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Ichnology and paleoecology of the Jurassic Aztec Sandstone

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ICHNOLOGY AND PALEOECOLOGY OF THE JURASSIC AZTEC SANDSTONE

By

Heather Marie Stoller

Bachelor of Science
Muskingum University
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A thesis submitted in partial fulfillment of
the requirements for the

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ABSTRACT

Ichnotology and Paleoecology of the Jurassic Aztec Sandstone

by

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In this study I describe and interpret tracks and trackways of the Jurassic Aztec Sandstone of southern Nevada and southern California. This study involved mapping of all known tracks and trackways, including foot length, stride length, and trackway width. Photogrammetric data, collected by Bureau of Land Management scientists, were utilized for several trackways in Red Rock Canyon National Conservation Area.

More than three hundred tracks belonging to five ichnotaxa were documented within the Aztec Sandstone, including about 165 tridactyl Grallator tracks, 250 tetradactyl (four-toed) Brasilichnium tracks, and 7 arthropod trackways of Octopodichnus and Paleohecura. Four of the five ichnotaxa were not previously reported from the Aztec Sandstone. The trackway finds are similar to the most common tracks found in the correlative Navajo Sandstone, although the diversity of tracks is much higher in the Navajo. One type of track examined in this study has not been reported from the Navajo Sandstone. The higher diversity within the Navajo is almost certainly partly due to the much longer history of systematic investigation. All but one of the discovered tracksites in the Aztec were unknown prior to October 2011.
Where possible, in the case of the *Grallator* trackways I calculated the speed of the trackmaker. Speeds range from 0.7 mph (0.35 m/sec) to 8.5 mph (3.8 m/sec). In one trackway, pauses in the animal’s steps are also recorded. Several of the tracksites contain multiple ichnotaxa on the same bedding plane, and sometimes trackways of different ichnotaxa overlap each other. From details such as these, some aspects of the paleoecology of the Aztec Sandstone can be inferred. The *Grallator* trackmakers were carnivorous theropod dinosaurs, which probably preyed on the herbivorous *Brasilichnium* trackmakers. The *Brasilichnium* trackmakers fed on unknown plants. Some tracksites reveal evidence that the trackmakers resided near or visited the same area repeatedly over an extended period of time, which implies the sustained availability of food.
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CHAPTER 1

INTRODUCTION

The purpose of this study is to describe and interpret individual tracks and trackways in the Jurassic Aztec Sandstone, and to use the interpretations to reconstruct the Early Jurassic ecosystem of southern Nevada. Many publications contain descriptions and interpretations of trackways in the correlative Navajo Sandstone of Utah, Arizona, and Colorado (e.g., Lockley, 1996; Loope and Rowe, 2003); however, very few published papers describe tracks within the Aztec Sandstone. Reynolds (2006) and Reynolds and Mickelson (2006) reported tracks in the Aztec Sandstone in the Mescal Range of southeastern California (Figure 1), but prior to the beginning of this study, no published papers had described tracks in southern Nevada. In a Geological Society of America abstract, Rowland and Mercadante (2007) described therapsid tracks in the Aztec Sandstone of Valley of Fire State Park, but no other occurrences of tracks had been reported in the Aztec Sandstone in southern Nevada. On November 21, 2011 the Las Vegas Review-Journal reported the discovery of dinosaur tracks in Red Rock Canyon National Conservation Area (Brean, 2011). This report led to other discoveries. Red Rock Canyon (Figure 2), Valley of Fire State Park (Figure 3), and the Gold Butte area (Figure 4) in Southern Nevada, and the Mescal Range near Mountain Pass in California, all contain extensive exposures of Aztec Sandstone, providing excellent opportunities to find trace fossils of the animals that lived in this region in the Jurassic, and tracksites are now known from all of these areas. Aspects of this study have been published in Stoller et al. (2013) and Rowland et al. (in press).

The Aztec Sandstone is Early-Middle Jurassic in age (Stoller et al., 2013;
Rowland et al., in press). It is a remnant of a huge sand sea, which includes the Aztec, Navajo, and Nugget Sandstones, all of which contain conspicuous cross-bedding (Loope and Rowe, 2003). Prior to Miocene extension, the Aztec and Navajo formations were contiguous bodies of rock (Marzolf, 1993); they have different names only because the geologists who named them did not yet know that they were part of the same Jurassic sand sea, separated by post-depositional tectonic activity. The Navajo Sandstone is commonly considered to be entirely Early Jurassic in age (e.g., Peterson and Pipiringos, 1979), however Marzolf and Anderson (2005, p. 287) argued, “the age of the top of the Navajo Sandstone probably is as young as Bajocian (ca. 170 Ma).” The Bajocian Stage is early Middle Jurassic; the Early-Middle Jurassic boundary is placed at 174.1 Ma (Ogg and Hinnov, 2012). In the Cowhole Mountains of eastern California, the Aztec Sandstone interfingers with volcanic rocks that date between 173 and 170 Ma (Reynolds, 2006b), thus there is little question that the Aztec Sandstone is partly Middle Jurassic.

The Aztec Sandstone is 636 m thick at its type section near Goodsprings, Nevada (Hewett, 1931). However, in the Mescal Range, in eastern California it is only 333 m thick (Fleck and Reynolds, 1996). In the Mescal Range the Aztec Sandstone is lithologically different from the red-orange, fine-to-medium-grained, quartz sandstone of the Aztec Sandstone in other locations; there it consists of siltier sandstones, which are overlain by green-yellow, flat-bedded sandstones (Evans, 1971). Although these locations are lithologically different, many of the same vertebrate and invertebrate trace fossils are found in all of them.

Eolian depositional systems, such as the system represented by the Aztec Sandstone, are open systems driven by cycles of heat from the sun. The resulting wind
transported sand-size particles and eventually deposited them in another location (Christiansen, 2009). The lithified cross-beds record the direction the wind was blowing when the dunes were deposited (Christiansen, 2009). Stokes (1978) described cross-bedding and associated animal tracks in the Navajo Sandstone, and Marzolf (1983) documented that the winds that deposited the Aztec Sandstone predominantly blew toward the southwest.

1.1 Geographic Setting

The tracks included in this study are located in four different areas: Red Rock Canyon National Conservation Area (RRCNCA), Valley of Fire State Park, and the Gold Butte area, all within Nevada, and the Mescal Range in California. RRCNCA, established in 1990, is located 10 miles west of Las Vegas, Nevada. Valley of Fire State Park is 55 miles northeast of Las Vegas, and only 6 miles from Lake Mead. Gold Butte is 52 miles south of Mesquite, NV and 120 miles northeast of Las Vegas. The Mescal Range is located in southern California, 55 miles southwest of Las Vegas (Figure 1).
Figure 1: Geographic locations of the tracksites in the study area. RRCNCA= Red Rock Canyon National Conservation Area. VOF= Valley of Fire State Park.

1.2 Geologic Setting

RRCNCA and Valley of Fire State Park each contain multiple tracksites and
several ichnotaxa. The bluffs of sandstone are remnants of the Jurassic dunes that occupied southern Nevada, and adjacent.

RRCNCA, which is managed by the Bureau of Land Management, consists of cliffs of Aztec Sandstone (Figure 2). Tracksites occur in several widely dispersed areas within the conservation area.

The geologic setting of Valley of Fire State Park is similar to that of RRCNCA (Figure 3), however all of the tracksites discovered to date occur within an area smaller than one kilometer in diameter.

The Gold Butte area is mostly controlled by the Bureau of Land Management, but some parts of the area lie within the Lake Mead Recreation Area managed by the National Park Service. Geologically the area is known for its granite porphyry (Leighton, 1952), but the Aztec Sandstone also occurs as bold outcrops (Figure 4).

The Mescal Range is the smallest of the four areas, yet the highest diversity of tracks has been reported from that area (Reynolds, 2002, 2006a, 2006b). Reynolds and Mickelson (2006) reported the occurrence of pterosaur tracks in the Aztec Sandstone in the Mescal Range, but this interpretation is controversial. In 2009, paleontologists from the San Bernardino County Museum and from the Los Angeles County Museum of Natural History collected several tracks and trackways to protect them from vandalism, including the only dinosaur tracks found in the state of California (Springer et al., 2009). These tracks in the collections of the San Bernardino County Museum and the Los Angeles County Museum of Natural History were examined as part of this study. However, since those tracks had already been described by Reynolds (2006b) and Reynolds and Mickelson (2006), they are not included in this study in great detail.
Figure 2: Geologic map of RRCNCA (Longwell et al., 1965). Ja is Aztec Sandstone. Tracks occur at multiple locations.
Figure 3: Geologic map of Valley of Fire State Park and surrounding area (Longwell et al., 1965). Ja is Aztec Sandstone. Star indicates the general area in which tracks have been found.
1.3 Ichnology

A Jurassic trackway record is found on every continent except Antarctica. Trace fossils have been a growing interest in these deposits (Loope, 2008), including traces of arthropods as well as vertebrates (Ahlbrandt et al., 1978). Trace fossil diversity is
connected to the level of the water table and climatic conditions, but in desert settings the water table usually lies below the accumulation line (Mountney and Jagger, 2004). The diversity of arthropod ichnotaxa in the Aztec Sandstone is relatively high, including three ichnogenera, indicating that climatic and moisture conditions were suitable for arthropods. In dry eolian deposits, trace fossils may not be preserved, but in some places they may form in grain-flow layers on the dune slip faces in damp sand during rainy seasons (Sadler, 1993; Loope, 2006).
CHAPTER 2

METHODS

2.1 Field Work

The methods used in this study included mapping, photographing, recording GPS coordinates, and cataloging track-bearing locations within the Aztec Sandstone. To map each tracksite I used a grid system. In most cases I used chalk to create a grid, excluding RRCNCA as our permit did not allow the use of chalk. For one tracksite we used a grid constructed of PVC pipe with holes drilled every ten cm and string stretched across the rectangular PVC grid. At another RRCNCA site we used a volleyball net as a grid; the squares in the net are 10 cm by 10 cm. As a general rule, I used grids that were 10 cm by 10 cm squares, except in cases of large tracksites where 20 cm by 20 cm grids were used, and then scaled in the same fashion as the decimeter grids. After the grids were laid, I created a rough sketch map of the tracks in the grid. I recorded the details of each individual track on the sketch map. These details include length and width of each track, trackway stride and width, and pace angulation. These details allowed me to determine the speed the trackmaker was traveling, using Alexander’s equation for calculating speeds (Alexander, 1976).

Photography played a large role in collecting information regarding each track, since large-scale photographs were used to create images and illustrations in Adobe Illustrator. Close-up photos of certain tracks provided the divarication angle, which reveals specific details about each foot.

After each tracksite was detailed and photographed, it received a catalog number and was placed on a master list (Appendix 1). Some tracksites are subdivided to identify specific trackways located at that tracksite. For example, there are two trackways at
tracksite UNLV-AZ-008; these are numbered 008.1 and 008.2. At tracksites UNLV-AZ-004, 005, 006, and 008 photogrammetric data were collected by BLM scientists Neffra Matthews and Brent Breithaupt. Photogrammetry is a technique in which special reference panels are placed on the bedding plane adjacent to the tracks (Milner et al., 2012). Multiple overlapping photos are taken, and with the help of specialized software a seamless, distortion-free image of the trackway surface can be produced (Milner et al., 2012). In this study photogrammetry was implemented only on selected RRCNCA tracksites in collaboration with BLM scientists. UNLV-AZ-012, in Valley of Fire State Park, is the only site where a silicone mold was created to replicate the morphology of the tracks, allowing a detailed analysis to take place in a lab setting. This technique involved first filling cracks in the rock with clay, so that the silicone did not flow into them. Next, a clay wall, approximately 2-3 cm high, was constructed around the perimeter of the area to be molded; the purpose of this wall was to constrain the liquid silicone. Then a liquid sealant was applied to the rock, so that the mold would peel off easily. Once the surface was prepared, a high quality, liquid silicone (GI-1000) was poured onto the surface and allowed to set. Multiple layers of silicone were applied, with a layer of burlap laid in between them to prevent the mold from tearing. After the silicone had cured completely, the clay dam was removed, and the silicone mold was peeled off the rock surface. The clay crack-fillings were removed as well. This mold will be used for future Brasilichnium studies that Dr. Steve Rowland may supervise, and will remain at UNLV throughout all of the necessary research.

Precise locations of the tracksites studied are not provided, at the request of RRCNCA and Valley of Fire State Park managers.
2.2 Museum Work

In 2009, dinosaur tracks from the Mescal Range of California were collected and placed in the San Bernardino County Museum and the Los Angeles County Natural History Museum (Springer et al., 2009). To examine these tracks it was necessary to travel to these museums. It was hoped that the tracks would be curated in a fashion that would allow me to analyze them in the museums’ collections, but this turned out not to be the case. I was able to examine some of the tracks in the museum collections, but the majority of the Mescal Range data were collected from information provided by the museum staff, including original site maps.
CHAPTER 3
DESCRIPTION OF TRACKSITES AND ICHNOGENERA

3.1 Ichnogenus *Grallator*

The ichnogenus *Grallator* was described by Hitchcock (1858) based on tracks in the Connecticut Valley. His collection is housed at Amherst College in Amherst, Massachusetts. Dinosaur tracks, including *Grallator*, are well known in the southwestern United States. *Grallator* tracks occur primarily in the Upper Triassic-Lower Jurassic (Milner et al., 2006).

A three-toed dinosaur track, *Grallator* is the most common dinosaur track in the Navajo Sandstone (Rainforth and Lockley, 1996; Irmis, 2005), where it typically occurs in inter-dune environments (Rainforth, 1997). These are small, tridactyl tracks of a bipedal, theropod dinosaur; tracks in the Navajo range in length from 5 cm to 15 cm. Rainforth (1997) described *Grallator* tracks as having well defined pad and claw impressions and narrow divarication angles, but tracks in the Aztec Sandstone are usually lacking in those details. Olsen et al., (1998) suggested that *Grallator, Anchisauripus*, and *Eubrontes* are divisions of an ontogenetic growth series with *Grallator* being the smallest of the three.

3.1.1 Red Rock Canyon National Conservation Area

There are four *Grallator* tracksite in the Red Rock Canyon National Conservation Area (RRCNCA), each at a different location. This section will focus on these tracksites, providing details such as track and trackway dimensions and divarication angles.
This tracksite includes the first dinosaur tracks found in Nevada (Brean, 2011), located in the red-orange, iron-rich sandstone of the Calico Basin region. The tracksite lies on top of thin, planar strata, approximately 1.35 meters above the base of a cross-bedded section. This tracksite contains approximately 44 individual, tridactyl tracks on a single 8-m-long surface, with nearly all of the tracks pointed in the northwest direction. Preservation is poor at this site, and unlike other *Grallator* sites, no well-defined features are visible. This tracksite, along with several others, was documented using photogrammetry software. This allowed a higher quality of analysis, revealing tracks and trackways that were not visible with traditional mapping techniques (Figure 5).

The tracks range in size from 11 to 12 cm in length, and between 7 and 9 cm in width, but due to the poor preservation, many tracks occur as isolated, irregular-shaped depressions (Figure 6). Three trackways have been documented on this surface, ranging in length of 0.6 meters to 1.8 meters.
Figure 5: Photogrammetric map of tracksite 004 containing approximately 44 *Grallator* tracks. Colors indicate elevation changes in millimeters.
Figure 6: Photograph of tracksite 004 displaying approximately 22 *Grallator* tracks. Scale is 10 cm long, divided into decimeters.

**UNLV-AZ-005**

Tracksite 005 is located approximately 200 meters north of tracksite 004, and has just one individual track preserved (Figure 7). This well-preserved track is nearly bilaterally symmetrical and is located on a narrow bedding plane, on a partially covered surface. This track, which is coated with rock varnish, is approximately 11.8 cm long and 9.3 cm wide.

Photogrammetric data collected at this site were used to create a detailed topographic map, a low angle, oblique-view image of the track, and cross sections, displaying that the deepest portion of the footprint is on the imprint of digit III (Figure 8).
Figure 7: Individual *Grallator* track from tracksite 005. See Figure 8 for photogrammetric analysis of this track.
Figure 8: Photograph and photogrammetric data from tracksite 005 showing contour map and cross sections of track (Rowland et al., in press).
Tracksite 008, located in the Pine Creek area of RRCNCA, consists of 17 tridactyl *Grallator* tracks on a 10-meter-long boulder of varnished sandstone, tilted at 38° (Figures 9-12). The 17 tracks are well preserved within one continuous trackway, roughly 3.5 meters long (Figure 9). Due to the fact that the boulder is loose and has moved an unknown distance downslope, it is impossible to reconstruct the original orientation of the block.

The tracks at this site average 14 cm long and 8 cm wide with a divarication angle of 37° between digits II and III (Figure 10). The individual tracks are identified with letters “a” through “q” in Figure 11. The tracks have broad heels and have the appearance of webbing between digits. Reynolds (2006b, p. 22) reported similar tracks in the Mescal Range, which he attributed to “a composite metatarsal pad.” Details of the site 008 trackway are shown in Figure 11, including the trackway stride and width. In one portion of the trackway (tracks k and l of Figure 11), the animal apparently literally stopped in its tracks, leaving two footprints side-by-side; then it stepped forward into a second pause, leaving two more footprints (tracks m and n of Figure 11). The animal then stepped forward with its right foot with the same pace as prior to the double pause.

As illustrated in Figure 12, the quality of preservation at this location is the best found thus far in the Aztec Sandstone, so I interpret circumstances permitting these tracks to be preserved differently than those at the other locations. Other *Grallator* tracks in the Aztec Sandstone have been interpreted as “undertracks,” which are impressions made on a surface that is some distance beneath the actual surface on which the animal walked (Stoller et al., 2013 and Rowland et al., in press). But in this case I interpret the tracks to
have been impressed directly into an exposed layer of moist sand, which is preserved as the trackway surface exposed at this site.

Figure 9: Photogrammetric image of site 008 displaying the trackway and resting stance.
Figure 10: (A) Photograph of a well-preserved *Grallator* track at site 008.1 (B) Sketch of the same track displaying size and divarication angle.
Figure 11: *Grallator* trackway at site 008.1 displaying trackway width and stride.
Figure 12: Photograph of site 008.1 with 20 cm volleyball-net grid over 3 *Grallator* tracks.

**UNLV-AZ-017**

This tracksite contains several different tracks and trackways. *Grallator* trackways deposited at this site record the fastest movement of dinosaurs that has so far been documented in the Aztec Sandstone. Unlike the other tracksites containing multiple trackways, the tracks at this location are all traveling in different directions. The average length of the tracks is 10.5 cm, and the stride of the two trackways is 137 cm and 104 cm (Figure 13). Sketches of two trackways are in Figure 14. Arthropod tracks are also found at this site, as well as one individual track of a non-dinosaur, possibly a synapsid.
Figure 13: Photograph displaying a *Grallator* trackway with 5 tracks leading away from the camera.

Figure 14: (A) A well-preserved trackway at site 017 with a 104 cm stride. (B) A poorly preserved trackway with a stride of 137 cm. This track has the fastest traveling speed documented in the Aztec Sandstone.
3.1.2 Valley of Fire State Park

Although Valley of Fire State Park spans approximately 42,000 acres, the three *Grallator* tracksites in the park are located within 100 yards of each other. The tracksites, although close in proximity, have extremely different modes of preservation.

**UNLV-AZ-001**

Tracksite 001 is located on an outcrop of bedrock 10 meters wide and 20 meters long, with an approximate relief of 1.7 meters (Stoller et al., 2013). Located in the middle of the outcrop are six individual *Grallator* tracks in a distinct trackway (Figures 15, 16). Preservation at this site is very poor, and the visibility of the tracks is heavily dependent on sun angles (Figure 17). The individual tracks average approximately 12 cm long and 10 cm wide, although the preservation makes precise measurements impossible. The trackway has a stride of 52 cm, with a trackway width of 18 cm (Figure 16).

These tracks are interpreted as undertracks, like most of those found in RRCNCA. Manning (2004), found that moisture content between 2-24% by weight is needed to preserve distinct dinosaur tracks in sand. Above 24% moisture, the sand is not cohesive and flows under its own weight. This trackway apparently formed in fairly wet sand, causing the sediment to adhere to the bottom of the dinosaur’s foot as it exited the impression (Rowland et al., in press).
Figure 15: Map of site 001 in Valley of Fire State Park with *Grallator* and *Paleohelcura* trackways (Stoller et al., 2013).
Figure 16: Photograph of site 001 showing eight *Grallator* tracks in one distinct trackway.
Tracksite 002 is located on the side of a large, overturned boulder, but unlike all of the other *Grallator* tracksites in this study, this site is a cross-section of bedding that displays disturbed laminae (Figure 18). The disrupted zones are approximately 9 cm wide at the top, decreasing in size downward. Loope (2006) described such disturbances in the Navajo Sandstone, using the descriptive terms shown in Figure 19. I interpret these tracks to have been impressed into dry sand by small, theropod dinosaurs, as illustrated in Figure 20.
Figure 18: Individual track sand disturbance at site 002 created by a tridactyl footprint.

Figure 19: Illustration of site 002 labeling the marginal upfold, central downfold, and the base of the undisturbed bed above the track. Terminology after Loope (2006).
UNLV-AZ-003

Tracksite 003 is similar to 002, as it is located on a large, allochthonous block of the Aztec Sandstone which has been turned onto its side, displaying the track in an almost vertical position. Fourteen individual poorly preserved tracks, all pointing in the same direction, are located on this boulder, six of which occur in one recognizable trackway (Figure 21a).

One individual track, with no claw marks, can be seen in Figure 18B, showing the length and width to be approximately 5 cm. These tracks display an asymmetrical divarication of digits. The divarication angles on this track display that the angle between digits II and III is greater than the angle of III and IV. It can be concluded that this track is a left footprint.

Each track in this trackway displays a divarication angle similar to that of the track shown in Figure 21b, with the same symmetry. Thus I conclude that the tracks in
this trackway are all left feet. There are several explanations for this one-legged trackway, some of which are more plausible than others. One explanation is that moist sand was unevenly distributed, so the animal walking through the area stepped in moist sand with its left foot but dry sand area with its right foot. This would allow the left tracks to be preserved, while the right tracks would not be preserved. However, this explanation is not my preferred explanation due to the fact that this dinosaur’s trackway width would be small, based on the track spacing measurements of 18.7 cm. The small, tridactyl dinosaur that is inferred to have deposited this track would have had a small hip width, resulting in a narrow trackway width. The small chance of the dinosaur perfectly straddling the dry and moist sand boundary consistently is very small, and no other sedimentological evidence is present to support this hypothesis.

Another hypothesis about the left-legged trackway is the animal was walking diagonally or horizontally across a steeply sloping surface. The animal’s foot on the upslope side of the body would sink deeper into the sand than would the foot on the downslope side. This situation might record undertracks from the upslope foot, and no tracks from the downslope foot.

The third and final hypothesis is that the animal was injured and was hopping on its left foot. However in this case the track spacing would be less consistent. After considering these possibilities, I conclude that the steeply sloping surface hypothesis is the most probable.
Figure 21: (A) Six left tracks in trackway 003; (B) close-up photograph of individual track.
3.1.3 The Mescal Range

The *Grallator* tracks in the Mescal Range were the first documented tracks in the Aztec Sandstone. These were removed by the San Bernardino County Museum and Dinosaur Institute of the Natural History Museum of Los Angeles County in 2008 for preservation (Springer et al., 2009).

**UNLV-AZ-009**

This tracksite number was designated for the tracks collected by the San Bernardino Museum staff. They are currently located in an off-site storage facility. The tracks were removed by carefully cutting a large slab of sandstone into ninety-five smaller pieces for transport. Each slab was given an alphabetical letter to specify the order of sandstone blocks once back at the museum location (Springer et al., 2009). The *Grallator* tracks on these sandstone blocks measure approximately 6 cm in length and 4 cm in width. The tracks are poorly preserved and many appear as isolated, distorted impression. Unfortunately, measurements such as trackway stride and the traveling speed of the animal are unavailable due to the segmentation of the original trackway.

**UNLV-AZ-010**

This tracksite number includes tracks currently located at the Dinosaur Institute of the Natural History Museum of Los Angeles County. The tracks were removed in the same fashion as those of Tracksite 009. Approximately sixty-one track impressions are located at an off-site facility, while approximately eight are displayed in the museum floor under glass. Precise size measurements were difficult to collect due to a 6 inch gap in between the floor on which I measured, and the tracks located below.
3.2. Ichnogenus *Brasilichinum*

Tracks of synapsids (the taxon that includes therapsids, mammals, and pelycosaurs) are also found in these sandstones. *Brasilichnium* is the most common synapsid track in the Navajo Sandstone (Irmis, 2005). *Brasilichnium* tracks are usually tetradactyl (four-toed), with detailed features not well preserved. So many of the tracks are ambiguous, and very few of them have claw impressions. *Brasilichnium* is the most common ichnofossil, found in the dune facies (as opposed to interdune facies) throughout the Nugget, Navajo, and now the Aztec Sandstone (Rainforth, 1997).

3.2.1 Red Rock Canyon National Conservation Area

*Brasilichnium* tracks have been found in only one location in RRCNCA, intermixed with *Grallator* tracks at Tracksite 008.

**UNLV-AZ-008.2**

Tracksite 008 is unlike any other tracksite found in RRCNCA in that two different ichnogenera appear together; not only on the same bedding plane, but the trackways appear to cross. The *Grallator* tracks found on this site (as discussed earlier), are located on a 10-meter long boulder, arranged in a distinct trackway near one edge of the boulder. The *Brasilichnium* tracks occur on the same bedding plane, crossing diagonally across the *Grallator* trackway (Figure 22).
Figure 22: Sketch of site 008 showing *Brasilichnium* and *Grallator* tracks crossing on the same bedding plane.
These *Brasilichnium* tracks average 2.5 cm in length and 3.8 cm in width (Figure 23). There appears to be several *Brasilichnium* trackways leading in the same direction, which is the same direction as the *Grallator* tracks. There are also dozens of individual *Brasilichnium* tracks present at this site that do not occur in recognizable trackways.

![Figure 23: Brasilichnium tracks at site 008.2 heading in the same direction as the Grallator tracks on the same bedding plane.](image)

3.2.2 Valley of Fire State Park

There is only one documented tracksite containing Brasilichnium tracks in Valley of Fire State Park. It was the first of any track found in the Aztec Sandstone of southern Nevada (Rowland and Mercandante, 2007).

**UNLV-AZ-012**

This *Brasilichnium* tracksite is located *insitu* on the very top of an outcrop approximately 10 meters wide and 8 meters long at a 50-degree angle. Approximately
100 individual tracks occur in 12 sub-parallel trackways on this single slab that traverse up the slip face of the dune (Figure 24a). The individual trackways are approximately 1.5 meters long containing tracks that range in length from 2.0 cm to 3.8 cm and 2.2 cm to 4.1 cm in width. The sizes of these tracks agree with other *Brasilichnium* tracks reported by Reynolds (2006b), in the Mescal Range. This tracksite is important because this was the earliest example of synapsids exhibiting gregarious behavior (Figure 24b) (Rowland and Mercandante, 2007). During the current study another tracksite with abundant, subparallel *Brasilichnium* trackways was discovered in the Gold Butte area (Tracksite 011).

Figure 24: (A) Photograph of twelve *Brasilichnium* trackways traversing up a dune face; (B) Photograph of tracks of different size, documenting gregarious behavior (tracksite 011).
3.2.3 Gold Butte Nevada

To date, the greatest documented occurrence of *Brasilichnium* tracks is located in the Gold Butte area, approximately 50 miles from Mesquite, Nevada. Tom Cluff and Michele Burkett from Mesquite alerted me to one trackway surface. Our group then discovered dozens of other trackways on multiple bedding planes in the same area.

**UNLV-AZ-011**

The trackways are all parallel, running up the slip face of a dune. There are many tracks on several bedding planes making it apparent that the animals exhibited this behavior for years. Tracks at this site average 2.06 cm in length and 2.94 cm in width with claw impressions visible on a few (Figure 25). Size differences of the animal tracks, as at site 012, strongly suggest that gregarious behavior was present at this site as well (Table 1). Hundreds of tracks are located at this site, including dozens of trackways with strides measuring 12.78 cm on average. Four trackways are illustrated in Figure 26.

Several things are different at this tracksite, one being that only 4 trackways are preserved with desert varnish (UNLV-AZ-011.1). The majority of the tracksites preserved in the Aztec Sandstone, have a layer of desert varnish present, but the *Brasilichnium* tracks at this location have little to no varnish present.
Figure 25: *Brasilichnium* tracks at site 011 with claw impressions visible.
Figure 26: Sketch of site 11.1 showing 4 trackways parallel to each other.
Table 1: Track length and width, stride, and trackway width measurements of tracks at tracksite 011.1.

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3.3 Ichnogenus *Octopodichnus*

Ichnogenus *Octopodichnus* is a commonly known invertebrate trace fossil found in Paleozoic eolianites (Brady, 1947; Sadler, 1993; Hunt and Lucas, 2007) and it shows up at multiple locations in the Aztec. *Octopodichnus* (eight-footed trace) is the track of a scorpion-type arthropod (Brady, 1947), with 4 legs on each side.

3.3.1 Red Rock Canyon National Conservation Area

**UNLV-AZ-006**

Only one *Octopodichnus* trackway has been documented in RRCNCA. It is located only meters from one of the best-preserved dinosaur tracks in the Aztec Sandstone (UNLV-AZ-005), but not on the same bedding plane. In December 2011, the Bureau of Land Management documented the *Octopodichnus* track using photogrammetry (Figure 27). As is visible in Figure 27, only one side of the 8-legged track is preserved for the majority of the trackway. The remaining 4 legs reappear farther into the trackway. Each of the 4 legs spans a distance of 3 cm (Figure 28). This stride is consistent with other *Octopodichnus* tracks found the Navajo Sandstone. The trackway surface is stratigraphically lower than tracksite 005, but both occur within the same cross-bedded set.
Figure 27: Photogrammetric image of site 006 with colors and contours for elevation changes of 1 millimeter.
Figure 28: Close-up photogrammetric image and photograph of tracksite 006.
3.4 Ichnogenus *Paleohelcura*

*Paleohelcura* is the most common invertebrate trace fossil in the Coconino Sandstone (Gilmore, 1927). Brady (1947) showed that *Paleohelcura* occurs in a variety of morphologies, reflecting different behaviors. Two of these morphologies are found in the Aztec Sandstone. It is inferred that *Paleohelcura* tracks are tracks of a scorpion similar to modern scorpions, but presumably different from the *Octopodichnus* trackmakers.

### 3.4.1 Red Rock Canyon National Conservation Area

**UNLV-AZ-014, 015, 016**

*Paleohelcura* was documented at 3 locations in RRCNCA: 014, 015, and 016. *Paleohelcura* trackways in RRCNCA average 8 cm in length with three small tracks every 1 cm in a triangular pattern (Figure 29). According to Brady (1947), *Paleohelcura* tracks sometimes show a tail drag between the sets of footprints, but the tail drag is absent at all of these RRCNCA sites (Figure 30). Although the *Paleohelcura* tracks in RRCNCA display the same behavior, the dimensions of the individual tracks vary from 0.5 cm (tracksite 015) to 1.25 cm (tracksite 014). Other *Paleohelcura* trackways are found throughout the Aztec Sandstone, but multiple trackways on the same bedding plane are found only at tracksite 015.
Figure 29: Tracksite 015 displaying three *Paleohelcura* trackways on same bedding plane in RRCNCA.

Figure 30: Tracksite 014 showing a single *Paleohelcura* track with much larger individual tracks than found elsewhere in the Aztec Sandstone.
3.4.2 Valley of Fire State Park

UNLV-AZ-001

Located at the same site as the *Grallator* tracks mentioned previously, are two *Paleohelcura* trackways (or possibly one long trackway) displaying two different behaviors within centimeters of each other. The trackway consists of sets of three individual tracks arranged in parallel rows with overlapping footprints (Figure 31). No tail drag is present in this morphology. The trackway continues for 5 cm before fading out for 6 cm and then continuing another 9 cm.

Figure 31: Tracksite 001 showing a *Paleohelcura* trackway with no tail drag.

Located half a centimeter stratigraphically below the other trackway is another trackway displaying the same behavioral mode as seen at the RRCNCA *Paleohelcura* sites, with three individual tracks in a triangular pattern, but with a tail drag (Figure 32).
This trackway is approximately 8 cm long and tapers out before the previous trackway ends. Brady (1947) described similar behavioral variants of *Paleohelcura* occurring in the same trackway. In the UNLV-AZ-001 case, two different animals may have made the trackways.

![Paleohelcura trackway at tracksite 001, displaying a different behavior.](image)

**Figure 32:** *Paleohelcura* trackway at tracksite 001, displaying a different behavior.

### 3.5 Ichnogenus A (“10-cm strider”)

Although the previous four ichnotaxa are known in other locations, such as the Navajo or Coconino Sandstone, this ichnotaxon has not been documented elsewhere. This trackway occurs in both RRCNCA and Valley of Fire State Park. The trackmaker could have been either a therapsid or a mammal.
3.5.1 Red Rock Canyon National Conservation Area

UNLV-AZ-013

Located in two locations in RRCNCA, these mammaloid trackways are found in the same areas as *Octopodichnus* and *Paleohelcura* trackways, but on a different bedding plane. These trackways range in length of 0.7 m to 2.4 m, containing a total of approximately 35 tracks. The individual tracks are quite small at only 1.0 to 1.5 cm in length and 1.2 to 1.6 cm in width, which is much smaller than *Brasilichnium* tracks. The stride is approximately 10 cm, so our informal name for this track is the “10-cm strider.”

3.5.2 Valley of Fire State Park

UNLV-AZ-002.2

Only one ichnogenus A trackway was found in Valley of Fire State Park. It is located on the same loose boulder as *Grallator* tracksite UNLV-AZ-002, but the boulder is overturned from its original position, therefore the ichnogenus A trackway occurs on the underside of the loose boulder as it now sits. This 74 cm trackway contains 20 tracks that are 1.5 cm in length and 1.6 cm in width. The stride is approximately 10 cm. These measurements are comparable to the UNLV-AZ-013 tracks.
CHAPTER 4
PALEOECOLOGY OF THE AZTEC SANDSTONE

Based on the evidence presented in this study, three types of animals were sporadically present in the dune field desert preserved as the Aztec Sandstone: (1) bipedal theropod dinosaurs, (2) tritylodont therapsids, and (3) arthropods (probably scorpions). Theropod dinosaurs were carnivores (Thulborn, 1990), and tritylodont therapsids were herbivores (Kermack, 1982). The arthropods, represented by the ichnogenera *Octopodichnus* and *Paleohelcura*, were very likely also part of the food web. In the North American deserts today, grasshopper mice of the genus *Onychomys* are still well known to prey on scorpions (Kays and Wilson, 2002). With this evidence, I suggest that synapsids of the Aztec desert may have fed on the scorpions. This note aside, the Aztec food chain was probably a very short one, as characterized in Figure 33.

The inferred food chain is supported by the fact that *Brasilichnium* tracks often occur in close stratigraphic association with *Grallator* tracks. For example, at tracksite UNLV-AZ-008 the tracks overlap. No plant fossils have been documented in the Aztec Sandstone, and only one coniferous plant fossil has been reported in the Navajo Sandstone (Parrish and Falcon-Lang, 2007). It is impossible to conclude that the *Brasilichnium* trackmakers fed on that plant, so the food chain is impossible to extend.
Although the food chain cannot go beyond *Brasilichnium*, details of the feeding/living behavior are available. *Brasilichnium* trackmakers were permanent residents, probably living in burrows (Rowland and Mercandante, 2007). Tracksite UNLV-AZ-011 has over one hundred tracks and dozens of trackways on multiple bedding planes, all heading up a dune-face. These tracks were impressed into the sand over an extended period of time. *Brasilichnium* trackmakers were apparently gregarious (Rowland and Mercandante, in press), which implies a moderately large population, and implying that the herbivore food source was reasonably plentiful.

In 1994, Lockley et al., proposed a series of vertebrate ichnofacies, although Hunt and Lucas (2007) have argued that these should be considered ichnocoenoses because
they represent traces of specific communities (Buatois and Mangano, 2011). Vertebrate ichnofacies occur less commonly than invertebrate ichnofacies, but in some cases vertebrate and invertebrate ichnofacies directly correlate or occur in the same environment (Hunt and Lucas, 2007), such as at Tracksite 008.
CHAPTER 5

GRALLATOR TRACKMAKER SPEED ANALYSIS

In this study I documented ten *Grallator* trackways that are suitable for trackmaker speed analysis. It is necessary for a trackway to have at least three tracks, which allow the stride to be measured. If for any reason the strides were not consistent for a particular trackway, it was omitted from the calculations. Using Alexander’s (1976) equation, by measuring the stride and foot length it is possible to calculate speed. Alexander (1976) used the Froude number to study the gait of different vertebrate animals. The Froude number is a dimensionless number that is useful for characterizing the interaction of inertia and gravity. For the purpose of characterizing animal gait patterns, the Froude number is the ratio of centripetal force around the center of motion—the force of the foot moving around the hip—to the weight of the animal. By studying animals of different sizes and weights, Alexander determined that animals with similar gaits, even if they are different sizes, have the same Froude numbers. In this context the Froude number becomes \( u^2/gh \) where \( u \) is speed, \( g \) is acceleration of free fall, and \( h \) is the hip height.

Alexander (1976) measured the stride length and speed of a wide variety of tetrapods. He used these data to develop the following empirical formula in which the Froude number is related to hip height and stride length: \( V = 0.25g^{0.5} SL^{1.67} h^{-1.17} \) where \( V \) is the speed of the trackmaker in m/sec, \( g \) is the acceleration due to gravity, \( SL \) is the stride length, and \( h \) is the hip height.

To apply this relationship to the question of dinosaur speeds, Alexander measured dinosaur skeletons and determined that every dinosaur foot length is proportional to hip
height. For small, bipedal dinosaurs with a foot length of less than 25 cm, the hip height is 4.6 times the foot length.

Thulborn (1990) analyzed Alexander’s method and developed a different equation, one for a running animal since the running phase has both feet off the ground at the same time. This equation was not used in the final calculations in this study, due to implausible speed results. One possible reason for the inaccurate results is, just like humans, dinosaurs ran on their toes, so the foot length may be incorrect, which then affects the hip height, and this may have skewed the results. I used Alexander’s original equation to determine speeds.

All speed measurements were calculated in meters/second (m/sec) and converted to miles to hour (mph) (Table 2). The trackways in the Aztec Sandstone record a wide range of trackmaker speeds, ranging from 0.35 m/sec to 3.79 m/sec. These speeds fall into the average of bipedal theropods analyzed by Alexander (1976) and Thulborn (1990) which travel 1.1 m/sec to 3.61 m/sec. Hip heights range from 27.6 cm to 78.2 cm. The greatest hip height (78.2 cm) belongs to the slowest trackmaker, whose speed was 0.35 m/sec, while the fastest dinosaur (3.79 m/sec) had a hip height (41.4 cm) that was roughly average among the ten trackways analyzed. Figure 34 is a histogram that shows the speed determined for the ten trackmakers.
<table>
<thead>
<tr>
<th>Trackway #</th>
<th>Hip Height (h) (cm)</th>
<th>Stride Length (SL) (cm)</th>
<th>M/S</th>
<th>MPH</th>
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<tbody>
<tr>
<td>4.4</td>
<td>59.8</td>
<td>103</td>
<td>1.53</td>
<td>3.42</td>
</tr>
<tr>
<td>4.3</td>
<td>55.2</td>
<td>112</td>
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<tr>
<td>4.2</td>
<td>46</td>
<td>92</td>
<td>1.72</td>
<td>3.85</td>
</tr>
<tr>
<td>17.1</td>
<td>41.4</td>
<td>52</td>
<td>0.75</td>
<td>1.68</td>
</tr>
<tr>
<td>17.3</td>
<td>41.4</td>
<td>137</td>
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<td>17.4</td>
<td>57.5</td>
<td>49</td>
<td>1.85</td>
<td>4.15</td>
</tr>
<tr>
<td>17.12</td>
<td>36.8</td>
<td>104</td>
<td>2.75</td>
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<tr>
<td>8.1</td>
<td>78.2</td>
<td>51</td>
<td>0.35</td>
<td>0.77</td>
</tr>
<tr>
<td>3</td>
<td>27.6</td>
<td>40</td>
<td>0.78</td>
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<tr>
<td>1</td>
<td>55.2</td>
<td>55</td>
<td>0.59</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 2: Data collected with the measurements used for calculating dinosaur trackmaker speeds.
Figure 34: Graph of trackway speeds for ten trackways found in the Aztec Sandstone. Speeds are in mph. and m/sec.
CHAPTER 6

SUMMARY

In this study I describe and interpret tracks and trackways of the Jurassic Aztec Sandstone of southern Nevada and southern California. This study involved mapping of all known tracks and trackways, including foot length, stride length, and trackway width. Photogrammetric data, collected by Bureau of Land Management scientists, were utilized for several trackways in Red Rock Canyon National Conservation.

More than three hundred tracks belonging to five ichnotaxa were documented within the Aztec Sandstone, including about 165 tridactyl *Grallator* tracks, 250 tetradactyl (four-toed) *Brasilichnium* tracks, and 7 arthropod trackways of *Octopodichnus* and *Paleohelcura*. The trackway finds are similar to the most common tracks found in the correlative Navajo Sandstone, although the diversity of tracks is much higher in the Navajo. This study can be used as a reference for comparison studies throughout the correlative sandstones. The higher diversity within the Navajo is almost certainly partly due to the much longer history of systematic investigation. All but one of the discovered tracksites in the Aztec was unknown prior to October 2011, and more discoveries are likely to follow.

Where possible, in the case of the *Grallator* trackways I calculated the speed of the trackmaker. Speeds range from 0.7 mph (0.35 m/sec) to 8.5 mph (3.8 m/sec). In one trackway, the dinosaur temporarily stopped and then proceeded on. Several tracks of different ichnotaxa overlap each other. From details such as these, some aspects of the paleoecology of the Aztec Sandstone can be inferred. The *Grallator* trackmakers were carnivorous theropod dinosaurs which probably preyed on the herbivorous *Brasilichnium* trackmakers. In several locations in the study area, both ichnotaxa are preserved in the
same area, but this does not indicate a hunting scene between the *Grallator* and *Brasilichnium* trackmakers. Evidence is available that the trackmakers resided near or visited the same area repeatedly over an extended period of time, which implies the sustained availability of food.

### 6.1 Future Work

As the popularity of these tracks increases, more discoveries will be documented, and the master list of trackways and ichnotaxa will increase. Photogrammetric software is a valuable resource for analyzing trackways revealing details missed by other techniques. Photogrammetric data will be collected in the future on all tracks and trackways in the study area, possibly by a future student, resulting in a photogrammetric database of Aztec Sandstone tracks. If the amount of track locations increases, more evidence for the paleoecology may be available as well.
### APPENDIX 1

<table>
<thead>
<tr>
<th>Locality Name</th>
<th>Location</th>
<th>Ichnotaxon</th>
<th>Number of Tracks</th>
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</thead>
<tbody>
<tr>
<td>UNLV-AZ-001.1</td>
<td>VOF</td>
<td><em>Grallator</em></td>
<td>8</td>
</tr>
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<td><em>Paleohelcura</em></td>
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<td>VOF</td>
<td><em>Grallator</em></td>
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</tr>
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</tr>
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<td>VOF</td>
<td><em>Grallator</em></td>
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</tr>
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<td><em>Grallator</em></td>
<td>44</td>
</tr>
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<td>RRCNCA</td>
<td><em>Grallator</em></td>
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</tr>
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<td>RRCNCA</td>
<td><em>Octopodichnus</em></td>
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<td>VOF</td>
<td><em>Grallator</em></td>
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</tr>
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<td><em>Grallator</em></td>
<td>14</td>
</tr>
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<td>UNLV-AZ-008.2</td>
<td>RRCNCA</td>
<td><em>Brasilichnium</em></td>
<td>~30</td>
</tr>
<tr>
<td>UNLV-AZ-009</td>
<td>Mescal Rge</td>
<td><em>Grallator</em></td>
<td>~69</td>
</tr>
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<td><em>Grallator</em></td>
<td>9</td>
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<td><em>Brasilichnium</em></td>
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<td>RRCNCA</td>
<td>Ichnogenus A</td>
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<td><em>Paleohelcura</em></td>
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<td>~15</td>
</tr>
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<td><em>Paleohelcura</em></td>
<td>2</td>
</tr>
<tr>
<td>UNLV-AZ-017.11</td>
<td>RRCNCA</td>
<td>Synapsid</td>
<td>1</td>
</tr>
</tbody>
</table>

Appendix 1: Table of all tracksite names, locations, ichnogenus, and approximate number of tracks at each site. VOF= Valley of Fire State Park, RRCNCA= Red Rock Canyon National Conservation Area, SBCM= San Bernardino County Museum, LACMNH= Los Angeles County Museum of Natural History, Mescal Rge= Mescal Range, CA.
Fleck, R.J. and Reynolds, R.E., 1996, Mesozoic stratigraphic units of the eastern Mescal Range, southeastern California. San Bernardino County Museum Association Quarterly, Vol. 43, No. 1, p. 49-54.


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