CONTROLS ON THE OCCURRENCE OF VERTEBRATE TRACKS IN THE JURASSIC GYPSUM SPRING AND SUNDANCE FORMATIONS, BIGHORN BASIN, U.S.A.

by

ELLIOT JULIAN HATTARKI BLAKE

(Under the Direction of Steven M. Holland and Sally Walker)

ABSTRACT

The Jurassic Gypsum Spring and Sundance Formations of the Bighorn Basin host several vertebrate trackways. Sequence-stratigraphic studies indicate several other potential trackway horizons in coastal facies. In June–July 2021, I tested for the presence of new trackways in these units. I discovered 5 trackways containing 318 vertebrate tracks along horizons hypothesized to harbor tracks. Two trackways with 149 tracks from swimming reptiles were found in the Gypsum Spring Formation. Three trackways with 169 tridactyl prints were discovered in the Canyon Springs Formation near the Red Gulch Dinosaur Tracksite (RGDT). One unidentified track was observed in the Windy Hill Sandstone at Sykes Mountain. Considering the distance searched, I expected to find more trackways. New tracks appear to have been made by vertebrates previously known from the Gypsum Spring and Sundance Formations. Given the diversity of the overlying Morrison Formation, it is surprising that a greater trackway diversity was not found.

INDEX WORDS: Gypsum Spring Formation, Sundance Formation, Jurassic, trackways

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DEDICATION

This thesis is dedicated to my friends and family, for their constant support and to my late father who has been my role model since day one.

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CHAPTER 1

INTRODUCTION

Chapter 1 and Chapter 3 of this thesis provide introductory and concluding remarks about the research project. The first chapter includes a brief background that supplies context for this study, and the third chapter discusses ideas for future work. Chapter 2 is formatted as a separate, individual manuscript with its own introduction, methods, results, discussion, and conclusions.

Vertebrate fossil and trace preservation provides information on the Earth's past ecosystems (Philips et al. 2007). Moreover, interpretation of traces also provides information about an organism that is often unavailable from preserved skeletal remains (Philips et al. 2007). Vertebrate tracks, specifically, tend to be relatively abundant in the Mesozoic strata of the western United States, and many are only recently being extensively documented (Kvale et al. 2004; Jennings et al. 2006; Connely 2006; Foster 2007; Clark and Brett-Surman 2008; Adams et al. 2014).

In the Bighorn Basin of north–central Wyoming specifically, Mid-Jurassic trackways within the Gypsum Spring and Sundance Formations are well-known (Kvale et al. 2001, 2004; Adams et al. 2014). These trackways are estimated to be between 170 and 167 million years old, and they preserve traces of swimming terrestrial reptiles and bipedal dinosaurs (Kvale et al. 2004). It is speculated that many more thousands of tracks exist in this region but are still covered by sediment (Kvale et al. 2001, 2004).

The first purpose of this study is to test for the occurrence of undocumented trackways within tidal-flat, eolianite, and other coastal facies of the Jurassic Gypsum Spring and Sundance Formations. Recent sequence-stratigraphic studies have indicated the presence of numerous tidal-flat horizons and other coastal facies in the Gypsum Spring and Sundance Formations, as well as the geographic distribution of these facies (McMullen et al. 2014; Danise and Holland 2018; Holland and Wright 2020). Currently trackways are known from a small fraction of these exposures. This suggests that many more undiscovered tracks may be present in coastal deposits of the Gypsum Spring and Sundance Formations.

The second purpose is to test whether new trackways host a greater diversity of vertebrate taxa in coastal deposits of the Gypsum Spring and Sundance Formation than previously reported. The older Kayenta Formation and the overlying Morrison Formation are host to an impressive number of vertebrate body and trace fossils, but there is a ~26 m.y. gap between these without any body fossils. By identifying new taxa previously unreported in the Gypsum Spring and Sundance, this study will contribute to a better understanding of the paleoecology of Jurassic coasts and the potential behaviors of coastal-dwelling organisms.

CHAPTER 2

CONTROLS ON THE OCCURRENCE OF VERTEBRATE TRACKS IN THE JURASSIC GYPSUM SPRING AND SUNDANCE FORMATIONS, BIGHORN BASIN, U.S.A.[1]

[1] Controls on the Occurrence of Vertebrate Tracks in the Jurassic Gypsum Spring and Sundance Formations, Bighorn Basin, U.S.A., E. Blake. To be submitted to *Palaios*.

ABSTRACT

The Jurassic Gypsum Spring and Sundance Formations of the Bighorn Basin of north central Wyoming host several well-studied vertebrate trackways. Sequence-stratigraphic studies indicate the presence of several other potential trackway horizons in coastal facies. In June–July 2021, I tested for the presence of new trackways in these units. I discovered 5 trackway localities containing 318 vertebrate tracks, all at horizons hypothesized to harbor potential tracks. Two trackways with 149 tracks from swimming terrestrial reptiles were found in the middle limestone-rich member of the Gypsum Spring Formation. Three trackways with 169 narrow-toed tridactyl prints were discovered in the Canyon Springs Formation near the Red Gulch Dinosaur Tracksite (RGDT) and Yellow Brick Road Dinosaur Tracksite (YBRDT). Finally, one unidentified wide-toed track was observed in a float block from the uppermost Windy Hill Sandstone at Sykes Mountain. Considering the distance searched, I expected to find more trackways. All new tracks appear to have been made by vertebrate taxa previously identified at other trackways in the Gypsum Spring and Sundance Formations. Given the diversity of the overlying Morrison Formation, it is surprising that a greater trackway diversity was not found.

INTRODUCTION

Preserving individual tracks or more extensive trackways is typically uncommon because of rapid degradation from erosion and deformation (McKee 1947; McKeever 1991; Philips et al. 2007). Bioturbation and burial deformation are both known to disturb tracks made in sediment, or even destroy them entirely (McKeever 1991). However, numerous well-documented trackways have been observed throughout the Mesozoic, and they are preserved by a wide range of mechanisms (Stokes and Madsen 1979; Kvale et al. 2004; Connely 2006; Jennings et al. 2006; Lockley and Foster 2006; Philips et al. 2007; Clark and Brett-Surman 2008; de Souza Carvalho et al. 2013). This research seeks to clarify the mechanisms that aid in trackway preservation as well as the specific conditions required for lithification.

In this study, I searched for previously unreported vertebrate tracks within tidal-flat, eolianite, and other coastal deposits in the Jurassic Gypsum Spring and Sundance Formations of the Bighorn Basin in north-central Wyoming. These coastal facies are characterized as environments at or near the interface between land and a body of water. Some trackways are already known in these rocks, such as the Red Gulch (RGDT) and Yellow Brick Road Dinosaur Trackways (YBRDT) near Shell, Wyoming and pterosaur prints from Alcova Reservoir and the Bighorn NRA (Logue 1977; Kvale et al. 2001; Adams et al. 2014). The Gypsum Spring and Sundance Formations were once thought to be largely marine, but sequence-stratigraphic studies reveal the existence of previously unrecognized coastal facies (Danise and Holland 2018). Although the previously documented trackways are all from coastal facies, most coastal deposits remain unexplored for trackways. This suggests that potentially many trackways in the Gypsum Spring and Sundance are yet to be found.

This study also examines whether trackways in these units are preserved in association with microbial mats. Four of the six previous studies of trackways reported from these units preserve evidence of microbial stabilization (Kvale et al. 2001, 2004; Adams et al. 2014). Studies in other parts of the geologic record also report microbial mat preservation of trackways in coastal deposits (Marty et al. 2009; de Souza Carvalho et al. 2013; Dai et al. 2015; Noffke et al. 2019). This suggests that microbial mats may be generally important for trackway preservation in the Gypsum Spring and Sundance Formations.

BACKGROUND

Geologic Setting

The Sundance Seaway formed in an elongated, retro-arc foreland basin in western North America, and the seaway had an opening to the Pacific Ocean near the Yukon-Alaska border. The Cordilleran volcanic arc and a fold and thrust belt bounded the seaway to the west, and the North American craton bounded it to the east (Blakey 2014; Fig. 1). Terrestrial and coastal alluvial plain deposits from the seaway record Jurassic basin subsidence, paleogeography, and paleoclimate (DeCelles 2004; Danise and Holland 2018).

In the Bighorn Basin study area, facies were deposited along a ramp with a gentle depositional dip to the north–northwest. Paleogeographic reconstructions place Wyoming at 35° to 40°N during the Middle Jurassic (Blakey 2013; McMullen et al. 2014; Fig. 1). The northward drift of North America through the Middle Jurassic led Wyoming and other surrounding areas to shift from a subtropical arid belt into more humid climates (Boucot et al. 2013; Danise and

Holland 2017). Coastal deposits are present in siliciclastic, carbonate, and evaporite systems and they were deposited in the Middle to Upper Jurassic (Bajocian to Oxfordian; ~170–155 m.y.).

Stratigraphy

This study focuses on the Gypsum Spring and Sundance Formations (Fig. 2). The Gypsum Spring unconformably overlies the Triassic Chugwater Group, and the overlying Sundance Formation is conformably overlain by the Jurassic Morrison Formation, deposited on a fluvial–lacustrine–wetland coastal plain (Danise and Holland 2018; Holland and Wright 2020). Jurassic depositional sequences J-1 to J-4 stem from a regional framework of unconformities used to correlate rocks in the western interior of the United States (Danise and Holland 2018).

The Gypsum Spring was deposited on a mixed evaporite–carbonate–siliciclastic ramp and comprises three informal members (lower, middle, and upper; Clement and Holland 2016; Danise and Holland 2018). The lower member contains thick gypsum with maroon mudstone and was deposited in a siliciclastic desert environment with widely distributed salinas and sabkhas (Fig. 2, 3). The middle member is dominated by shallow marine carbonates and desert mudflats and contains the sole coastal deposits of the Gypsum Spring Formation, specifically tidal-flat facies known to have trackways (Kvale et al. 2001, 2004). The upper member is dominated by maroon mudstone and was deposited in siliciclastic desert mudflats.

The Sundance Formation consists of cyclic shallow-marine siliciclastic mudstone and sandstone, shallow-marine carbonate, and coastal siliciclastic rocks deposited on a northwestward-dipping mixed siliciclastic-carbonate ramp (McMullen et al. 2014; Holland and

Danise 2017). The lowermost member, the Canyon Springs Member, is dominated by carbonate rocks deposited in shallow subtidal, ooid shoal, and peritidal environments (Fig. 2, 3). These peritidal facies contain several dinosaur trackways, such as the Red Gulch Dinosaur Trackway, Flitner Ranch Trackway, and Yellow Brick Road Trackway (Kvale et al. 2001, 2004; Adams et al. 2014). The overlying Stockade Beaver Shale was deposited on the distal portions of the mixed carbonate- siliciclastic shelf (McMullen et al. 2014). Offshore mudstone facies are to the west, whereas offshore transition facies are present eastward. The Hulett Member contains a variety of facies deposited in a carbonate ramp depositional system, including open shallow subtidal, ooid shoal, lagoonal, and eolian facies (McMullen et al. 2014; Danise and Holland 2018). The Redwater Shale is a dominantly mudstone member deposited on a wave-dominated siliciclastic shelf with offshore, shoreface, and shell bed facies. The uppermost member of the Sundance Formation, the Windy Hill Sandstone, was deposited in prograding coastal facies and shares a sharp contact with overlying fine-grained terrestrial deposits of the Morrison Formation (Holland and Wright 2020).

History of previously recorded trackways

Previous studies have documented five vertebrate trackways in the Gypsum Spring and Sundance Formations (Kvale et al. 2001, 2004; Harris and Lacovara 2004; Fig. 2, 4). Because the Sundance had long been considered marine, some of these trackways were encountered accidentally, and subsequent searches revealed additional trackways nearby (Kvale et al. 2001, 2004).

The Gypsum Spring Dinosaur tracksite interval is located in the middle member of the Gypsum Spring Formation, and it occurs near the top of a coarsening-upward cycle (Kvale et al. 2001). The top of the track-bearing bed comprises limestone interbedded with calcareous shale and microbial elephant wrinkles (Kvale et al. 2001, 2004). Tracks at this locality are tridactyl prints of small theropods, and they are preserved in a micritic substrate deposited in a peritidal setting.

The Red Gulch, Yellow Brick Road, and Flitner Ranch Dinosaur tracksites are all located in a mid-Bathonian limestone unit at the top of the Canyon Springs Member of the Sundance Formation. The Red Gulch Dinosaur tracksite preserves thousands of tridactyl prints of small theropods, and it is exposed in a coated-grainstone substrate over a 15 hectare area (Kvale et al. 2001). Thin-section analyses reveal that framework grains in the rippled trackway surface underwent an early rim-cement phase, and carbonate grains were microbially micritized (Kvale et al. 2001, 2004).

The Flitner Ranch Dinosaur tracksite is the least extensive of the three Canyon Springs trackways and is located on privately owned land. This trackway is 600 meters from the Red Gulch dinosaur tracksite, and it preserves tridactyl prints, although the number of tracks has not been reported.

The Yellow Brick Road Dinosaur tracksite preserves more than 600 tridactyl tracks of small bipedal theropods within a 150 square meter area (Adams et al. 2014). Trackways at this site are notably different from those found at Red Gulch, in that they are oriented to the northwest and southeast rather than to the south and southwest. Petrographic analyses suggest a partially lithified and cohesive substrate with plasticity attributed to water saturation, early rim-cement, and microbial stabilization.

Tracks from the uppermost Windy Hill Member have been reported south of the Bighorn Basin at Alcova Reservoir. This site preserves pterosaur trackways and abundant swim tracks of swimming terrestrial reptiles (Logue 1977; Meyers and Breithaupt 2014).

METHODS

During a 6-week field session, I tested whether new vertebrate trackways are present in coastal facies of the Gypsum Spring and Sundance Formations in the Bighorn Basin of Wyoming. Permissions for land use were acquired from the Bureau of Land Management, Bureau of Reclamation, and National Park Service, for searching for potential trackway surfaces on public land, and from private landowners. Large bedding-plane exposures of coastal facies were scouted during midday for more careful investigation during intervals of optimal low-angle light near sunrise and sunset. These exposures were searched for up to several kilometers laterally from initial localities where coastal facies had previously been reported (McMullen et. al 2014; Clement and Holland 2016; Danise and Holland 2018; Holland and Wright 2020; Fig. 1, 2).

During scouting, GPS coordinates were taken approximately every 400 meters. At each new trackway horizon, the location was recorded, and a small hand broom was used to remove loose debris before photography and trackway measurements. The Paleontological Resources Protection Act prevents the public disclosure of coordinates, so they are not reported here, but they have been filed with the Bureau of Land Management. Trackways were described and measured with respect to individual print length, width, depth, pace, pace angle, stride, digit dimensions, and azimuth (Fig. 5). Trackway photographs were taken for developing digital 3D trackway models. Photos were taken when light was most optimal in the morning or evening. Photogrammetric scanning, using the iOS app Scaniverse, was implemented to generate structure-from-motion digital recreations of track morphology.

Where possible, a detailed section covering a 2–5 meter interval spanning a trackway horizon was measured to place the trackway in stratigraphic context. Features such as grain size, color, bedding thickness, sedimentary structures, trace fossils, and microbial features were described.

A 1-kg hand sample from each trackway bed was collected for a thin section to describe the lithology and to aid in recognizing microbially induced sedimentary structures. Samples were taken approximately 2 meters from any track to avoid damage to the tracks. Wherever possible, hand samples were obtained from fractured blocks loosened at the edge of track bearing horizons to avoid using a hammer. Photographs were taken of hand samples to show their location relative to the track.

Trackways were left in place and not damaged in any way. While distilled water was applied with a paint brush to enhance photograph contrast, no marking substances or molding compounds were applied to tracks.

Four areas were searched for potential trackways (Fig. 6). The Red Gulch area was selected due to its proximity with the well-known Red Gulch Dinosaur Tracksite (RGDT) and the Yellow Brick Road Dinosaur Tracksite (YBRDT; Kvale et al. 2001; Adams et al. 2014).

Since these sites are well known to preserve numerous vertebrate tracks, it is reasonable that newly exposed nearby exposures preserve tracks as well. Additionally, preliminary investigations with Google Earth revealed that many limestone exposures spanning that area may have only been recently uncovered. Areas along the eastern flank of Sykes Mountain were also searched for trackways. This site was chosen because of previously reported pterosaur tracks from the Windy Hill Member (Harris and Lacovara 2004). The southern and eastern ends of Sheep Mountain were searched for potential trackways, due to the abundant bedding surfaces in the Canyon Springs Member and the middle member of Gypsum Spring. The eastern end of Sheep Mountain was chosen specifically because of the good exposure of the eolian facies of the Hulett Member. Finally, an area west of Shell, Wyoming referred to as Dirty Annie's (from a local tourist spot, now closed) was investigated for trackways. Exposures in this region are mostly in the Canyon Springs and Windy Hill members, and many potentially track-bearing bedding surfaces were unearthed recently.

RESULTS

Gypsum Spring Formation

Walking surveys covering 34.22 miles were conducted in the middle member of the Gypsum Spring Formation. Two new trackways were reported from this unit at two different study sites. The first trackway is on the upper bedding surface of a limestone near the north end of Sykes Mountain (North Sykes Mountain locality; Fig. 6A, 9A). The second trackway is preserved at the southern end of Sheep Mountain in a similar limestone bedding- plane (South Sheep Mountain locality; Fig. 6B, 9B).

The North Sykes Mountain tracksite preserves dozens of swim tracks, all interpreted to belong to either crocodiles or small–medium bipedal theropods (Kvale et al. 2001; Fig. 7). Stratigraphic measurements from a nearby outcrop show that the trackway is overlain by interbedded lime mudstone, marl, and fossiliferous limestone (Fig. 8A). Based on previous studies of the Gypsum Spring Formation, this trackway formed in a peritidal setting, and it is characterized by vortex ripples (Kvale et al. 2004; Dai et al. 2015; Davies et al. 2016; Fig. 3). Other nearby exposures extending 400 m to the south are of coastal facies suitable for track preservation. Track occurrences are nonetheless limited to this one limestone surface. Thin section analysis reveals that the main trackway surface is composed of a peloidal packstone with interspersed micritized skeletal fragments (Fig. 10A).

Tracks consist of 2–3 shallow parallel grooves approximately 5.0 cm long and are spaced apart by an average distance of 4.2 cm (Fig. 7). Tracks are typically aligned along a SW–NE axis (Fig. 11).

The South Sheep Mountain trackway preserves hundreds of theropod swim tracks, although only 50 were measured from one segment of the trackway (Fig. 7, 12). The track-bearing surface is overlain by additional limestone beds, separated by beds of maroon mudstone, gypsum nodules, and thin layers of gray marl (Fig. 13). Similar to what was observed at the North Sykes Mountain tracksite, the track-bearing surface here is also characterized by vortex ripples, which is consistent with a peritidal setting. Evidence of microbial stabilization was not observed on this trackway. Many nearby exposures reflect facies types potentially capable of preserving tracks, but no tracks were found on these surfaces. This suggests that more tracks may be present but are still buried. Thin sections show that the track-bearing horizon is composed of a peloidal packstone (Fig. 10B).

Swim tracks at South Sheep Mountain are preserved as 2–3 shallow parallel grooves and have an average length of 3.8 cm (Fig. 7). Average distance between parallel grooves is 3.2 cm. As at North Sykes Mountain, track azimuths at South Sheep Mountain reveal a southwest–northeast alignment (Fig. 11).

Canyon Spring Member

Walking surveys covering 23.8 miles were conducted in the Canyon Spring Member (Fig. 6). Three new track sites were discovered near the Red Gulch and Yellow Brick Road track sites (Fig. 6C, 9C). These trackways contain 169 well-preserved tridactyl theropod prints. Tracks at all three sites are similar to those reported at the nearby RGDT and YBRDT, and they are exposed on the same bedding-plane as those sites. Furthermore, similarities in track morphology suggests that the trackmakers were the same small theropods reported from the RGDT and YBRDT (Fig. 14). The Dino Ridge trackway is located along a prominent limestone ridge approximately 350 meters west of the YBRDT. The Rattlesnake Alley trackway is approximately 1200 meters east of the RGDT. The Lonely Tree trackway is located 100 meters east of the YBRDT. Trackways were not discovered along Sheep Mountain, reflecting the northward transition from peritidal facies near the RGDT and YBRDT to shallow subtidal and ooid shoal facies along Sheep Mountain.

The Dino Ridge tracksite extends 300 meters and preserves 83 tridactyl theropod prints (Fig. 14). The trackway is underlain by interbedded limestone and marl, and it is immediately overlain by the Stockade Beaver Shale (Fig. 8B). Based upon previous studies in the area, tracks were most likely developed in a peritidal setting (Kvale et al. 2001, 2004; Adams et al. 2014; Fig. 3). Nearby exposures reflect similar coastal facies; however, no tracks were found at these locations. The composition of the track-bearing surface is primarily a peloidal packstone with small amounts of bivalve fragments and micritized ooids (Fig. 10C).

Tracks at Dino Ridge consistently preserve three distinct toes, and tracks are in some cases overprinted by additional tracks (Fig. 14, 16). Mean track length is 13.22 cm (Fig. 15). Track azimuths indicate travel to the south and to a lesser degree, to the north (Fig. 11).

The Rattlesnake Alley trackway preserves 27 tridactyl theropod prints, which are distributed over 100 meters of exposure. A stratigraphic section extending 2 m below the main track surface contains beds of rippled lime mudstone interbedded with thin layers of marl (Fig. 8C). Vortex ripples are preserved at the top of the track-bearing surface, consistent with deposition in a peritidal setting. The trackway surface is immediately overlain by the Stockade Beaver Shale. The trackway substrate is composed of a skeletal ooid-peloid grainstone with minor amounts of shell fragments and a high degree of micritization (Fig. 10D). The presence of non-spherical ooids suggest that the track-bearing substrate was compacted, which may indicate enhanced substrate competency.

Although not as extensive, the tracks found at Rattlesnake Alley are nearly as well-preserved as those observed at Dino Ridge. A greater proportion of these tracks are overprinted, making their morphologies hard to determine (Fig. 16). Many tracks at this locality are also partially covered, and many other nearby potential track-bearing horizons remain unexposed. Mean track length is 16.0 cm, and most prints indicate southward travel (Fig. 11, 15).

The Lonely Tree locality preserves 57 tracks which are distributed across numerous discontinuous limestone exposures extending 50 meters to the east. Tracks at the Lonely Tree locality are generally of lower quality than the tracks reported at Dino Ridge and Rattlesnake

Alley. One reason for this may be that the tracks at Lonely Tree may have been uncovered recently.

While many tracks at this site preserve all three toes, less-developed prints preserve only two toes. Furthermore, tracks at Lonely Tree tend to be highly distorted (Fig. 14). Mean track length at Lonely Tree is 14.72 cm (Fig. 15).

Canyon Springs exposures northeast of the Red Gulch area were also searched for potential trackways (e.g., Dirty Annie's; Fig. 6D). Despite the exposure of several bedding-planes with track-bearing potential, no tracks were observed.

Hulett Member

Walking surveys covering 2.26 miles were conducted in eolian deposits of the Hulett Member. In most regions, the Hulett is poorly exposed. However, extensive eolianites along the southeastern flank of Sheep Mountain were searched for tracks where bedding-planes are well exposed (Fig. 6E, 9D).

No tracks were found in Hulett eolian deposits, even though the unit shows evidence for early lithification. Raindrop impressions were found preserved on a bedding surface of a carbonate ooid grainstone, which is consistent with sedimentary structures observed in other eolian trackway studies (McKee 1947; McKeever 1991; Fig. 17). Each raindrop impression is less than a centimeter in diameter and is 1–2 mm deep. Based upon other trackway studies in eolian deposits, the rainfall that creates raindrop impressions may increase substrate competency and the potential for preserving tracks (McKeever 1991).

Windy Hill Sandstone Member

Walking surveys covering 10.94 miles were conducted in the uppermost Windy Hill Member (Fig. 6F). No extensive trackways were reported from this unit, which is surprising considering that tracks have been reported in the Bighorn NRA and Alcova and Seminoe Reservoirs in south-central Wyoming (Logue 1977; Harris and Lacovara 2004; Meyers and Breithaupt 2014). While trackways were not discovered, one or possibly two tracks were found preserved on the upper surface of a float block of sandstone at the southern end of Sykes Mountain.

The isolated track is 3.3 cm wide and 2.6 cm long, with four forward-pointed curved toes, one laterally pointed toe, and a faint heel impression (Fig. 18). The laterally pointed digit suggests that the track was made with a left limb of some vertebrate, possibly a turtle (Brent Breithaupt, pers. comm.). Furthermore, a faint impression of a smaller track with a similar shape and size is present directly in front of the larger track (Fig. 18). The sandstone bearing the track preserves current-ripple lamination, which is consistent with Windy Hill tidal-flat facies (Holland and Wright 2020).

DISCUSSION

Rarity of trackways and trackway preservation

A total of approximately 71.2 miles of Gypsum Spring and Sundance Formation exposures were searched in areas where trackways frequently occur, and the stratigraphy is well-known (McMullen et al. 2014; Danise and Holland 2018). However, following a 6-week field session, only 5 new trackways were discovered. This is surprising considering the amount of distance covered as well as how many bedding-plane exposures showed the potential to preserve tracks. The fact that tracks were not more common in these coastal deposits underscores the rarity of track preservation in general.

Gypsum Spring swim trackways and nearby exposures preserve vortex ripples and are consistent with a peritidal facies. Not all surfaces with vortex ripples preserve tracks, but in conjunction with the swim tracks they may be indicative of shallow subtidal conditions (Kvale et al. 2001, 2004). If this is the case, water depth may have constrained where taxa could imprint tracks into sediment. Tridactyl prints from intertidal facies have also been reported elsewhere in the Gypsum Spring, but none were found in this study (Kvale et al. 2004). Poor availability of exposures may be responsible, especially where rocks are highly jointed or still partially covered by sediment.

Newly discovered tracks from the Canyon Spring Member closely resemble those reported at the RGDT and YBRDT. Given the proximity of the new trackways to these sites (< 1 km), these tracks were most likely preserved in similar peritidal environments (Kvale et al. 2001; Adams et al. 2014). While these coastal deposits are ideal for trackway preservation, shoreline constraints and the need for firm substrates may restrict where trackways can occur (Adams et al. 2014).

Eolian facies of the Hulett Member were searched for potential trackways, but none were found. One reason may be that eolian settings have generally lower substrate cohesion. Cohesion in eolian substrates can be increased following periods of rainfall, as evident by the preserved raindrop impressions at Sheep Mountain (Fig. 17). Additionally, these deposits lack any reported evidence of microbial mats which would have aided trackway preservation.

Tidal-flat facies of the uppermost Windy Hill preserve a small fraction of vertebrate taxa in relation to the overlying Morrison Formation (Table 7). However, only two potential tracks were able to be found in a float block of rippled sandstone. Previous trackway studies in the Windy Hill have suggested that a drier substrate only permitted shallow track preservation, which restricts the preservation quality of the pes and makes the track more susceptible to erosion or trampling (Meyers and Breithaupt 2014).

Previous studies define well-preserved tracks as commonly showing sharp outlines with the possibility of small nails at the tips of toes (Scrivner and Bottjer 1986). Poorly-preserved tracks, on the other hand, often resemble shapeless craters with no distinguishable features. Based on this classification, all observed tracks discovered in this study would be classified as being well-preserved since they demonstrate clear outlines of the trackmaker footprint. This even includes the enigmatic turtle track found in a coarse-grained block of sandstone at the southern end of Sykes, given that two distinct heel prints are preserved, and faint claw marks can be observed.

Numerous environmental factors affect the quality of vertebrate track preservation, including substrate grain size, sediment moisture input, degree of trampling, and rate of burial (McKeever 1991). Trackway studies in other parts of the geologic record report well-preserved tracks mostly in fine-grained substrates (Stokes and Madsen 1979; McKeever 1991; Connely 2006; Lockley and Foster 2006; Lockley et al. 2008; Clark and Brett-Surman 2008; Meyers and Breithaupt 2014). Finer grain size allows for vertebrate prints to be more accurately molded and finer-grained sediment tends to be more cohesive. Trackway preservation is also possible in substrates characterized by fine to medium sand when sufficient mud is present, although tracks tend to be more poorly preserved as grain size increases (McKeever 1991). Rare instances of track preservation in coarser-grained sands and gravels often results in shapeless impressions with no significant morphological features being preserved (Philips et al. 2007).

Sediment moisture content plays a vital role in preserving different track morphologies (McKeever 1991). One individual trackmaker can be responsible for leaving tracks with a wide range of morphologies depending on the extent of saturation (Laporte and Behrensmeyer 1980). However, well-preserved tracks are not typically common in substrates that were either completely saturated or unsaturated (Laporte and Behrensmeyer 1980). They are instead common in substrates with intermediate water content, where sediment is considered moist or slightly damp (McKeever 1991).

Well-preserved tracks are most common when trampling and burial rates are both intermediate (McKee 1947; McKeever 1991). Increasing burial rates while maintaining the same level of trampling sometimes results in the preservation of isolated tracks (McKeever 1991).

Potential trackmakers

Two new swim trackways from the Gypsum Spring are located at the northern end of Sykes Mountain and southern end of Sheep Mountain. While previous studies have reported Gypsum Spring swim tracks north of the RGDT, they have yet to be reported from localities at Sheep Mountain and Sykes Mountain (Kvale et al. 2001, 2004). Individual tracks are preserved as two elongate scrape marks and were originally interpreted to be made by crocodiles (Kvale et al. 2001). However, recent studies suggest that they were possibly made by wading bipedal dinosaurs roughly the size of an ostrich (Kvale et al. 2001, 2004). They are now widely speculated to belong specifically to carnivorous theropods possibly foraging in a food-rich tidal-flat environment (Kvale et al. 2001; Adams et al. 2014).

Three new vertebrate trackways are preserved in exposures of Canyon Spring Sandstone Member near the RGDT and YBRDT (Dino Ridge, Rattlesnake Alley, and Lonely Tree). The tracks at these sites all demonstrate distinctive tridactyl morphologies and are comparable to those reported by previous trackway investigations at other nearby trackways (Kvale et al. 2004; Adams et al. 2014). Given their overall proximity to the RGDT, it is not surprising that the new tracks are so similar in size and morphology. Previous studies at the RGDT and YBRDT identify the potential trackmakers as small to medium theropods and noted that tracks are consistent with the *Carmelopodus* ichnogenus (Kvale et al. 2001; Lockley et al. 2008; Adams et al. 2014). This ichnogenus is noted for a distinct 2–3–3 phalangeal-pad impression and short metatarsal IV and is interpreted to have been made by medium-sized theropods (Lockley et al. 2008).

One isolated set of tracks is present in the upper surface of a loose sandstone block in the Windy Hill Sandstone at the southern end of Sykes Mountain. The larger of the two tracks is well-preserved despite the coarser substrate and faint impressions of heels, forward-pointed toes, and laterally pointed toes can be distinguished. The second, smaller track in front of the larger print is not as well-preserved, however it reflects an identical morphology with clear heel and toe impressions. Identifying the potential trackmaker is difficult owing to the lack of similar tracks nearby. However, Brent Breithaupt of BLM suggested that the track may have been made by a turtle. Track morphology is consistent with descriptions of turtle tracks reported from other tracksites in the Mesozoic rock record (Contessi and Fanti 2012; Lockley et al. 2015; Lida et al. 2018). Turtle tracks at those sites are similarly described as elliptical depressions, sometimes with faint claw marks (Contessi and Fanti 2012; Lockley et al. 2015). This track is also consistent with other reptile ichnites that have been identified previously in the Windy Hill Sandstone (Kvale et al. 2004).

Diversity

Only three taxa were identified as potential trackmakers among all the newly found tracks, and all of these trackmakers have been previously reported from these rocks (Kvale et al. 2001, 2004; Table 7). Given the relatively large diversity of the Early Jurassic Kayenta Formation of Utah and the overlying Late Jurassic Morrison Formation, it is surprising that more tracks belonging to a wider range of Middle to Late Jurassic taxa were not discovered (Table 7). Although previous studies have also acknowledged the low vertebrate diversity of the Gypsum Spring and Sundance relative to the Morrison, identifying why will provide a better understanding of why only certain vertebrates frequented Jurassic coastlines (Kvale et al. 2001, 2004).

The trackway interval within the Gypsum Spring is currently one of the most extensive track-bearing horizons in North America, but it preserves tracks made by only one or two vertebrate taxa (Kvale et al. 2004). Newly discovered swim tracks observed at Sykes Mountain and Sheep Mountain are consistent with those reported from time-equivalent units (Kvale et al. 2004; Lockley et al. 2008). Additionally, the potential trackmaker for newly reported sites from within the Canyon Spring Member appear to be the same small to medium sized theropods responsible for the tracks at the RGDT and YBRDT (Kvale et al. 2004; Adams et al. 2014).

Previous ichnological studies of the Gypsum Spring and Sundance in the Bighorn Basin proposed three hypotheses as to why diversity may be limited in the Gypsum Spring and Sundance Formations (Kvale et al. 2001). One possibility is that the climate during the mid-Bathonian and mid-Bajocian was more suitable for theropod communities and possibly limited food resources for other types of animals (Kvale et al. 2001). This may explain the relatively low proportion of sauropod traces relative to the overwhelming abundance of theropod trackways in these units. The second possibility is that other vertebrates simply did not frequent coastal zones at that time in North America (Kvale et al. 2001, 2004). Despite other vertebrates, such as the sauropods and pterosaurs reported in tidal-flat facies near Alcova Reservoir, the overall lack of diversity regionally may suggest that most vertebrates preferred inhabiting areas farther inland (Logue 1977). The last possibility is that there is actually hidden and yet undiscovered diversity in these rocks, although further investigation is required to discover tracks that may still be covered by sediment. The outcomes of this study are unable to conclusively indicate a greater hidden vertebrate diversity in the Gypsum Spring and Sundance Formation. However, many exposures were unable to be searched due to time constraints, meaning that potentially many more tracks are yet to be documented.

CONCLUSIONS

1. During a 6-week field session, walking surveys spanning 71.2 miles in coastal facies of the Gypsum Spring and Sundance Formations resulted in the discovery of 318 new vertebrate tracks at five different localities. This is less than what was expected, and track occurrences may have been rare owing to environmental factors such as substrate grain size, sediment moisture input, and extent of trampling/burial. Additionally, many exposures with trackways in the area may still be covered by sediment.
2. Swim tracks in the Gypsum Spring may have been made by either a crocodilian or bipedal dinosaur. All tridactyl prints found in the Red Gulch Area (Dino Ridge, Rattlesnake Alley, and Lonely Tree) are interpreted to have been made by the same small to medium theropods responsible for the nearby trackways at the RGDT and YBRDT.

The possible turtle tracks in the Windy Hill are consistent with other reptilian ichnites reported previously from the Windy Hill.

3. The lack of diversity in these rocks reveal key differences about trackway preservation in coastal and inland settings. Given the diversity of the vertebrate taxa that have been identified in the Kayenta Formation and the overlying Morrison Formations, there is a reasonable expectation that a similar diversity would be present in coastal deposits of the Gypsum Spring and Sundance Formations. However, the low trackway diversity of the uppermost Windy Hill Sandstone suggests that only a small portion of the Morrison fauna frequented the coastline.

CHAPTER 3

CONCLUSION

Previous vertebrate trackways from the Jurassic Gypsum Spring and Sundance Formations have been well documented; however, it is speculated that many thousands more may still be unreported (Kvale et al. 2001). This research has resulted in the discovery of 318 new vertebrate tracks distributed across five different trackways in the Gypsum Spring and Sundance Formations of the Bighorn Basin. Two of the trackways are in the Gypsum Spring Formation and preserve 149 swim tracks made by bipedal dinosaurs, speculated to be roughly the size of an ostrich. The other three trackways are located on the uppermost limestone bedding-plane in the Canyon Spring Sandstone Member of the Sundance Formation, and they preserve 169 tridactyl theropod prints. Although new trackways were discovered, the results of this study do not reveal hidden diversity present in the Gypsum Spring or Sundance Formations. More research may help to clarify this problem.

Many potentially track-bearing exposures were unable to be thoroughly investigated in some units, owing to a general lack of exposed bedding-planes. It is possible that even more trackways exist in this region but remain covered by sediment. Over time, the emergence of new potentially track-bearing horizons may yield even more trackways. Further research along these horizons is recommended in the future, as they still may preserve some indication of a greater diversity of vertebrate taxa in the Gypsum Spring and Sundance Formations. A longer field season would be dedicated to seeking out the lateral limits of trackways over a greater area. Doing so may provide insight into factors that control for the lateral extent of trackways.

Furthermore, while microbial features were documented at previous sites, such as the RGDT and YBRDT, none were observed at any of the new trackway surfaces reported in this study. More attention to fine-scale microbial features, such as elephant wrinkles, may be required to conclusively determine that these new tracks were preserved by microbial mats as well. While no evidence of microbial mat stabilization was observed at any of the new trackways, a more trained eye may be needed to identify these fine-scale surface features.

Finally, the methods used in this study can be applied to predict the occurrence of other vertebrate trackways preserved in coastal deposits elsewhere. I suggest that similar techniques be employed to search for trackways preserved in other transgressive surfaces throughout the geologic record to clarify why some select vertebrates of the Middle to Late Jurassic tend to thrive in coastal zones as opposed to other larger competitors.

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Table 1. Descriptions of potential track-bearing coastal facies from the Gypsum Spring and Sundance Formations (Adapted from Danise and Holland 2018).

Potential track-bearing facies	Lithology	Sedimentary Structures	Fossils
Open shallow subtidal	Thin- to medium-bedded skeletal to peloidal wackestone and packstone	Bioturbated	Bivalves (Liostrea, Camptonectes, Trigonia, Myophorella), gastropods (Procerithium, Nododelphininula, Lyosoma), crinoids, and ossicles
Ooid Shoal	Medium-to thick-bedded ooid grainstone with very fine sand to silt and micritized echinoderm grains	Large-scale trough cross stratification with vortex ripples and *Diplocraterion*	Rare bivalves and abundant crinoid ossicles
Restricted shallow subtidal	Light gray and red lime mudstone with some skeletal wackestone, limonite, and glauconite	Laminated, very thin beds	Bivalves (*Staffinella* and *Modiolus*)
Peritidal	Interbedded laminated dolomitic lime mudstone with nonlaminated and porous gray to pink dolostone	Stromatolitic to thrombolitic with raindrop impressions, halite pseudomorphs, and chert nodules	None
Eolian dune	Thickly bedded ooid grainstone	Large-scale sets of tabular cross-beds with overturned cross-bedding and	None

reverse-graded
pinstripe laminae

Table 2. Individual track measurements for the Dino Ridge trackway.

Track	**Length (cm)**	**Width (cm)**	**Left Digit (cm)**	**Middle Digit (cm)**	**Right Digit (cm)**	**Tip distance (Left–Middle; (cm)**	**Tip distance (Middle–Right; (cm)**	**Azimuth (°)**
1	13.6	15.2	5.8	9.8	3.9	8.2	9.6	164
2	11.6	11.8	4.5	9.0	6.1	9.6	9.5	147
3	13.5	13.2	4.1	9.5	3.5	9.5	9.5	341
4	11.0	12.6	5.5	8.5	N/A	9.0	N/A	346
5	13.5	18.8	8.5	12.3	8.2	10.2	10.6	173
6	17.1	16.3	6.1	12.7	6.9	11.6	11.9	348
7	11.5	12.3	4.6	11.3	5.5	10.9	10.6	207
8	9.1	12.1	5.0	8.1	4.5	6.9	6.9	181
9	11.6	13.1	4.6	9.2	5.5	8.6	6.9	150
10	17.6	12.9	6.8	9.4	6.3	9.2	11.0	175

11	12.8	13.3	5.6	9.7	5.6	9.5	11.2	158
12	11.6	13.6	5.8	7.5	4.1	7.5	9.4	162
13	14.5	16.1	6.1	8.2	4.2	11.1	9.9	165
14	7.5	7.0	3.0	4.6	4.5	5.2	3.1	150
15	11.1	14.9	5.1	8.5	4.1	8.3	8.5	188
16	17.5	18.1	N/A	15.4	10.1	13.1	N/A	24
17	6.5	10.5	2.8	5.9	2.9	5.1	5.4	12
18	13.1	13.3	5.9	9.8	4.9	9.0	9.6	174
19	17.0	13.9	8.8	14.0	7.5	12.5	11.9	157
20	14.9	17.9	6.2	12.6	8.5	7.2	10.1	2
21	16.1	13.4	5.5	9.5	5.5	9.9	11.5	339
22	11.2	11.0	3.5	6.9	6.0	9.6	8.3	174
23	14.6	11.8	5.2	7.4	4.2	11.0	8.9	188

24	13.1	13.0	5.8	8.0	4.6	10.4	8.4	164
25	15.6	15.6	6.3	8.5	6.2	12.9	10.9	194
26	15.4	14.7	5.4	11.9	7.9	9.9	11.6	139
27	17.9	21.6	7.8	13.9	6.8	12.5	13.4	162
28	14.1	16.1	6.2	10.1	6.4	10.4	10.6	187
29	9.4	11.2	3.8	6.4	4.4	8.8	8.4	158
30	18.2	20.4	5.3	11.9	4.6	13.4	12.9	300
31	11.7	11.2	5.2	8.8	5.7	9.6	9.2	169
32	12.8	12.2	5.2	8.0	N/A	8.9	N/A	179
33	12.2	11.8	5.7	8.9	5.5	10.1	9.2	150
34	16.6	14.9	4.9	7.1	5.8	9.2	9.7	174
35	17.7	16.2	7.2	9.2	6.9	12.2	13.4	15
36	12.4	11.3	3.3	8.5	4.2	10.3	11.0	192

37	11.0	16.2	4.1	10.2	7.6	10.3	9.8	182
38	12.2	13.2	4.1	8.6	5.1	7.6	10.8	192
39	12.4	13.5	5.2	9.2	4.5	11.6	10.6	165
40	14.2	13.5	6.2	8.4	5.5	9.6	9.6	11
41	12.5	16.8	8.6	9.6	4.8	12.1	11.8	180
42	11.6	9.7	3.9	7.1	4.8	8.1	8.0	340
43	12.6	11.2	6.2	7.9	4.5	7.9	3.9	192
44	10.7	13.3	3.8	7.9	4.9	9.8	4.4	188
45	15.1	17.5	7.1	11.9	6.8	10.8	11.2	201
46	13.4	13.5	4.8	10.1	4.7	9.5	11.9	17
47	12.9	13.4	5.8	8.5	5.5	8.5	9.9	5
48	11.6	11.9	5.5	9.2	5.8	8.5	8.5	182
49	11.9	13.9	5.1	11.6	N/A	10.2	N/A	341

50	12.9	12.5	3.6	6.8	4.2	9.3	7.7	174
51	11.5	11.5	N/A	6.9	4.6	10.2	N/A	351
52	12.8	12.2	3.9	8.9	5.2	10.4	11.9	3
53	12.4	13.2	3.6	7.2	4.8	9.5	10.1	187
54	15.2	19.4	7.6	11.6	7.2	12.8	13.0	187
55	19.9	17.1	6.9	11.9	7.6	12.2	13.6	24
56	12.9	13.5	N/A	12.0	6.0	N/A	11.8	183
57	10.8	11.8	3.1	5.5	4.8	7.5	6.1	195
58	7.0	7.5	3.1	3.6	2.4	5.3	5.0	169
59	10.0	4.1	3.8	6.1	2.9	8.2	8.1	203
60	13.4	9.9	4.0	5.9	4.5	6.1	6.6	348
61	8.8	10.1	4.8	5.9	4.8	6.5	5.1	165
62	9.8	11.4	2.7	5.8	4.2	5.6	6.9	173

63	19.3	20.8	5.9	13.9	7.8	16.9	13.5	129
64	13.9	12.4	4.2	9.1	5.9	10.1	9.8	178
65	11.5	12.5	5.9	10.4	5.4	9.2	9.3	148
66	N/A	13.5	N/A	9.8	7.9	8.9	N/A	332
67	11.1	12.9	5.2	9.2	6.5	9.8	7.1	189
68	13.2	12.8	4.4	10.9	6.1	10.9	10.8	82
69	12.4	12.2	4.6	6.9	5.9	8.9	9.8	187
70	10.6	15.8	N/A	9.8	5.3	12.1	N/A	178
71	10.1	8.6	4.1	7.0	4.1	7.5	7.7	346
72	17.1	18.5	5.8	13.1	7.1	12.5	12.2	160
73	N/A	11.2	N/A	9.5	6.4	7.8	N/A	335
74	10.3	13.1	5.5	7.4	5.1	7.1	8.0	181
75	13.5	14.0	4.5	10.5	5.3	10.2	10.8	185

76	15.4	15.0	6.5	11.6	5.8	15.8	10.9	216
77	14.2	15.5	6.1	12.5	8.8	11.9	11.0	149
78	8.5	8.9	4.9	5.2	3.8	6.5	6.4	327
79	19.2	15.0	8.0	11.9	8.6	15.6	14.5	3
80	16.5	15.1	4.7	9.8	7.5	11.2	13.0	311
81	13.9	17.4	4.8	13.2	5.2	10.9	9.6	319
82	14.4	14.5	5.5	7.1	5.7	8.1	8.9	144
83	16.0	15.5	7.0	11.5	7.9	10.9	11.1	131

Table 3. Individual track measurements for the Rattlesnake Alley trackway.

Track	Length (cm)	Width (cm)	Left Digit (cm)	Middle Digit (cm)	Right Digit (cm)	Tip distance (Left–Middle; cm)	Tip distance (Middle –Right; cm)	Azimuth (°)
84	11.5	18.1	4.8	10.5	6.5	15.1	12.0	183
85	16.1	14.9	5.5	10.2	6.5	12.0	12.5	136
86	9.0	12.4	3.5	7.2	3.5	7.1	7.5	146
87	16.8	14.9	6.1	11.5	7.5	10.4	12.4	45
88	7.6	11.0	N/A	7.8	6.5	6.1	N/A	172
89	17.4	16.5	6.9	12.3	7.4	12.0	14.1	193
90	19.3	17.9	8.4	9.0	5.5	13.1	13.6	7
91	14.7	13.5	6.6	9.1	5.1	8.0	10.2	189
92	14.4	15.1	6.2	9.5	5.0	10.5	10.1	179
93	15.6	15.6	6.6	8.5	6.4	10.6	11.5	145

94	14.4	15.8	4.8	7.5	4.8	9.2	8.6	297
95	13.7	17.4	6.2	12.8	4.4	13.5	13.4	169
96	18.4	17.2	7.6	11.5	7.2	11.4	11.6	332
97	19.4	18.1	6.6	9.4	7.2	11.4	11.6	155
98	14.8	13.9	7.0	7.8	5.9	10.2	8.0	182
99	11.5	12.8	4.5	8.0	4.0	8.9	8.1	262
100	22.3	20.5	4.8	16.4	5.1	21.5	16.4	184
101	16.4	14.6	4.4	7.6	5.2	10.4	11.4	310
102	21.5	18.9	N/A	4.0	7.6	N/A	13.1	197
103	14.9	16.5	6.5	8.5	5.9	8.7	9.5	172
104	17.8	14.1	4.5	7.6	6.6	10.5	10.7	230
105	15.5	13.9	5.9	8.6	5.6	13.2	8.4	18
106	17.7	18.8	6.3	13.0	6.5	12.0	11.8	191

107	17.1	17.9	6.6	9.7	6.8	10.6	10.6	167
108	12.7	14.1	5.9	9.1	5.6	8.1	8.1	189
109	14.7	17.5	5.7	10.4	6.0	10.0	9.7	210
110	22.0	21.9	6.4	13.9	7.5	14.8	13.2	179
111	16.8	18.6	7.5	11.9	6.4	10.2	0	207

Table 4. Individual track measurements for the Lonely Tree trackway.

Track	Length (cm)	Width (cm)	Left Digit (cm)	Middle Digit (cm)	Right Digit (cm)	Tip distance (Left–Middle; cm)	Tip distance (Middle–Right; cm)	Azimuth (°)
112	15.0	15.0	6.0	8.0	7.0	8.0	N/A	196
113	14.0	14.0	3.9	6.4	5.5	8.1	11.6	286
114	21.5	20.5	5.4	7.1	6.2	14.1	15.0	129
115	14.5	12.9	4.5	7.6	3.8	10.2	10.4	326
116	15.1	15.7	5.5	9.2	6.4	7.5	9.0	318
117	12.2	18.1	6.8	12.0	5.3	8.8	11.0	151
118	14.5	12.4	7.5	9.2	4.5	8.5	8.6	312
119	13.0	16.6	4.4	11.2	4.0	11.6	10.4	310
120	10.3	8.5	3.6	5.8	4.6	5.6	N/A	300
121	7.8	10.4	3.7	6.4	4.4	5.0	5.2	300

122	18.5	17.9	7.4	12.9	6.0	11.3	11.5	225
123	17.0	17.5	6.8	12.1	5.8	11.0	13.0	285
124	16.2	12.1	7.5	7.5	6.1	7.3	8.4	317
125	16.9	17.8	6.5	13.9	N/A	13.6	N/A	192
126	17.4	19.0	6.2	12.1	6.2	12.0	12.3	313
127	21.5	15.6	9.5	9.8	7.2	15.6	11.1	128
128	17.6	14.8	7.9	10.0	7.2	12.8	11.6	173
129	11.2	14.1	6.8	9.6	5.0	9.9	9.4	317
130	14.8	19.2	6.6	13.6	3.8	10.9	12.3	354
131	14.4	12.5	6.6	9.5	6.4	9.8	10.8	321
132	11.6	11.5	6.5	9.0	4.5	10.0	7.8	133
133	13.0	16.0	5.9	9.1	5.9	10.6	9.8	142
134	16.2	22.0	7.0	14.4	8.3	13.2	13.1	301

135	13.2	15.3	4.5	8.1	5.3	9.4	9.6	338
136	14.8	15.2	7.9	10.1	5.2	9.8	10.9	350
137	12.1	13.5	5.8	10.8	5.5	10.2	8.6	145
138	12.2	16.5	5.5	9.1	5.5	11.5	8.1	354
139	14.2	11.5	4.9	9.9	7.6	9.9	8.9	305
140	22.5	18.1	9.5	13.5	N/A	14.5	N/A	354
141	25.0	20.5	10.5	10.5	8.8	16.9	13.8	177
142	18.2	16.5	6.5	10.5	6.4	14.1	8.9	298
143	16.9	14.0	6.1	10.5	6.5	10.1	13.4	323
144	12.6	11.0	3.6	8.0	5.8	6.0	9.5	326
145	14.4	11.9	5.7	8.4	6.3	9.6	9.2	324
146	16.9	16.5	5.4	10.2	6.2	11.1	10.5	143
147	13.3	15.2	4.5	9.5	4.9	11.9	10.5	348

148	10.1	10.6	5.5	9.8	4.2	7.5	8.3	228
149	15.5	17.9	7.5	12.5	5.0	11.1	10.2	339
150	16.5	17.5	5.8	11.2	5.2	12.5	12.9	191
151	12.1	11.0	4.9	7.6	4.9	9.2	6.7	292
152	7.1	6.2	3.2	4.1	2.3	4.4	4.3	316
153	11.5	10.0	5.5	5.8	4.8	7.4	7.4	52
154	13.9	14.5	5.4	9.5	4.5	9.5	9.5	17
155	11.6	14.5	6.5	8.5	6.2	10.9	7.0	182
156	17.1	13.1	6.1	9.5	5.2	11.1	11.5	299
157	17.1	20.2	6.1	12.2	5.4	13.6	13.6	230
158	12.8	13.4	5.8	10.2	4.2	8.1	9.1	343
159	14.2	14.6	5.0	10.4	5.5	9.5	10.6	23
160	9.6	15.1	4.4	7.1	3.5	8.2	8.6	312

161	9.8	12.1	3.3	7.4	3.6	7.6	7.8	316
162	15.6	18.1	6.5	8.1	7.2	10.5	10.7	283
163	16.1	17.2	5.6	10.9	8.8	9.2	11.8	344
164	15.6	15.1	6.4	12.0	7.5	14.1	11.6	308
165	16.5	19.0	8.5	14.9	9.5	12.4	12.6	294
166	16.9	17.4	7.9	15.6	9.0	17.1	10.5	111
167	17.2	16.6	8.1	12.9	8.1	13.1	12.1	309
168	17.9	18.1	8.2	10.9	7.6	12.5	12.1	286
169	12.1	15.0	9.5	8.8	N/A	11.4	N/A	281

Table 5. Individual track measurements for North Sykes Mountain.

Track	Length (cm)	Width (cm)	Left Digit (cm)	Middle Digit (cm)	Right Digit (cm)	Tip distance (Left–Middle; cm)	Tip distance (Middle–Right; cm)	Azimuth (°)
170	8.7	8.5	7.1	8.2	N/A	6.0	N/A	315
171	7.2	12.9	7.8	9.9	5.5	4.2	6.2	252
172	8.8	9.8	4.8	7.0	6.5	5.5	5.3	227
173	4.6	11.9	5.9	8.7	N/A	4.0	N/A	285
174	7.9	13.9	9.1	13.0	N/A	5.8	N/A	206
175	5.4	9.2	3.9	7.2	4.2	4.2	4.1	277
176	7.4	9.4	8.9	9.0	5.5	3.8	3.6	262
177	3.4	9.8	9.8	8.9	N/A	4.8	N/A	234
178	4.5	10.5	10.5	9.1	N/A	3.6	N/A	217
179	5.6	11.5	6.9	8.6	N/A	6.2	N/A	248

180	8.6	12.5	6.7	9.0	8.1	2.4	4.2	220
181	4.7	6.4	7.1	7.2	N/A	3.0	N/A	248
182	7.9	11.7	7.1	9.1	4.9	6.5	6.6	255
183	8.9	9.1	4.5	7.9	5.2	5.6	3.6	207
184	5.5	6.1	6.5	8.0	N/A	3.5	N/A	271
185	9.9	14.1	N/A	10.5	6.9	8.4	N/A	352
186	4.9	6.6	5.5	4.8	4.5	4.6	2.5	276
187	9.1	11.2	N/A	8.0	7.4	4.1	N/A	313
188	9.8	10.2	6.2	7.9	6.1	5.1	5.5	228
189	7.9	N/A	N/A	N/A	N/A	7.4	7.2	332
190	3.9	5.5	N/A	3.1	3.9	3.5	N/A	198
191	4.5	13.6	8.9	11.5	N/A	5.0	N/A	203
192	6.1	7.4	6.1	7.1	5.1	3.4	3.8	210

193	9.0	9.4	3.6	6.5	6.4	5.0	5.8	227
194	3.8	8.1	N/A	7.5	7.1	3.7	N/A	294
195	8.2	11.5	7.0	8.5	7.9	7.9	5.1	238
196	5.6	8.2	7.8	5.7	2.0	3.5	3.1	233
197	4.0	9.5	6.1	8.5	N/A	4.4	N/A	247
198	4.4	9.4	N/A	10.0	6.5	3.9	N/A	306
199	7.6	N/A	4.5	8.1	6.6	3.1	4.6	215
200	4.0	10.1	10.1	N/A	9.6	3.4	N/A	218
201	3.5	10.2	9.4	N/A	8.2	2.9	N/A	233
202	9.0	12.1	3.6	10.4	8.3	6.1	4.6	202
203	7.9	7.5	4.1	6.0	6.5	4.1	4.0	218
204	6.5	5.4	4.1	4.6	4.9	3.2	3.0	214
205	7.6	7.9	3.5	6.6	6.3	5.4	2.5	239

206	2.5	6.1	5.1	N/A	5.2	4.5	N/A	243
207	3.7	12.0	12.4	N/A	9.6	4.4	N/A	269
208	2.9	4.0	3.5	N/A	4.0	2.6	N/A	239
209	3.1	8.8	9.4	N/A	7.4	3.2	N/A	218
210	3.5	7.5	5.8	N/A	6.6	3.5	N/A	281
211	7.0	9.9	4.1	7.5	7.9	5.5	4.5	280
212	3.5	7.1	5.5	N/A	5.8	4.4	N/A	218
213	3.5	8.8	8.0	N/A	5.3	12.7	N/A	238
214	4.2	7.7	6.0	N/A	7.0	3.5	N/A	252
215	5.5	6.1	2.6	6.4	4.2	3.0	2.8	217
216	8.6	10.1	3.8	10.5	6.7	5.1	7.1	225
217	3.1	13.5	3.2	N/A	9.2	3.8	N/A	220
218	4.0	8.0	6.0	N/A	5.8	5.6	N/A	219

219	3.0	12.8	12.5	N/A	8.6	3.9	N/A	225
220	10.5	9.5	3.5	5.7	5.5	6.0	5.4	237
221	5.5	7.2	5.9	N/A	7.4	3.2	N/A	250
222	4.1	6.8	3.1	N/A	5.7	3.0	N/A	243
223	3.4	7.4	5.4	N/A	7.6	2.6	N/A	221
224	7.5	5.5	5.0	5.4	5.1	3.5	3.7	224
225	2.5	6.9	4.5	N/A	6.9	3.3	N/A	218
226	3.6	8.2	7.8	N/A	7.4	3.2	N/A	245
227	4.6	11.2	9.1	N/A	10.0	5.1	N/A	213
228	3.7	15.6	6.4	N/A	12.5	7.5	N/A	247
229	2.8	5.0	3.9	N/A	4.0	3.0	N/A	300
230	3.1	10.5	6.1	N/A	9.9	2.8	N/A	259
231	2.6	8.8	5.4	N/A	8.4	2.5	N/A	229

232	4.3	8.4	7.3	N/A	8.0	3.1	N/A	234
233	1.6	13.5	11	N/A	9.6	3.5	N/A	206
234	3.0	10.4	7.4	N/A	6.7	4.4	N/A	184
235	3.9	8.2	4.4	N/A	6.7	3.1	N/A	263
236	3.7	6.6	6.6	N/A	13.5	4.1	N/A	284
237	3.9	8.6	8.6	N/A	4.4	4.2	N/A	269
238	5.8	10.6	6.4	N/A	6.8	4.5	N/A	220
239	4.3	7.2	5.8	N/A	7.0	3.6	N/A	198
240	3.4	5.9	3.4	N/A	5.2	3.5	N/A	218
241	2.8	3.7	3.1	N/A	3.4	3.0	N/A	266
242	2.8	4.0	2.6	N/A	3.6	3.0	N/A	267
243	3.8	7.2	4.9	N/A	7.2	4.4	N/A	217
244	3.4	7.4	6.9	N/A	6.4	4.2	N/A	269

245	2.6	8.8	8.8	N/A	5.2	2.5	N/A	227
246	2.8	7.8	2.5	N/A	7.8	3.1	N/A	201
247	5.5	5.2	5.2	N/A	5.1	3.8	N/A	230
248	2.2	8.7	4.5	N/A	7.9	3.9	N/A	291
249	4.0	8.2	6.6	N/A	8.2	5.4	N/A	184
250	3.0	5.2	5.2	N/A	3.5	2.4	N/A	301
251	3.0	6.6	5.7	N/A	5.7	3.2	N/A	204
252	3.1	8.5	6.2	N/A	6.5	4.1	N/A	228
253	2.1	6.1	6.1	N/A	4.2	2.4	N/A	185
254	2.5	5.7	4.6	N/A	5.7	2.9	N/A	234
255	4.5	17.3	16.4	N/A	10.5	6.1	N/A	206
256	2.9	4.8	3.5	N/A	4.5	3.3	N/A	277
257	8.6	8.2	3.4	8.0	4.8	3.5	4.4	244

258	2.9	2.8	1.9	N/A	2.2	2.9	N/A	197

Table 6. Individual track measurements for the South Sheep Mountain trackway.

Track	Length (cm)	Width (cm)	Left Digit (cm)	Middle Digit (cm)	Right Digit (cm)	Tip-to-tip distance (Right–Left; cm)	Azimuth (°)
269	3.6	7.9	8.6	N/A	7.2	3.4	248
270	4.0	7.1	6.7	N/A	5.0	3.9	254
271	4.3	6.2	4.1	N/A	4.4	3.9	246
272	3.0	3.8	3.0	N/A	3.3	2.9	288
273	3.6	6.0	4.1	N/A	5.5	3.8	309
274	3.2	6.3	6.1	N/A	3.2	2.4	339
275	2.7	5.2	2.8	N/A	3.2	2.2	269
276	6.8	9.1	5.5	N/A	8.4	1.5	269
277	2.0	6.5	5.7	N/A	5.7	2.2	226
278	8.7	8.2	5.5	N/A	4.2	4.1	254

279	2.5	6.7	5.5	N/A	4.8	3.0	264
280	3.0	4.5	2.9	N/A	4.7	2.4	248
281	2.7	4.5	3.7	N/A	4.5	1.6	268
282	3.8	7.5	7.0	N/A	4.6	4.5	250
283	3.1	8.8	4.9	N/A	5.7	3.5	275
284	6.1	6.2	5.8	N/A	4.6	2.9	215
285	7.5	6.2	3.8	N/A	3.5	4.0	357
286	3.3	5.0	3.0	N/A	5.4	2.9	220
287	4.2	7.9	7.9	N/A	5.7	3.7	244
288	2.9	6.2	5.7	N/A	4.5	2.9	229
289	4.2	7.9	7.9	N/A	5.0	3.5	249
290	3.7	7.0	5.2	N/A	5.4	2.7	260
291	3.5	4.2	4.2	N/A	3.4	3.4	261

292	3.6	5.8	5.4	N/A	5.4	2.5	275
293	3.6	5.9	5.8	N/A	4.1	3.3	268
294	5.5	8.6	5.7	N/A	7.9	4.9	232
295	3.3	5.0	5.0	N/A	3.4	2.7	232
296	4.3	8.9	8.2	N/A	7.6	4.6	223
297	4.1	7.0	5.5	N/A	6.0	3.8	227
298	3.9	9.1	9.1	N/A	8.8	2.6	239
299	4.4	8.2	6.1	N/A	6.3	4.4	277
300	2.6	9.4	8.7	N/A	9.1	2.7	275
301	2.3	6.8	5.4	N/A	5.6	2.6	353
302	2.4	6.4	6.0	N/A	3.4	3.6	279
303	4.3	8.4	6.9	N/A	4.0	3.5	294
304	3.8	7.7	6.6	N/A	7.1	3.2	285

305	3.8	8.4	6.4	N/A	6.6	4.4	269
306	2.5	5.9	5.6	N/A	5.5	2.6	327
307	5.4	8.4	3.5	7.9	8.4	2.4	219
308	3.6	4.8	3.3	N/A	4.6	3.2	354
309	3.5	4.8	4.5	N/A	3.4	3.0	248
310	5.2	8.9	6.5	N/A	8.0	2.7	248
311	3.8	6.2	6.0	N/A	4.8	4.0	219
312	3.9	8.2	4.8	N/A	5.7	3.6	221
313	2.6	7.5	6.0	N/A	6.2	3.2	214
314	3.9	7.9	5.2	N/A	7.9	4.4	247
315	3.6	9.9	9.9	N/A	8.9	4.1	289
316	4.9	9.5	7.4	N/A	9.0	3.0	255
317	2.4	5.9	5.4	N/A	4.2	2.6	217

318	2.4	6.6	3.5	N/A	5.9	2.8	264

Table 7. Table comparing taxonomic data from Foster (2007) and those taxa that have been reported in the Gypsum Spring and/or Sundance Formations.

Taxon	**Number of species reported from the Morrison Formation**	**Reported from Gypsum Spring / Sundance Formations**
Fish	6	No
Frogs	3	No
Salamanders	2	No
Turtles	4	Kvale et al. (2004)
Sphenodontids	3	No
Lizards	5	No
Choristoderes	1	No
Crocodylomorphs	6	Kvale et al. (2001)
Pterosaurs	6	Harris and Lacovara (2004)
Theropod dinosaurs	11	Kvale et al. (2001)
Sauropod dinosaurs	10	No
Armored dinosaurs	4	No
Ornithopod dinosaurs	5	No

Mammals	23	No

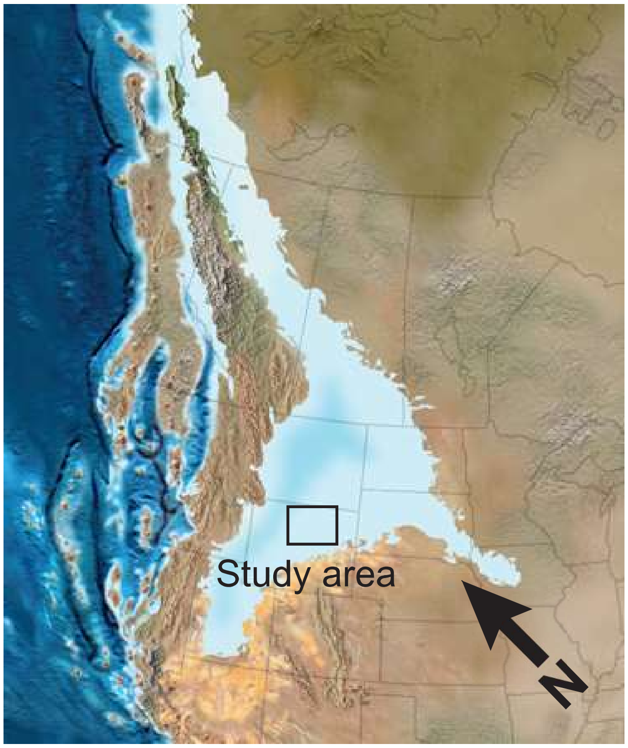

Study area
N

Figure 1. Paleogeographic reconstruction of the Sundance Seaway during the Middle Jurassic (Bajocian Stage ~170 Ma). Adapted from Blakey (2014).

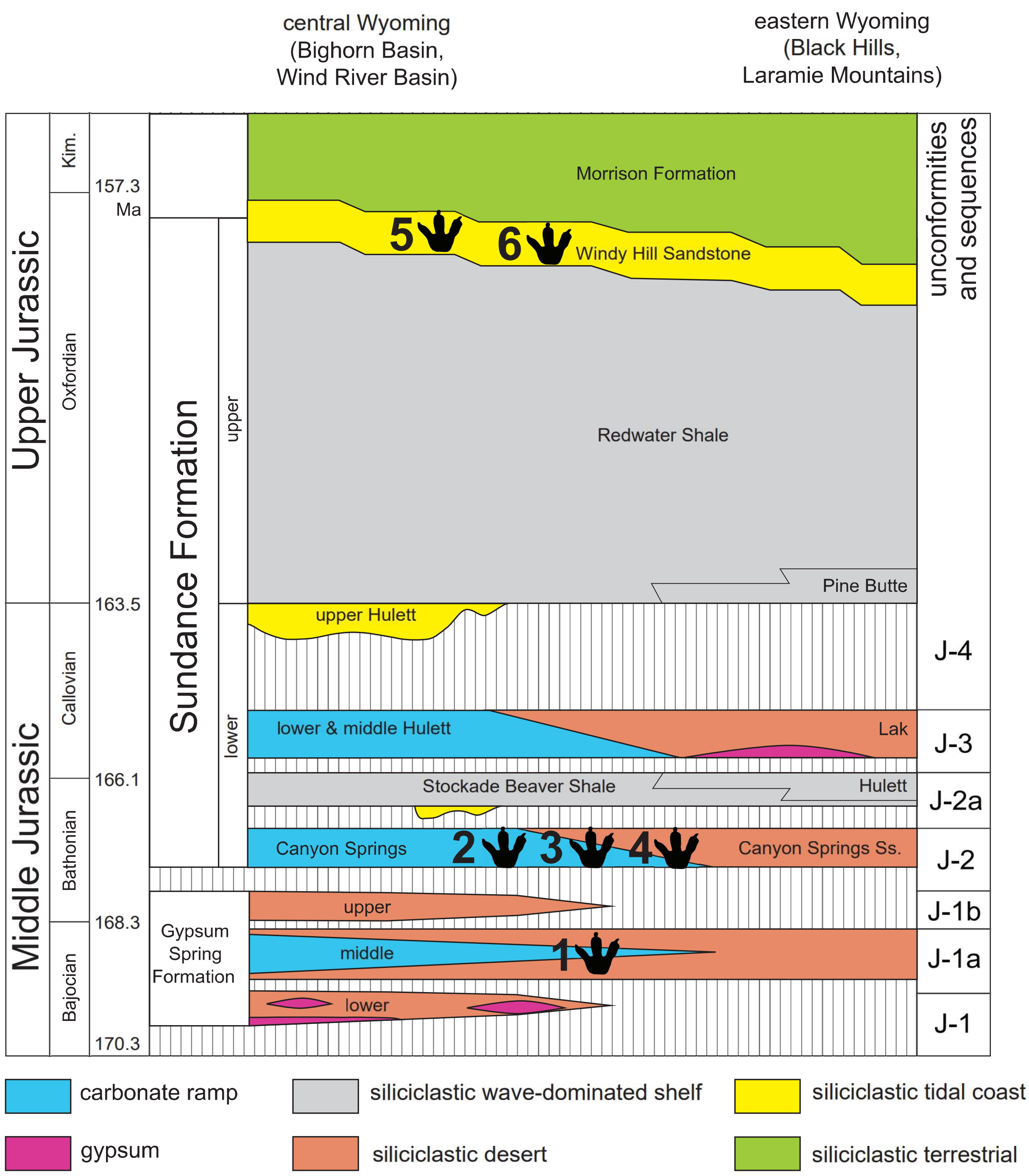
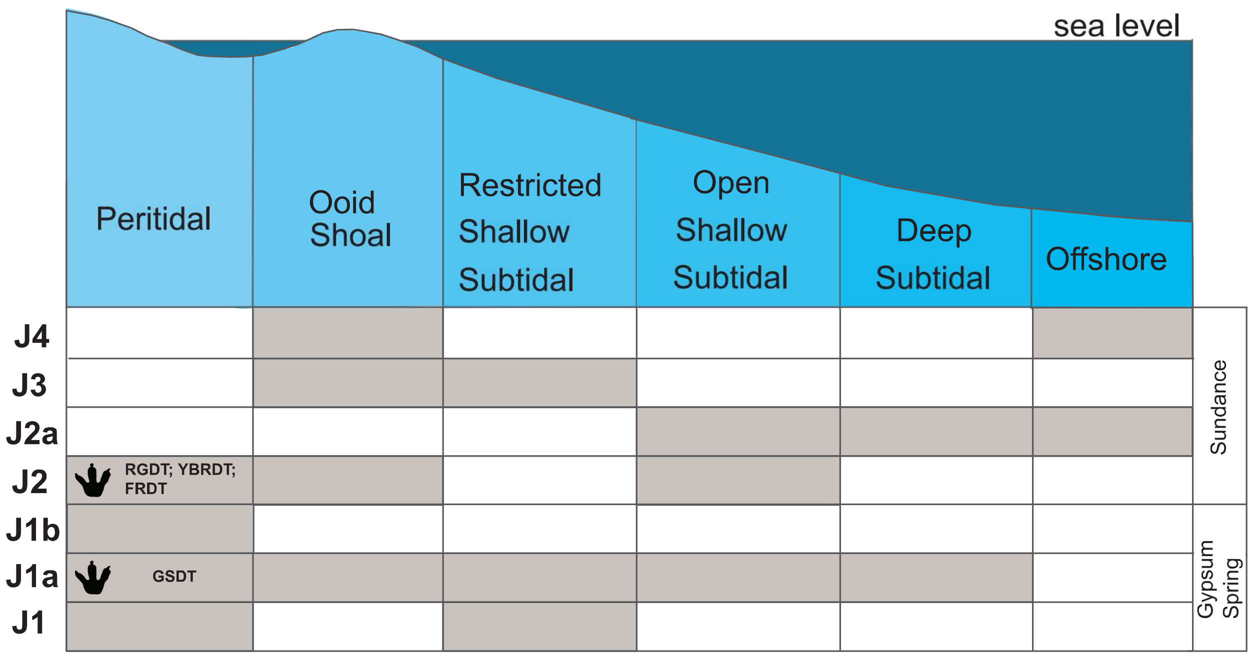

central Wyoming
(Bighorn Basin,
Wind River Basin)
eastern Wyoming
(Black Hills,
Laramie Mountains)
Upper Jurassic
Middle Jurassic
Kim.
Oxfordian
Callovian
Bathonian
Bajocian
157.3
Ma
163.5
166.1
168.3
170.3
Sundance Formation
upper
lower
Gypsum
Spring
Formation
Morrison Formation
5
6
Windy Hill Sandstone
Redwater Shale
Pine Butte
upper Hulett
lower & middle Hulett
Lak
Stockade Beaver Shale
Hulett
Canyon Springs
2
3
4
Canyon Springs Ss.
upper
middle
1
lower
unconformities
and sequences
J-4
J-3
J-2a
J-2
J-1b
J-1a
J-1
carbonate ramp
siliciclastic wave-dominated shelf
siliciclastic tidal coast
gypsum
siliciclastic desert
siliciclastic terrestrial

Figure 2. Sequence stratigraphy and lithostratigraphy of the Middle to Upper Jurassic in Wyoming (adapted from Danise and Holland 2018), showing six known trackways. 1: Gypsum Spring Dinosaur Tracksite (Kvale et al. 2001); 2: Yellow Brick Road Tracksite (Adams et al. 2014); 3: Red Gulch Dinosaur Trackway (RGDT; Kvale et al. 2001); 4: Flitner Ranch Dinosaur Trackway (Kvale et al. 2001); 5: Alcova Reservoir (Logue 1977); 6: Pterosaur tracks (Meyers and Breithaupt 2014).

A Carbonate Ramp System



B Siliciclastic Shelf System

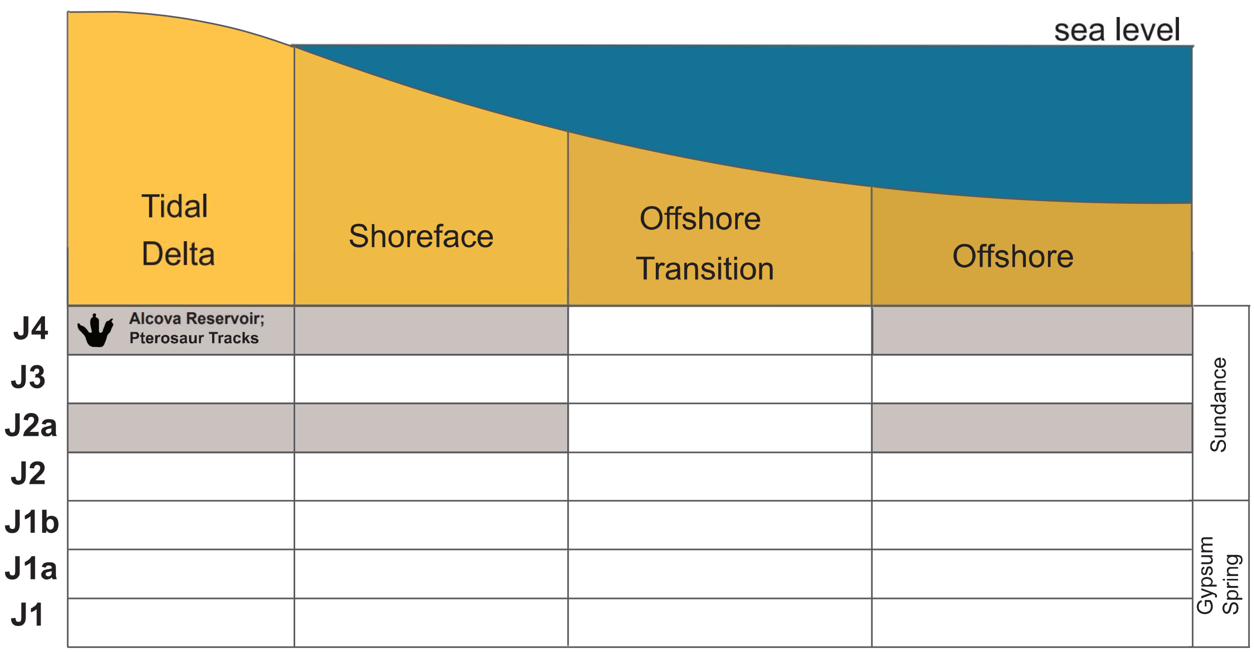


Figure 3. Time-environment diagram showing the preserved facies (gray) in each depositional sequence, and where trackways have been reported. Facies occurrences based on McMullen et al. (2014), Clement and Holland (2016), Danise and Holland (2018), and Holland and Wright (2020).

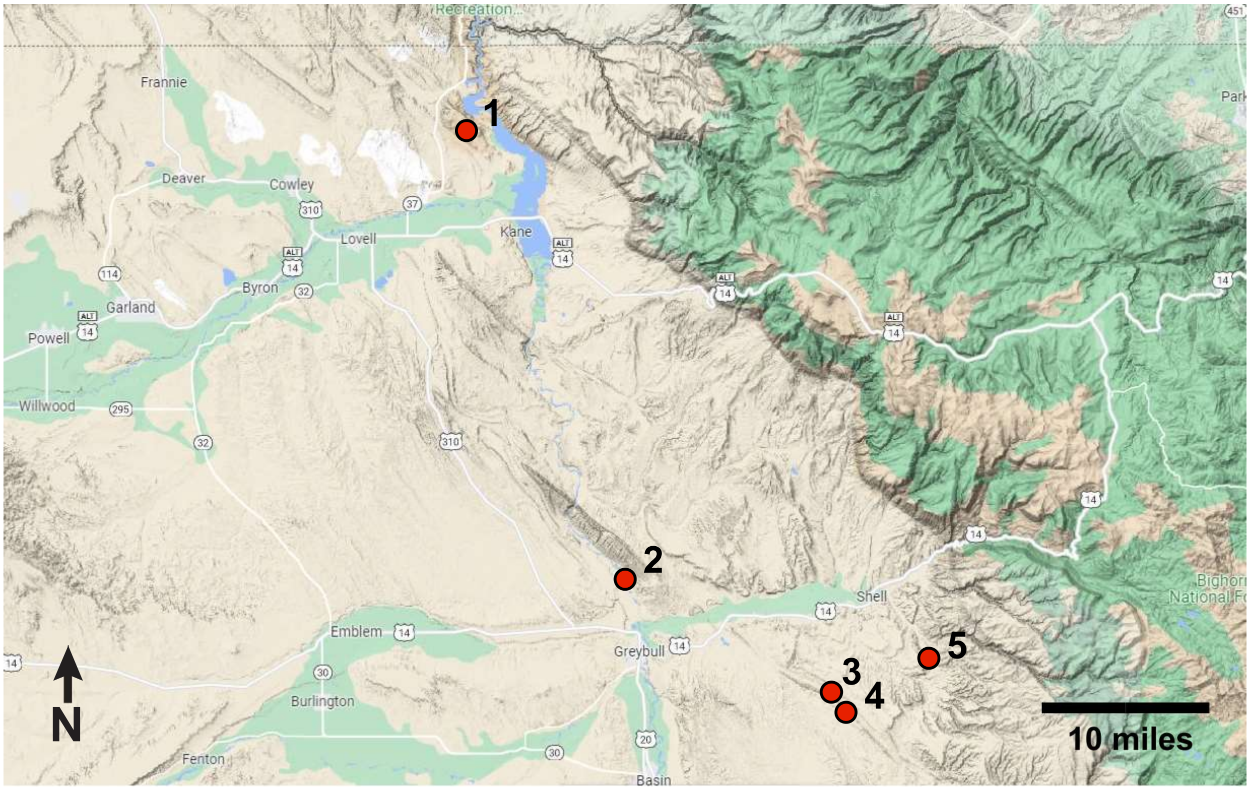

Recreation...
Frannie
Deaver
Cowley
Lovell
Kane
Byron
Garland
Powell
Willwood
Shell
Bighorn National Fo
Emblem
Greybull
Burlington
Fenton
Basin
1
2
3
4
5
N
10 miles

Figure 4. Geographic map of the Bighorn Basin showing the study area, with points indicating the location of known trackways. 1: Pterosaur Tracks; 2: Gypsum Spring Dinosaur Tracksite; 3: Red Gulch Dinosaur Tracksite; 4: Flitner Ranch Dinosaur Tracksite; 5: Yellow Brick Road Dinosaur Tracksite.

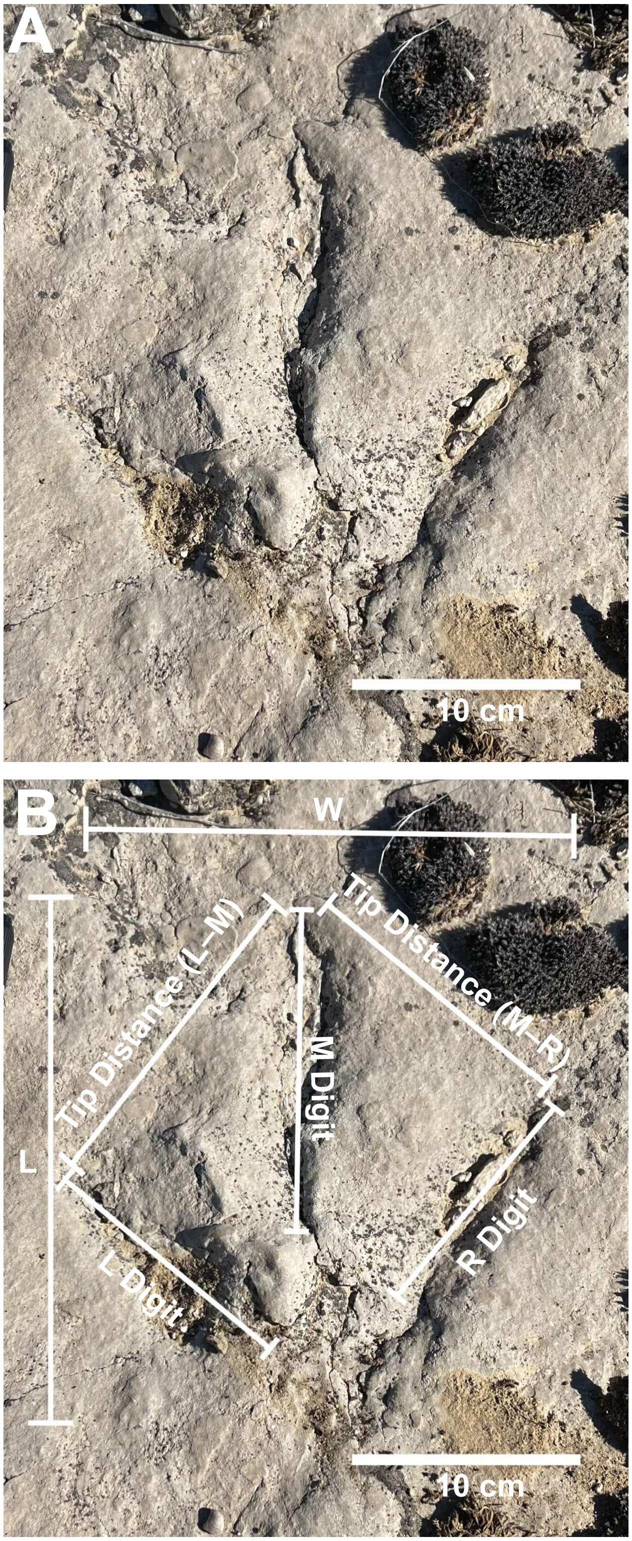

A
10 cm
B
W
L
Tip Distance (L–M)
Tip Distance (M–R)
M Digit
L Digit
R Digit
10 cm

Figure 5. Representative tridactyl print with white lines to show what is being measured. A) Raw image. B) Interpreted image.

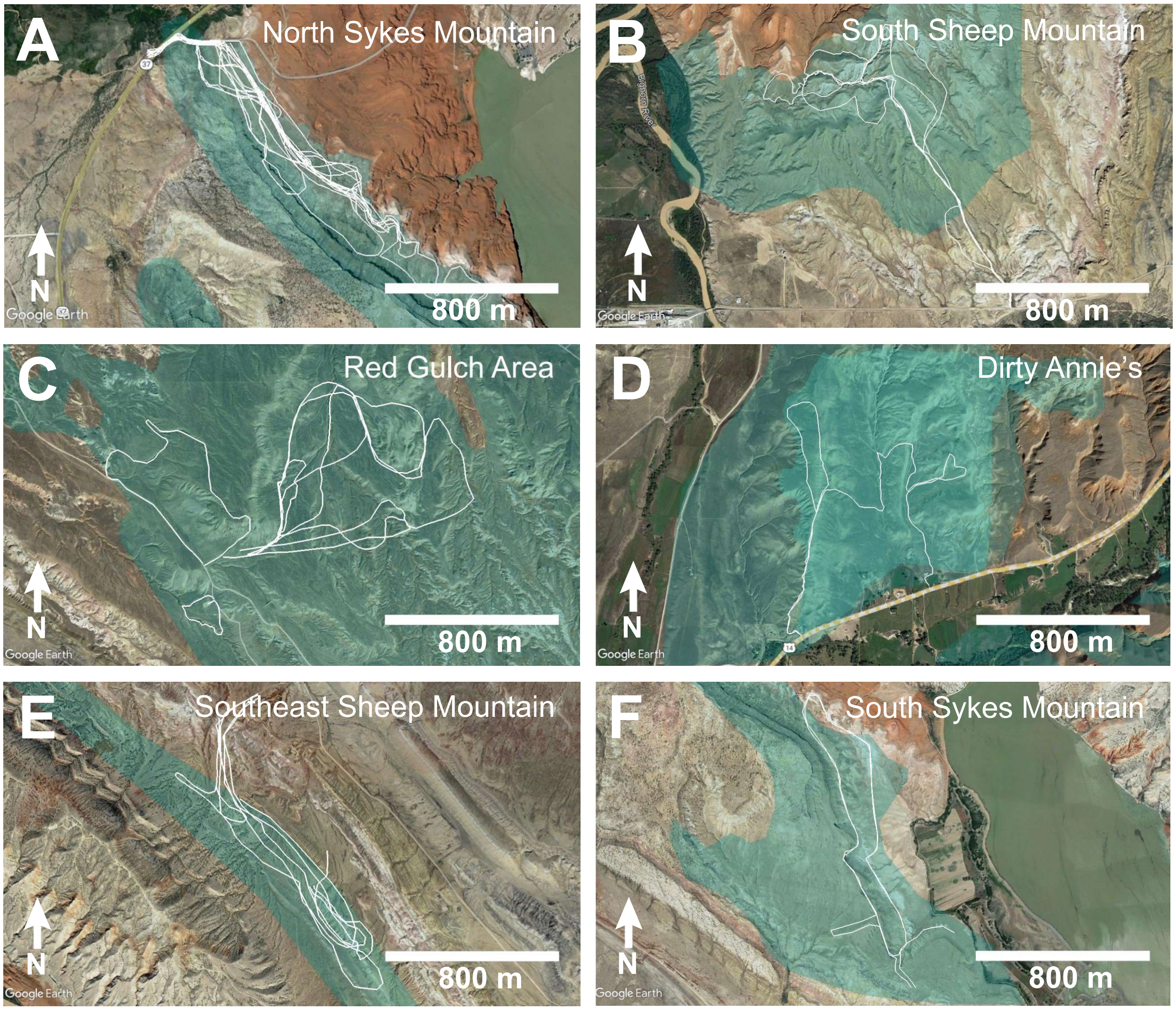

A
North Sykes Mountain
N
800 m
B
South Sheep Mountain
N
800 m
C
Red Gulch Area
N
800 m
D
Dirty Annie's
N
800 m
E
Southeast Sheep Mountain
N
800 m
F
South Sykes Mountain
N
800 m

Figure 6. Paths walked (white) in the Gypsum Spring and Sundance Formations in search of tracks. Blue-green overlays indicate areas of outcrop of Gypsum Spring and Sundance Formations. A) Vicinity of Red Gulch Dinosaur Tracksite (RGDT) and Yellow Brick Road Dinosaur Tracksite (YBRDT). B) Northern end of Sykes Mountain. C) Southeastern side of Sykes Mountain. D) Southern end of Sheep Mountain. E) Hulett eolian deposits on the southeastern flank of Sheep Mountain. F) Areas near Dirty Annie's west of Shell, Wyoming. Owing to the Paleontological Resources Preservation Act, precise coordinates cannot be shown on maps.

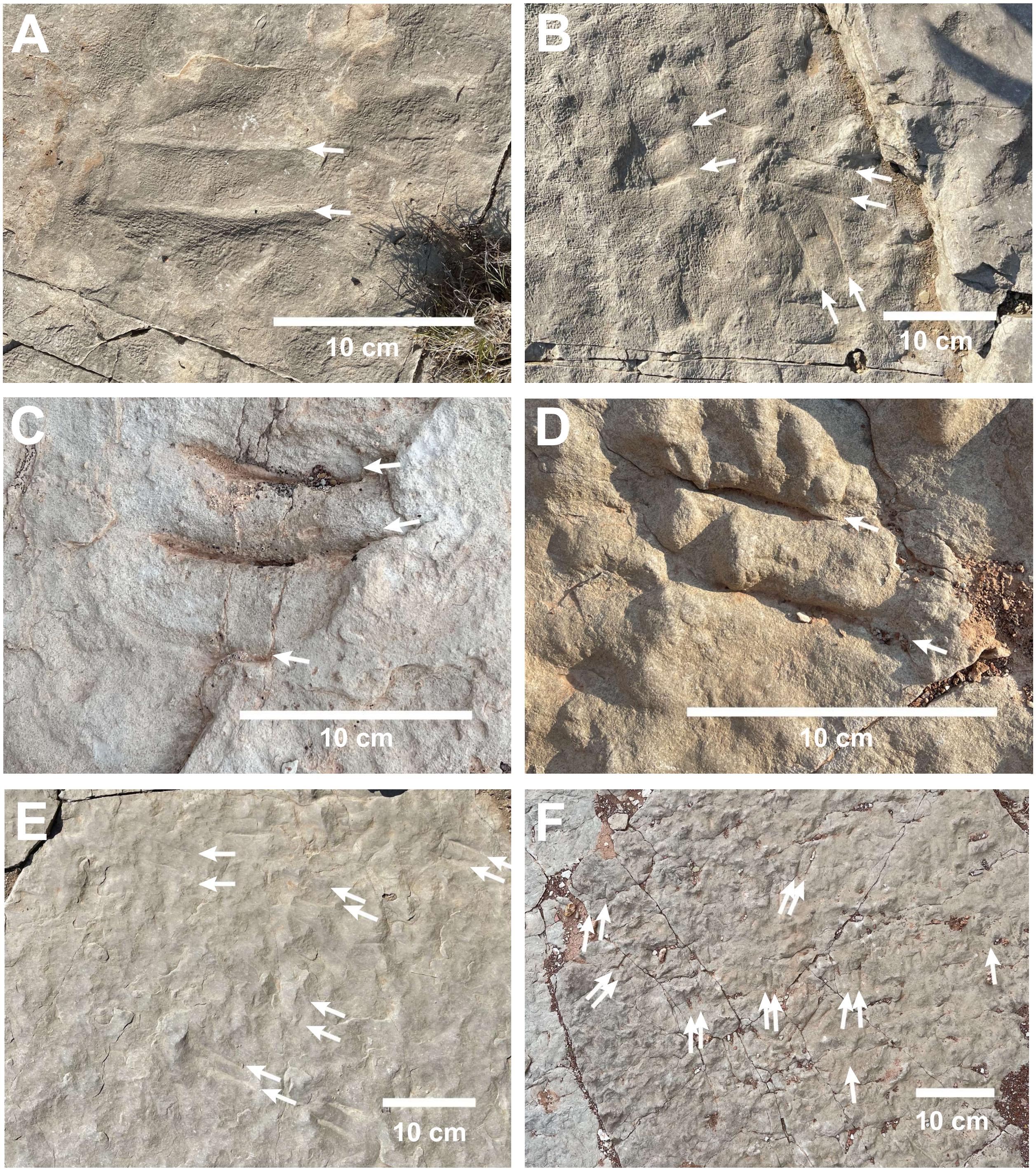

A
10 cm
B
10 cm
C
10 cm
D
10 cm
E
10 cm
F
10 cm

Figure 7. Representative theropod swim tracks in the middle member of the Gypsum Spring Formation, North Sykes Mountain locality. Tracks consist of two or three parallel grooves (arrows).

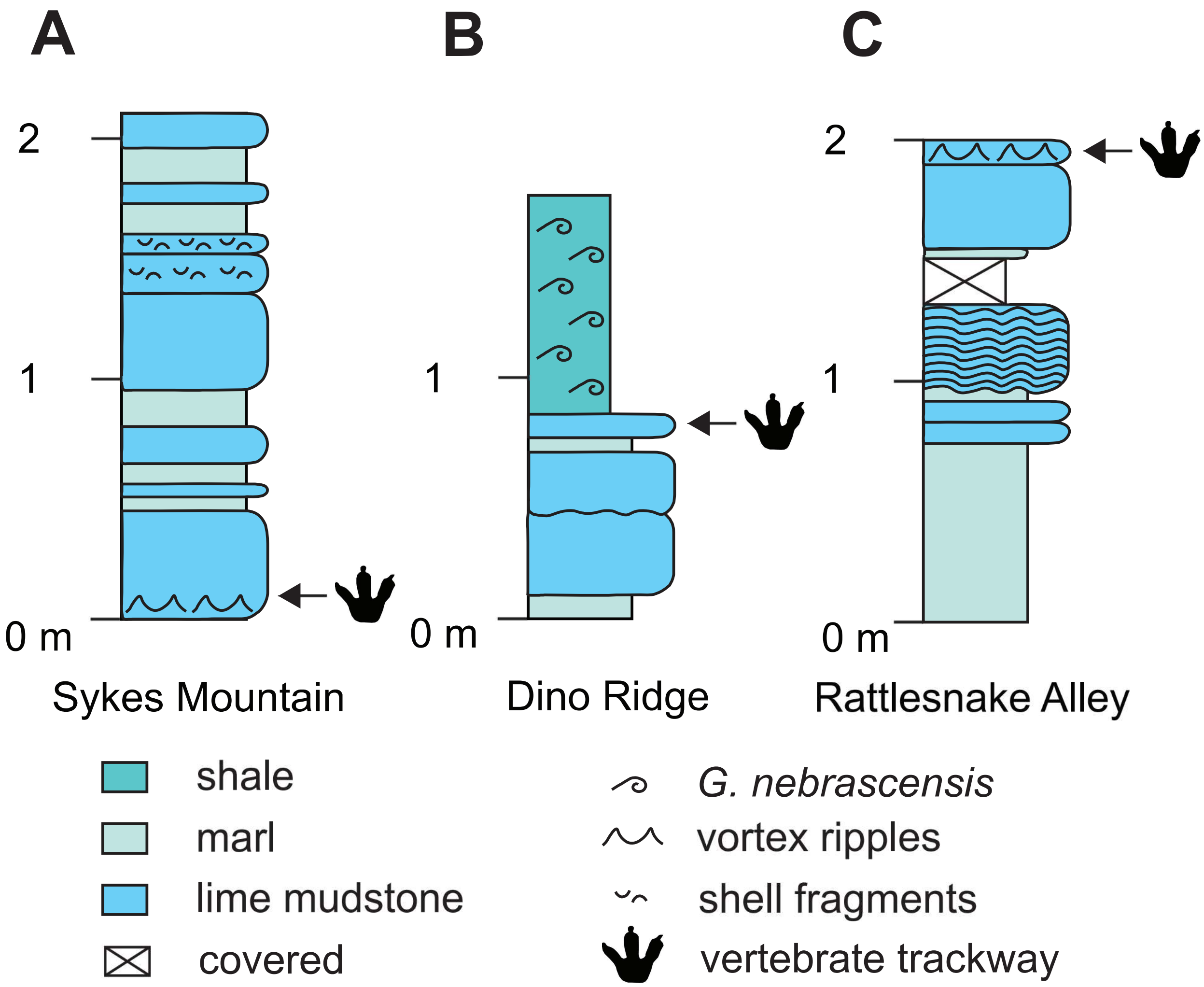

A
B
C
2
1
0 m
2
1
0 m
1
0 m
Sykes Mountain
Dino Ridge
Rattlesnake Alley
shale
marl
lime mudstone
covered
G. nebrascensis
vortex ripples
shell fragments
vertebrate trackway

Figure 8. Stratigraphic columns measured at trackways. A) Gypsum Spring B at Sykes Mountain. B–C) Canyon Spring Member, Red Gulch Area.

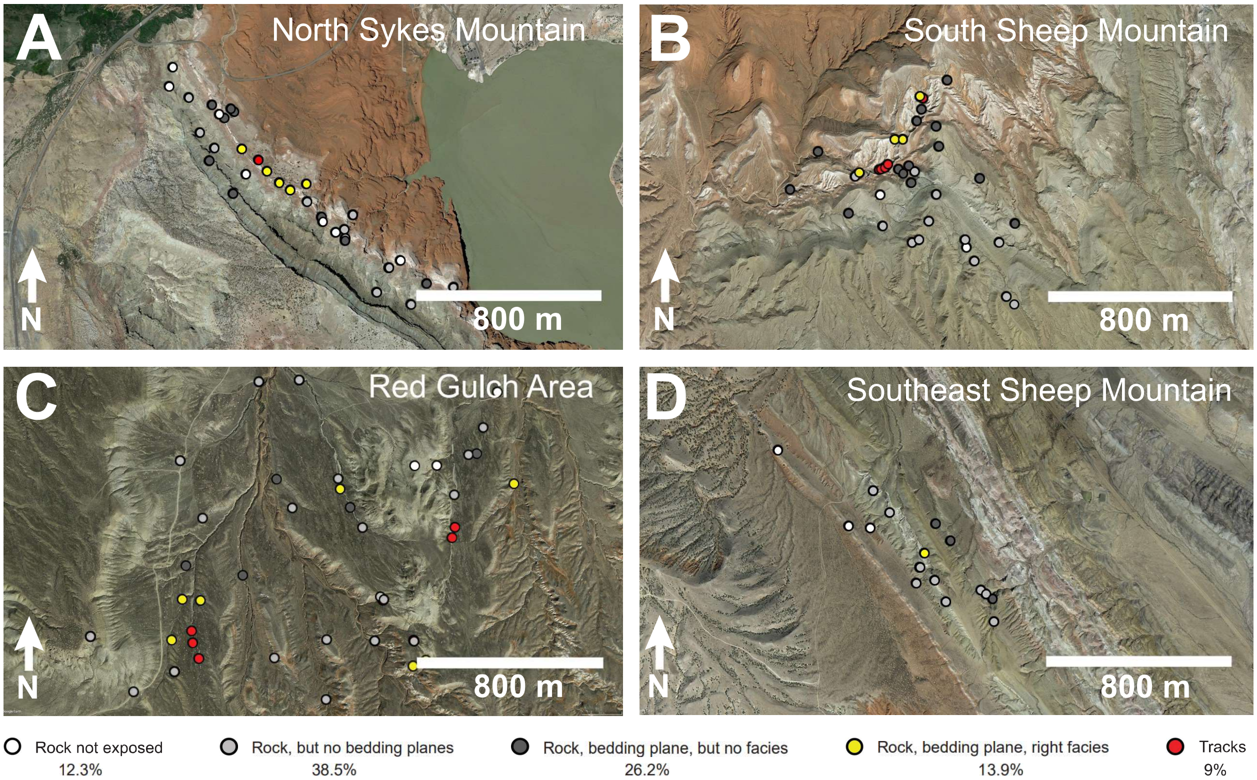

A
North Sykes Mountain
800 m
N
B
South Sheep Mountain
800 m
N
C
Red Gulch Area
800 m
N
D
Southeast Sheep Mountain
800 m
N
Rock not exposed
12.3%
Rock, but no bedding planes
38.5%
Rock, bedding plane, but no facies
26.2%
Rock, bedding plane, right facies
13.9%
Tracks
9%

Figure 9. Maps showing potential for trackway occurrences. Percentages indicate the proportion of available, potentially track-bearing surfaces. A) North Sykes Mountain. B) South Sheep Mountain. D) Red Gulch Area. E) Southeast Sheep Mountain

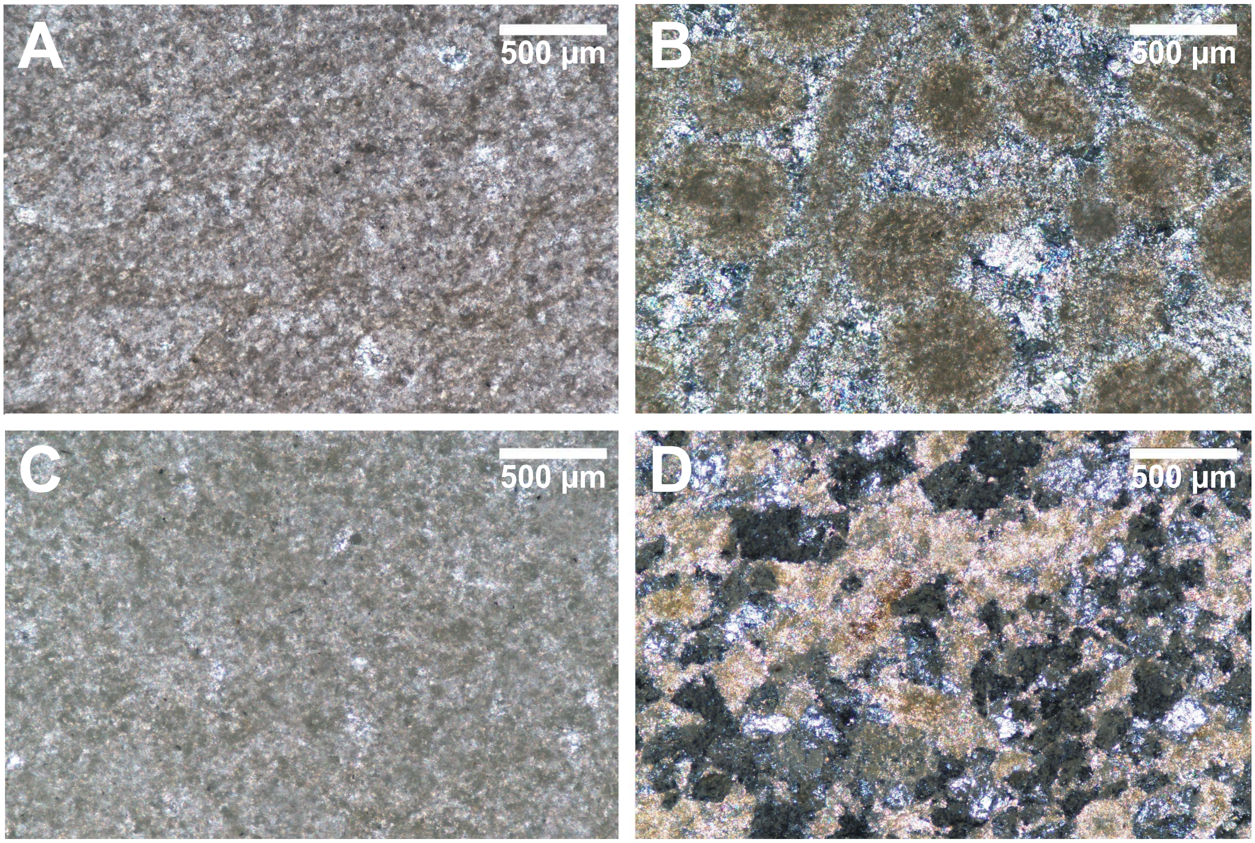

A
500 µm
B
500 µm
C
500 µm
D
500 µm

Figure 10. Photomicrographs of thin sections showing the lithologic characteristics of track-bearing horizons. All samples have varying degrees of micrite. A) Peloid packstone, Dino Ridge locality, Canyon Spring Member. Image taken under plane-polarized light. B) Skeletal ooid-peloid grainstone, Rattlesnake Alley locality, Canyon Spring Member. Image taken under cross-polarized light. C) Peloidal packstone, South Sheep Mountain, Gypsum Spring Formation. Image taken under plane-polarized light. D) Micritized ooid-peloid grainstone with skeletal fragments, Sykes Mountain, Gypsum Spring Formation. Image taken under cross-polarized light.

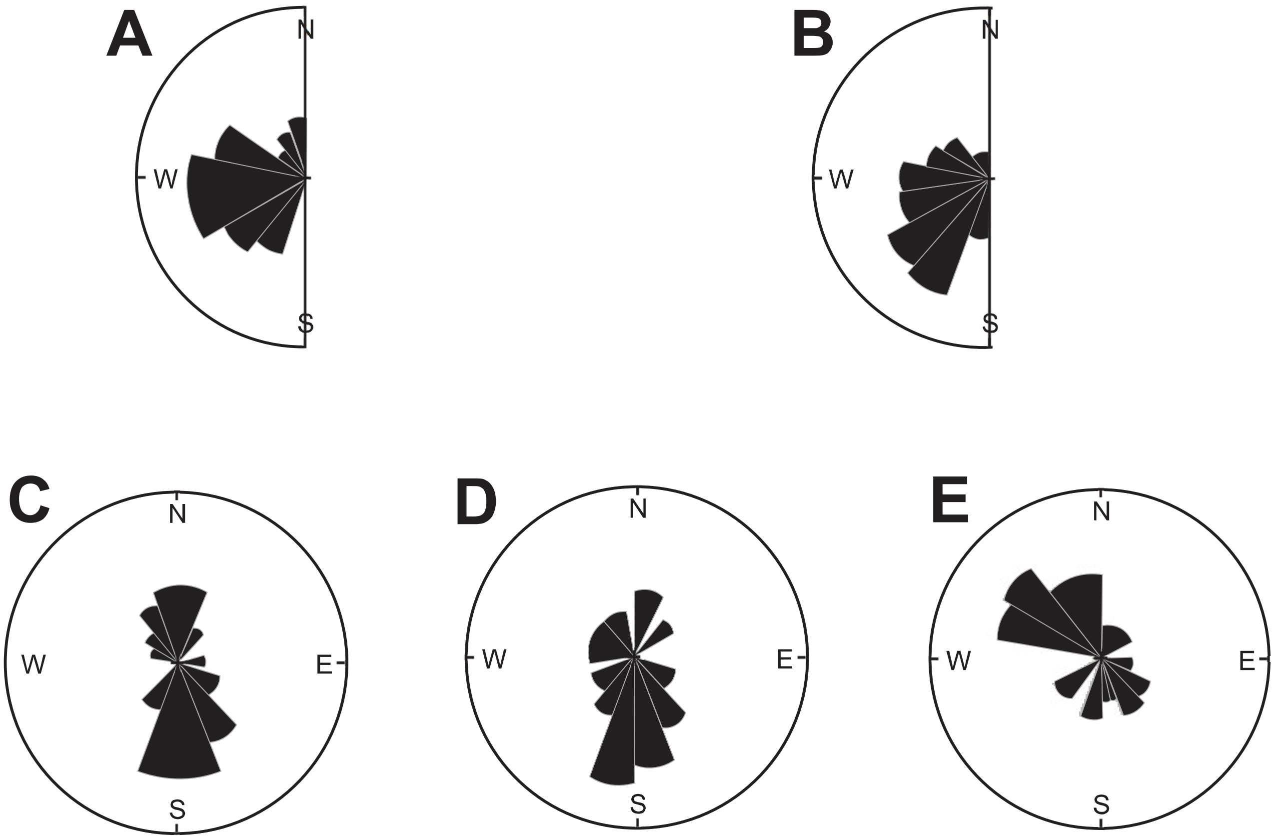

A
N
W
S
B
N
W
S
C
N
W
E
S
D
N
W
E
S
E
N
W
E
S

Figure 11. Rose plots of track azimuths. A) Swim tracks from the Gypsum Spring B, North Sykes Mountain locality. B) Swim tracks from the Gypsum Spring B, South Sheep Mountain locality. C–E) Tridactyl prints from the Canyon Spring Member, Red Gulch Area. Because swim tracks have no direction, only the west half of the rose diagram is plotted.

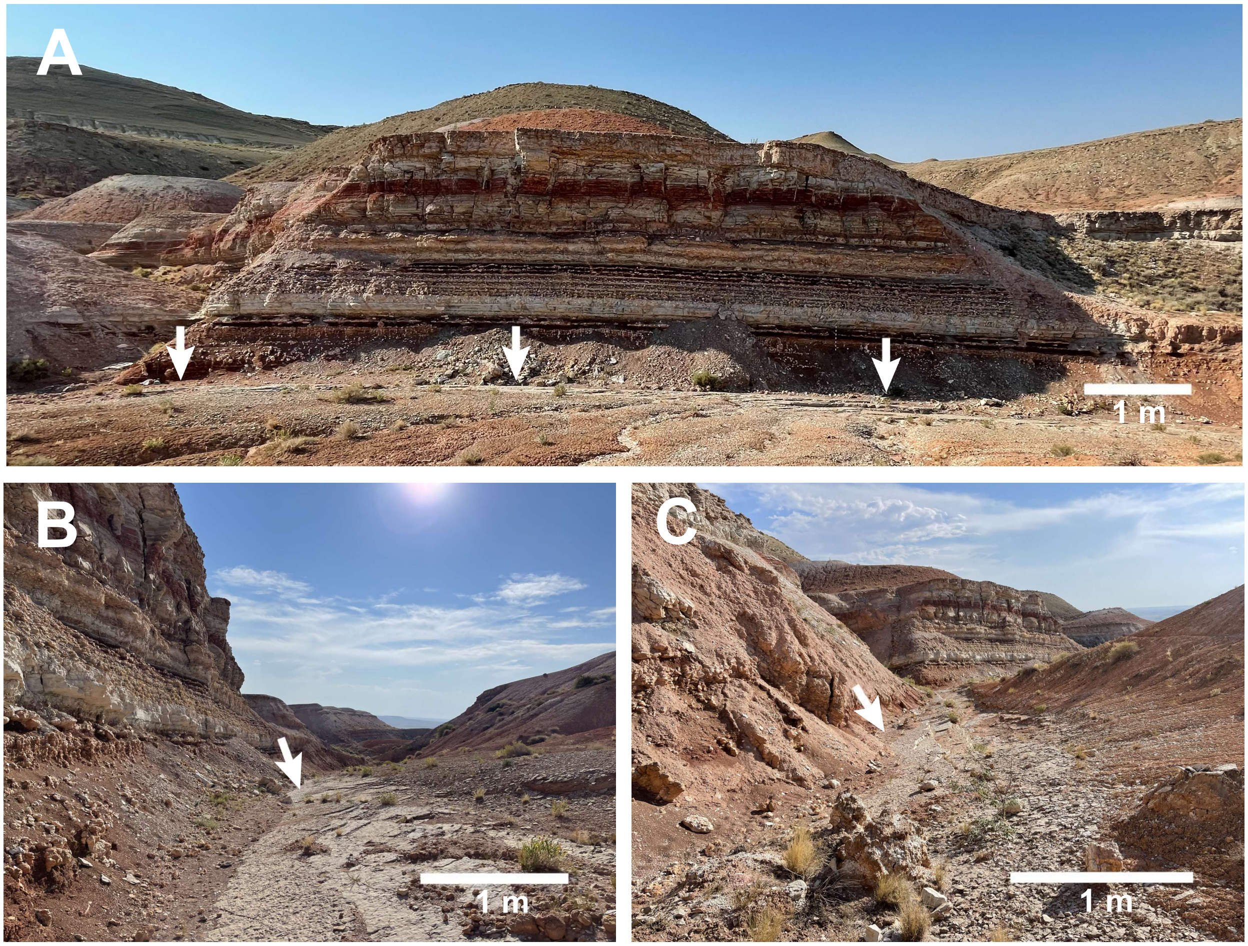
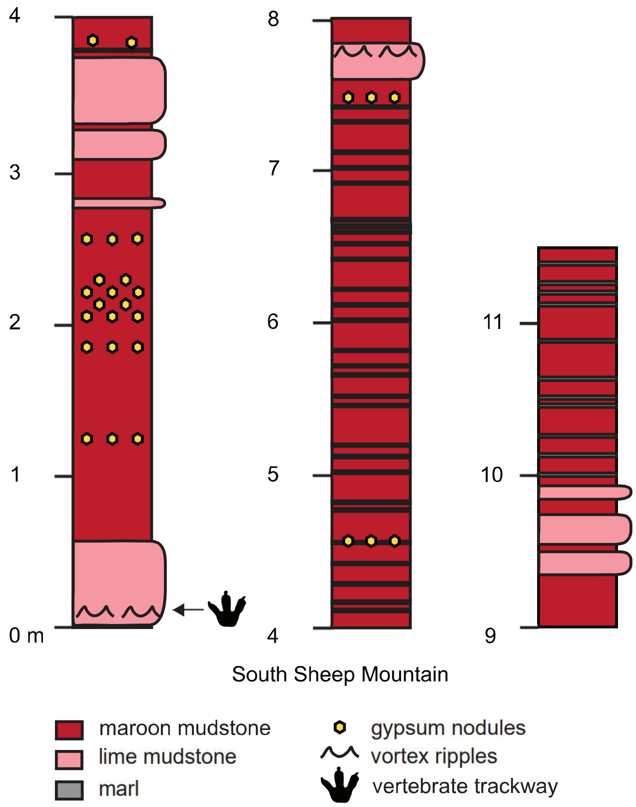

A
1 m
B
1 m
C
1 m

Figure 12. Representative photos of the swim track surface from the middle member of the Gypsum Spring Formation, at the southern end of Sheep Mountain. A) Main trackway surface. B–C) Partial trackway overviews.



4
3
2
1
0 m
8
7
6
5
4
11
10
9
South Sheep Mountain
maroon mudstone
lime mudstone
marl
gypsum nodules
vortex ripples
vertebrate trackway

Figure 13. Stratigraphic section measured from the Gypsum Spring B at the southern end of Sheep Mountain.

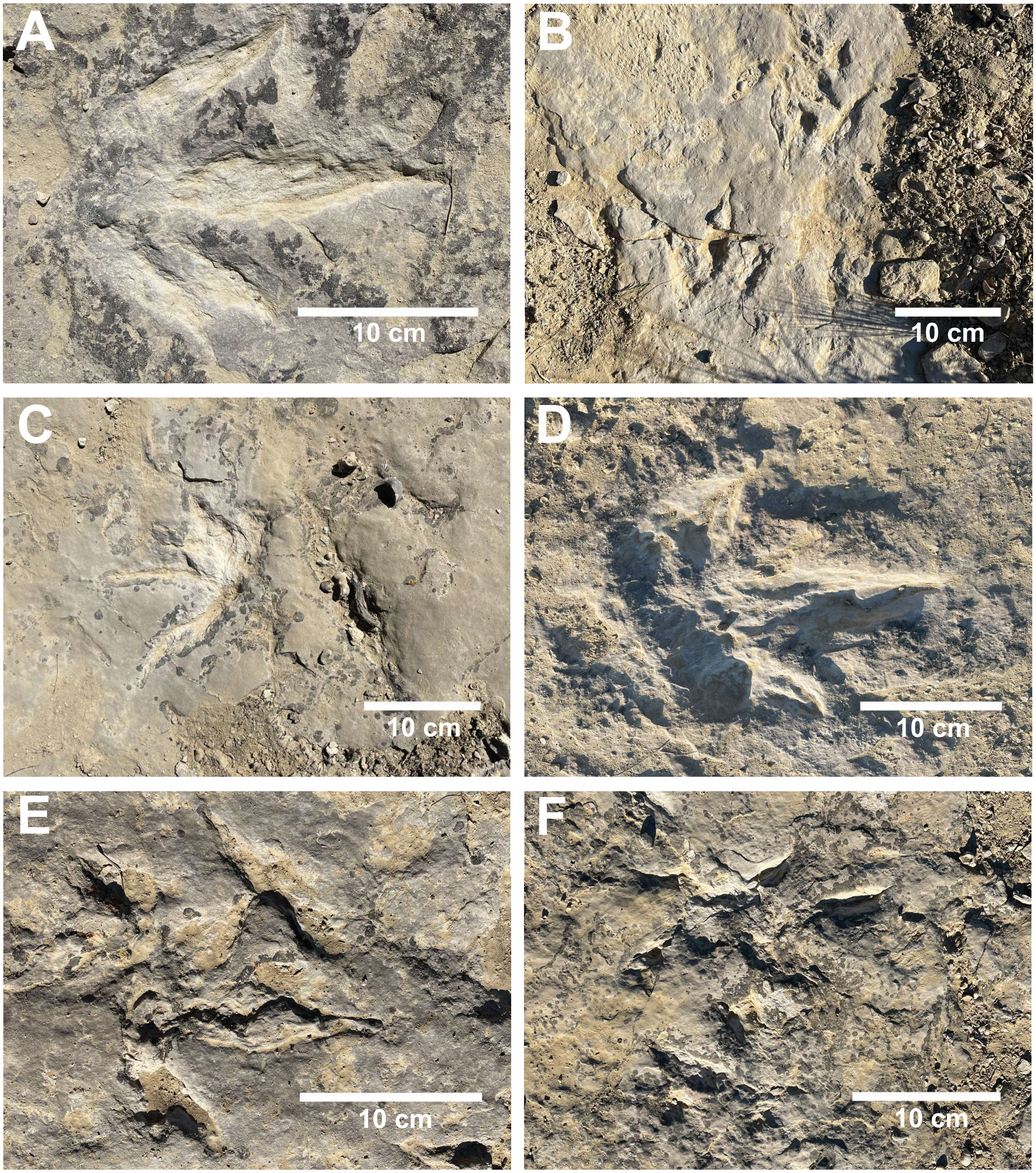

A
10 cm
B
10 cm
C
10 cm
D
10 cm
E
10 cm
F
10 cm

Figure 14. Representative tridactyl theropod prints from the Canyon Springs Member, Rattlesnake Alley and Dino Ridge localities. A–B) Theropod prints from Dino Ridge. C–D) Overprinted theropod prints from Rattlesnake Alley. E–F) Theropod prints from Lonely Tree.

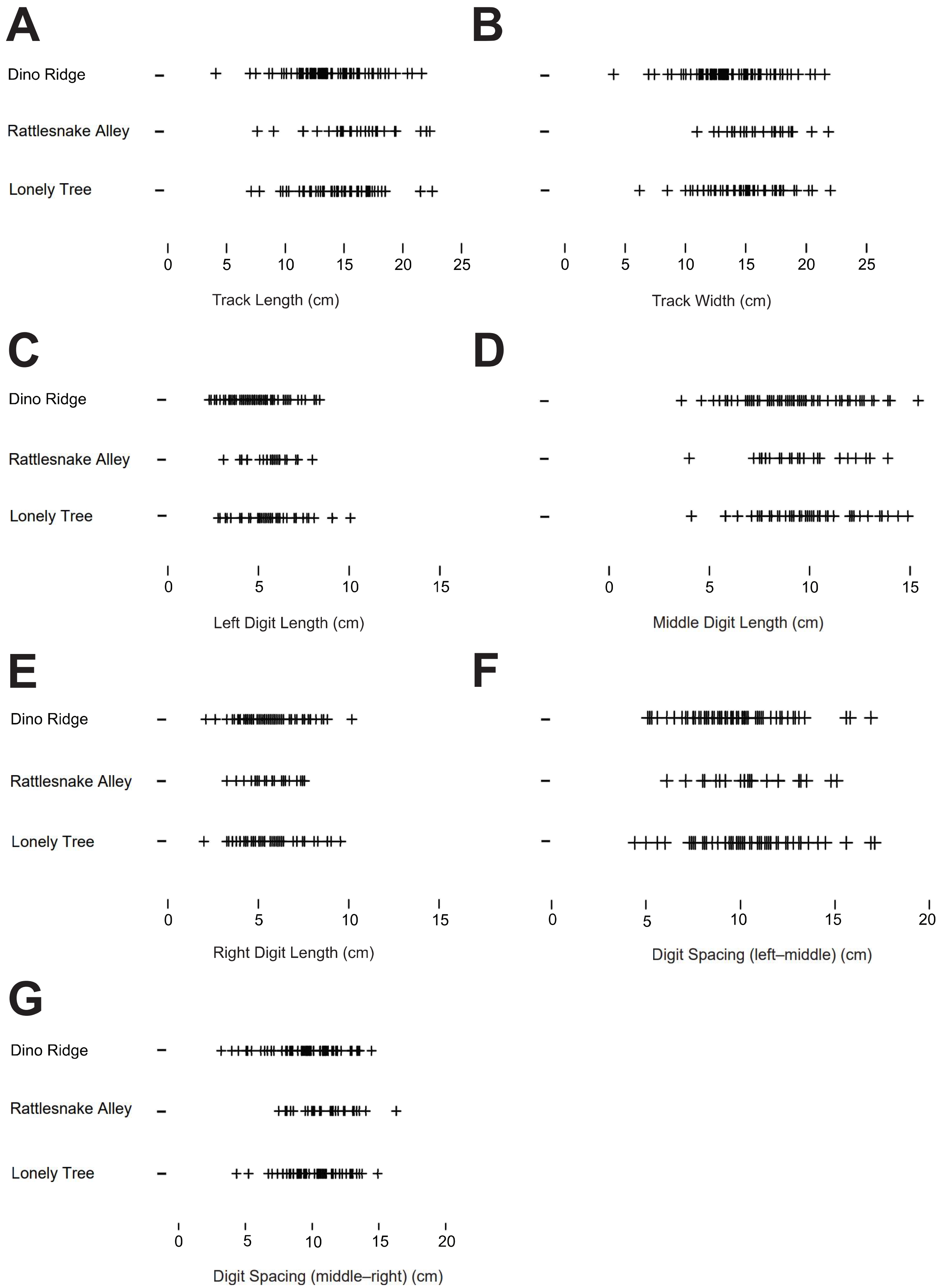

A
B
C
D
E
F
G
Dino Ridge
Rattlesnake Alley
Lonely Tree
0
5
10
15
20
25
Track Length (cm)
Track Width (cm)
Left Digit Length (cm)
Middle Digit Length (cm)
Right Digit Length (cm)
Digit Spacing (left–middle) (cm)
Digit Spacing (middle–right) (cm)

Figure 15. Strip charts with track measurements for the three theropod trackways near the Red Gulch and Yellow Brick Road track sites. A) Track length. B) Track width. C) Left digit lengths. D) Middle digit lengths. E) Right digit lengths. F) Left–middle digit distances. G) Middle–right digit distances.

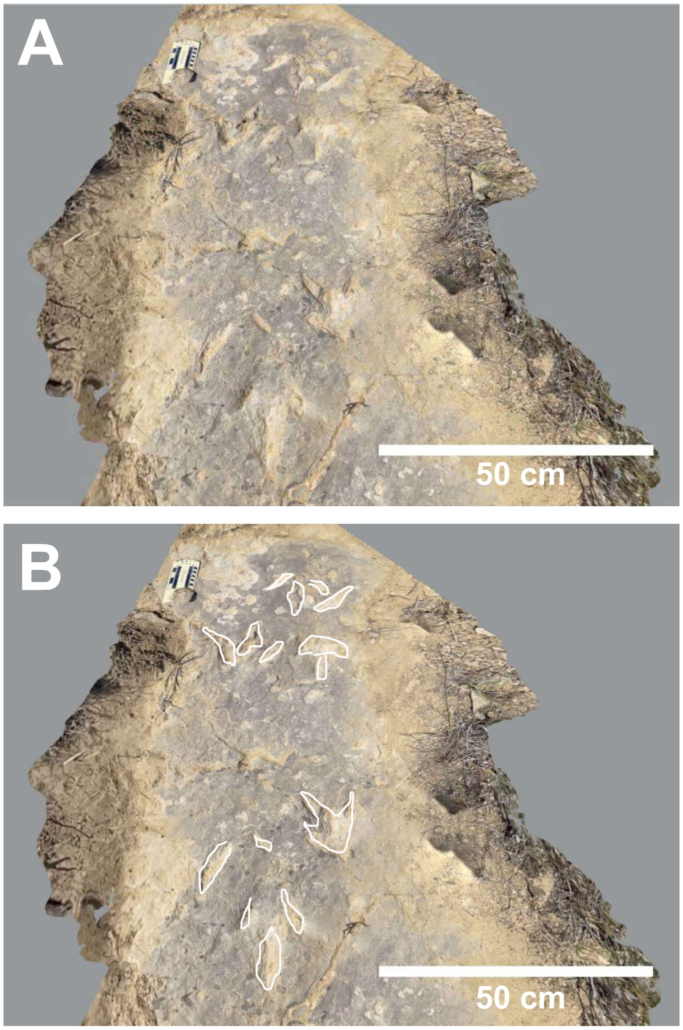

A
50 cm
B
50 cm

Figure 16. 3D models of a portion of track surface preserved in the Canyon Springs Member of the Sundance Formation at the Dino Ridge locality. A) Raw image. B) Interpreted image outlining tracks.


1 cm

Figure 17. Well-preserved raindrop impressions from southeastern Sheep Mountain on a bedding surface of eolian facies, Hulett Member, southeast Sheep Mountain.

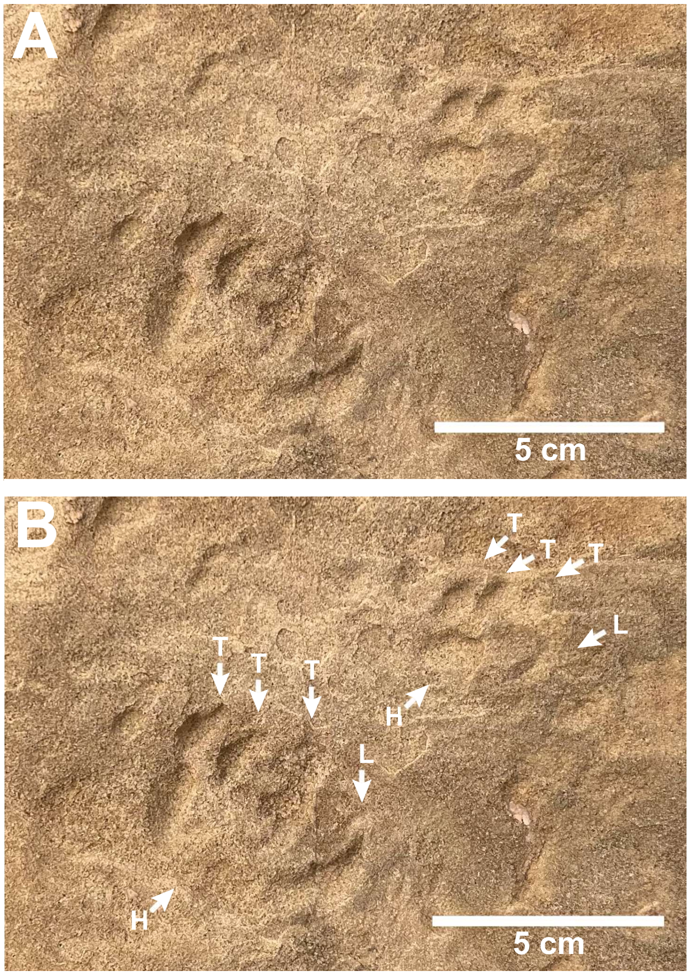

A
5 cm
B
T
T
T
L
T
T
T
H
L
H
5 cm

Figure 18. Pair of tracks from the Windy Hill Member at the South Sykes Mountain locality. This track was possibly made by a turtle (B. Breithaupt, pers. comm.). The track displays three (possibly four) forward-pointed toes (T) and one laterally printed toe (L). Faint heel impressions are also present (H). A) Raw image. B) Interpreted image.