) Capsule with four node-like features (arrow). (E) Enlargement of capsule. (F) Flat fibers (yellow arrow) with gypsum evaporite in the background (red arrow).

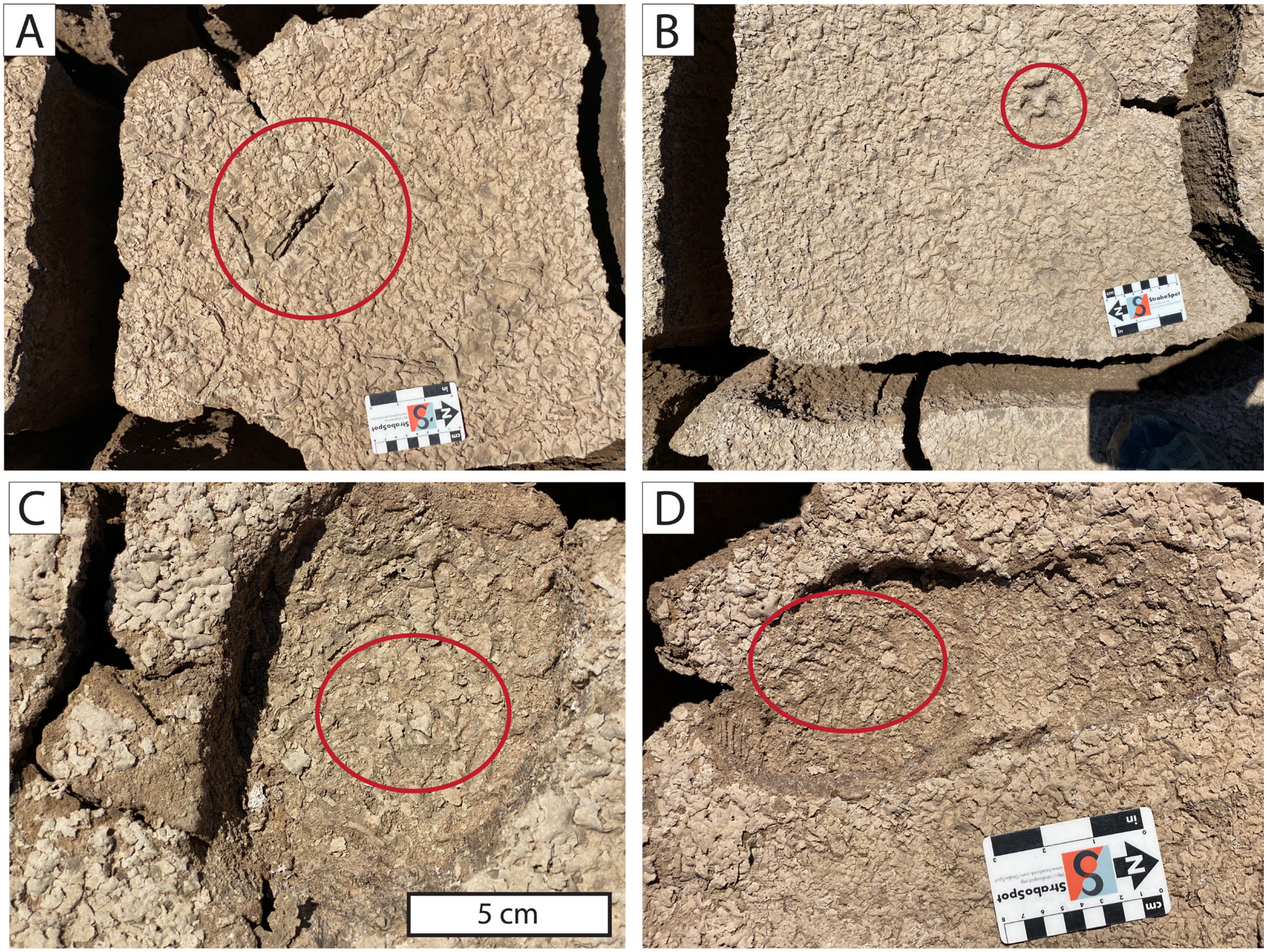


Figure 14. Field photographs of tracks in the blister MISS. (A) Weakly impressed Canada goose track (circle). (B) Isolated coyote track. Note the absence of broken fragments and similar coloration as to the associated mat (circle). (C) Human boot print. Note the fractured pieces of mat in the track (circle) and the well preserved tread lugs. Compare this style of preservation with that of B, brittle versus ductile behavior of mat deformation. (D) Human boot print with brittle fragments in the track (circle). Scales is in inches and centimeters.

tically deform. Since these blister mats are subjected to extensive destruction by desiccation and wind erosion, they may not be recognizable as a mechanism that enhances track preservation in the rock record.

These MISS and sediment deformation observations and inferred conditions indicate that the Lake Powell track types had a limited window for the development of the well-preserved tracks centered around the June–August 2020 time period, as water level peaked and dropped enough and dried after in the arid setting. Pustular MISS tracks formed near the high-water setting, with temporally equivalent blister MISS submerged. The blister MISS exposure was followed “quickly” by transverse track formation. Vertebrates that traversed the depression area out of the “track production window” of approximately two months, were not recorded in sediment or mat modification. In addition, the high-yield strength of the mat and underlying sediment may not have permitted the development of tracks from smaller fauna biasing the record towards larger fauna (Lockley and Hunt, 1995; Noffke and others, 2019)

Thulborn (1990) showed that footprints are most commonly preserved in depositional settings in which cyclic accumulation of sediments takes place. Rapid covering of tracks of sediment and overgrowth by microbial mats are significant factors increasing the potential preservation of footprints (Marty and others, 2009). Lacustrine sediments are sensitive indicators of variations in precipitation and snow pack in the source area on a yearly cycle (Barnett and others, 2005; Sadro and others, 2018). Lake Powell shoreline deposits are subjected to these types of annual lake-level fluctuations (figure 3), which would enhance the likelihood of track preservation.

SUMMARY

The Lake Powell deltaic shoreline at Hite is a natural laboratory to unravel the development of MISS and their controls on vertebrate track preservation. Two types of MISS were present, pustular and blister. Pustular MISS are restricted to the high-water line of the ponded area. FESEM examination identified preserved cyanobacteria interleaved with very fine silt and clay-size grains and freshwater diatoms. Canada goose tracks are isolated and as trampled zones. Lower elevations are characterized by blister MISS and are constructed of arching mats that separated from the underlying sediment by an open pore space. Ultimately over time, the blister mat arches are razed by desiccation and wind processes. FESEM and EDS indicate the presence of filamentous cyanobacteria, palisade *Bacillus*, and gypsum crystals on the mat arch of the blister. Vertebrate tracks in the blister mats consist of human and coyote trackways that traverse the blister mats area in contrast to the tracks restricted to the pustular mat zone, which circle the edge of the water indicating shoreline hunting or drinking behavior. Tracks in pustular MISS destroyed the original mat and subsequently the mat recovered with a smaller pustular texture development, implying the mats were moist when impressed. Tracks linked to the blister mat consisted of two different impression types: (1) destroyed mat texture with plastically deformed sediment, and (2) fragmented mat on top of the plastically deformed sediment in the true track. These vertebrate track types had a limited development window, centered on the two-month, high-water lake level followed by track formation in the lower elevations. Any vertebrates that traversed the area out of the “track preservation window” were not recorded in sediment deformation or mat modification as numerous generations of scat preserved on the sediment surface. Even during the optimal time period, smaller fauna cannot exert enough vertical pressure to affect the mat or the underlying sediment. Annual variation in precipitation inducing lake-level change will increase the preservation potential of the lake margin track systems.

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