USING PHOTOGRAMMETRY TO ANALYZE THE MORPHOLOGY, TAPHONOMY, AND SEDIMENT DEFORMATION OF BRASILICHNIUM TRACKWAYS ON A SLOPING SAND DUNE FROM THE NAVAJO FORMATION

by

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ABSTRACT

The ichnogenus *Brasilichnium* is widely distributed locally and is found stratigraphically on eolian sediments of the same western erg system of the Early Jurassic period. Exceptionally well-preserved synapsid trackways of *Brasilichnium* were discovered by researchers from the National Park Service in 2014. The sandstone slab (locality GLCA #357), located within Glen Canyon National Recreation Area (GLCA), is found in the Early Jurassic formation known as the Navajo Sandstone. This study investigates the morphology of the trackways fossilized on the lee side of a sloping dune face, provides interpretations of the sedimentary structures associated with locomotion, and their taphonomy in an eolian environment. The track-bearing surface is composed of eleven trackways including *Brasilichnium,* one *Grallator*-like trace, and a few unknown traces that are seen moving in different orientations relative to each other. This site, named Santucci's Site after the discoverer, was examined using structure-from-motion (SfM) photogrammetry to create 3D images of these tracks. These tetrapod tracks show the trackmakers walking on a dune slip face in an eolian environment and changing direction while doing so. Sedimentary features include grain flows, or "avalanches", located below the *Brasilichnium* tracks and two sets of wind ripples on the same track-bearing surface. These pes depressions show an imbalance of weight distribution while the animal was walking on the seemingly hyper-arid substrate. These trackways show bipedal and quadrupedal locomotion and a change of forward motion as the trackmakers strolled upslope, downslope, and diagonally across the face of a sloping dune.

In addition to morphological variation, SfM photogrammetry shows how this site has been impacted in modern times by the fluctuating water level elevations due to a recent megadrought over the western United States. Photogrammetry performed in 2014 and 2022 show large-grade weathering of these trackways over the span of eight years. This level of weathering largely affected the preservation of the trackways, but in a few ways helped expose a few new features.

PREFACE

This thesis is an original work by Maria de Jesus Rodriguez.

No part of this thesis has been previously published.

DEDICATION

This thesis is dedicated to my mother, Rosa Amalia. You began your solo journey north from El Salvador, crossing many borders under the night sky, for a piece of the American dream. Because of your immense courage, I can fulfill my own dreams. I couldn't have completed this thesis without your unconditional love and support. I am eternally thankful, amá.

"What intelligent things you say sometimes! One would think you had studied."

-Miguel de Cervantes Saavedra, *Don Quixote de la Mancha*

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CHAPTER 1: INTRODUCTION

1.1 GENERAL OVERVIEW

Ichnology is the science of tracks and traces produced by, past or present, organisms. Paleoichnology (the study of fossilized tracks and traces) includes lithified tracks, burrows, feces, dwellings, and other evidence of animal behavior (Gingras et al., 2012). These fossils depicting life traces are called ichnofossils (Gingras et al., 2012). Applied ichnology in research is a mingling of geological and paleontological disciplines (Frey, 1975). Studying the ichnological assemblages within geological units can result in information on the trackmakers, paleoenvironmental conditions, taphonomy classifications, geological age, and reconstruction of paleoecosystems (Frey, 1975; McIlroy, 2004; Gingras et al., 2012). Additionally, the role of ichnology in sedimentary environments allows for implications to biostratigraphy and identification of sequence stratigraphic surfaces in geological units (McIlroy, 2004).

The ichnogenus *Brasilichnium* has been discovered in several countries in South America, North America, Asia, Africa, and Europe (Leonardi and Carvalho, 2020). In the western United States, *Brasilichnium* is commonly found in eolian depositional environments of the Lower Jurassic within the coeval formations: the Navajo, Nugget, and Aztec Sandstones. The most extensive formation of the three, the Navajo Sandstone, has been widely documented to be one of the best examples of an eolian erg system that has generated copious studies of its diverse tetrapod ichnofauna, including *Brasilichnium* (Lockley and Hunt, 1995; Lucas et al., 2005; Kirkland et al., 2011; Lockley and Gierlinski, 2014; Lockley et al., 2014). Although vertebrate trace fossils in the Navajo Formation are extensive, it has produced very few body fossils (Lockley and Gierlinski, 2014). Therefore, finding traces of ancient desert trackmakers allows for the interpretation of terrestrial desert ecosystems and organisms' inhabitancy in an arid environment.

Glen Canyon National Recreation Area (GLCA) preserves one of the world's best examples of Mesozoic strata (Kirkland et al., 2010; NPS, 2014; Graham, 2016). It was established as a federally protected public land in 1972 to preserve the region's scenic, scientific, and historic resources, and to provide recreational use of the man-made reservoir, Lake Powell (Graham, 2016). It is located on the border of Arizona and Utah and encompasses over 500,000 ha of public land (Graham, 2016) (Figure 1.1). Along the margins of the lake's shoreline, extensive outcrops of the Glen Canyon Group are on display, most notably the Navajo Sandstone (Kirkland et al., 2010; Kirkland et al., 2011; Lockley et al., 2014; Graham, 2016). Exposures of sheer sandstone cliffs are made up of the extensive cross-bedding strata that is known of the Navajo Sandstone. In GLCA, this sandstone layer ranges from 355 m to 375 m in thickness (Kirkland et al., 2010; Kirkland et al., 2011). Due to the excellent outcrop exposures of Navajo Sandstone within GLCA, it is no surprise to find multiple localities of *Brasilichnium* within the park's boundary.

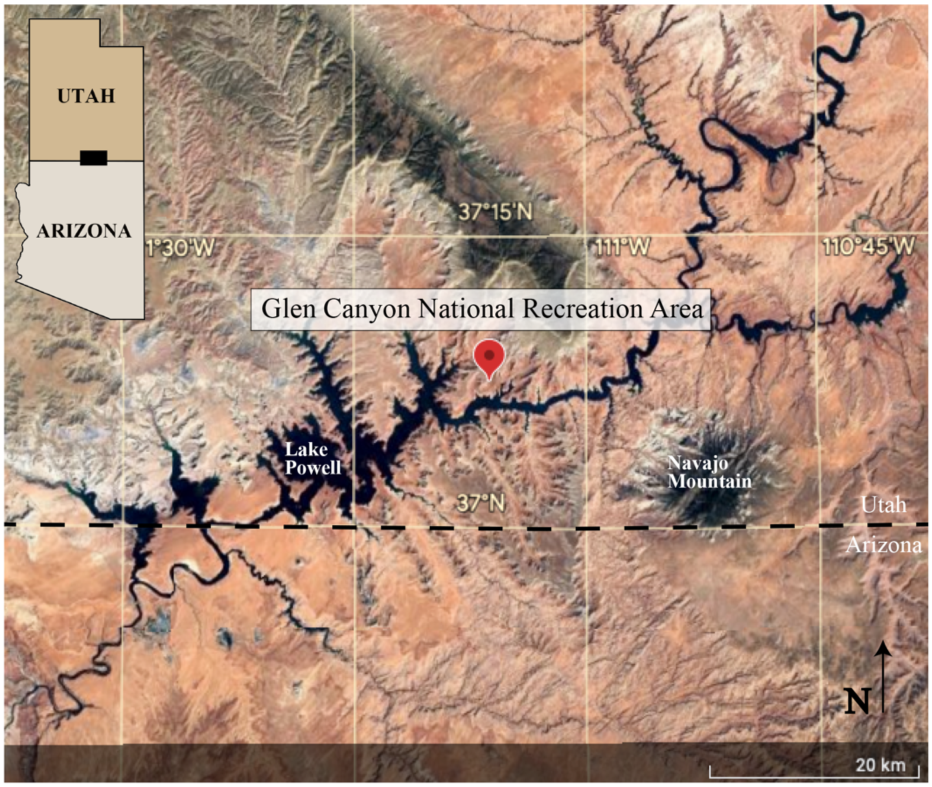

Figure 1.1 Google Earth satellite image of Glen Canyon National Recreation Area (GLCA).

Although many sites of *Brasilichnium* have been discovered, there has been much debate about the trackmaker's origin, nomenclature, and gait (Lockley, 2011; Porchetti et al., 2017; Leonardi and Carvalho, 2020). Additionally, taphonomy based on preservational bias attributed to eolian sediments complicates the descriptions of *Brasilichnium* morphology (Lockley, 2011). Eolian facies are a sub-optimal medium for trace preservation as they lack morphological detail commonly seen in other substrates, such as skin or digit impressions (Lockley, 2011). Therefore, the ichnological data of this project is based primarily on the sedimentary structures and features produced by the trackmaker(s) responsible for generating *Brasilichnium* traces, rather than the trackmaker's foot anatomy.

The accidental discovery of GLCA #357, also known as Santucci's Site, initiated an investigation that would span eight years. The photogrammetry data collected in 2014 was vital to this study as the orthomosaic model was utilized extensively for the analysis of this project. The second orthomosaic model created from the photogrammetry data collected in 2022 when the site was revisited, was futile. Furthermore, this locality provided a snapshot of the tetrapod ichnofauna in existence during the Lower Jurassic period. The track-bearing sandstone slab allowed for an analysis of the trace fossil assemblage that is unanswered by the body fossil record found in the Navajo Sandstone within GLCA. The specific objectives of this study are 1) to analyze the 3D orthomosaic model of GLCA #357, (2) to describe the various traces and sedimentological structures found on the track surface, and (3) to interpret the trackmaker's behavioral mobility reflected onto the eolian sediments of the dune slip face.

1.2 PALEOGEOGRAPHIC SETTING

The Navajo Sandstone of the Glen Canyon Group (Figure 1.2) represents a section of an extensive eolian erg that dominated much of Pangea's western margin in the Early Jurassic (Kocurek and Dott, 1983; Blakey et al., 1988; Loope et al., 2001). This sand sea was deposited as retroarc basin sediments on the subsiding Idaho-Utah trough (Kocurek and Dott, 1983; Blakey et al., 1988; Hassan et al., 2018). The main sedimentary sources of these wind-blown deposits originated from the cratonic sources located to the south and east of the basin. On the east side of the basin were the Ancestral Rockies and the Mogollon Highlands were located to the south of the basin (Kocurek and Dott, 1983; Blakey et al., 1988). This formation stretched as far north as present-day southeast Wyoming to as far south as northern Arizona (Hassan et al., 2018). The erg deposits thicken to the western side of the Utah-Idaho trough but begin to thin out in southeastern Idaho and California (Blakey et al., 1988). On the eastern side of the trough, the sandstone begins depositional thinning in New Mexico until it is truncated by the J-2 unconformity (Blakey et al., 1983).

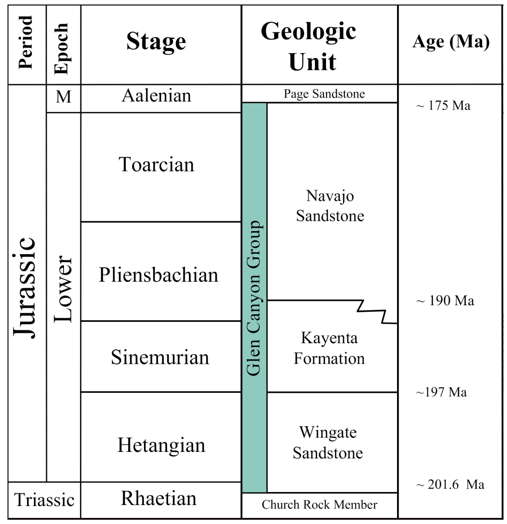

Figure 1.2 Geologic age of Glen Canyon Group (Modified from Kirkland et al., 2010).

During the deposition of the Navajo Sandstone, Pangea was located at approximately 10° - 17° N paleolatitude (Kocurek and Dott, 1983; Loope et al., 2001; Loope et al., 2004; Hassan et al., 2018). The cross-strata associated with the Navajo Sandstone was the result of an annual change of wind direction and pluvial episodes present during the deposition of these eolian sediments. The dominant wind direction of the Early Jurassic was northwesterly in the winter months due to the high-pressure zone located at the western margin of Pangea (Loope et al., 2001). This resulted in the southeastward migration of the sand dunes of the Navajo Sandstone. During the spring and autumn months, wind direction changed to northeasterly winds due to the trade winds connected to the Intertropical Convergence Zone (ITCZ) moving northward. This influenced the direction of sediment deposition by depositing obliquely up the slip faces. Additionally, the weaker trade winds in the summer transported heavy rains from the west that delivered as much as 2 mm of rainfall per day (Loope et al., 2001; Loope and Rowe, 2003). By analyzing the cyclic slump masses created by the heavy rainfall and calculating the rate of precipitation from the periodical interdune deposits, there is evidence of an opportunely and habitable ecosystem within the desert, wind-blown, cross-strata of the Navajo Sandstone (Loope et al., 2001; Loope and Rowe, 2003).

1.3 STUDY AREA AND DATA SET

The study area focuses on the ichnotaxa found on the lee side of a single sand dune from the Navajo Formation known as GLCA #357. This locality is located just north of the Arizona-Utah border within Glen Canyon National Recreation Area (GLCA). This research project was permissible under federal science research permit GLCA-2022-SCI-0013. According to federal regulations, specific coordinates of this locality are prohibited as public information therefore the location of the study site will remain confidential. The 2014 data set was received in January 2022 from Dr. Vincent Santucci (senior paleontologist) and Jack Wood (physical scientist) for the Geologic Resources Division of the National Park Service (NPS). The data set was a collection of 91 raw images of GLCA #357 photographed in 2014 during a park-wide paleontological survey held by NPS officials. This data set was used to produce a single 3D orthomosaic model that is the basis of this project (Figure 1.3). All measurements of trackways and sedimentary structures were collected using Adobe Photoshop by applying the ruler tool after calibrating the model by referencing the scale bars in the images.

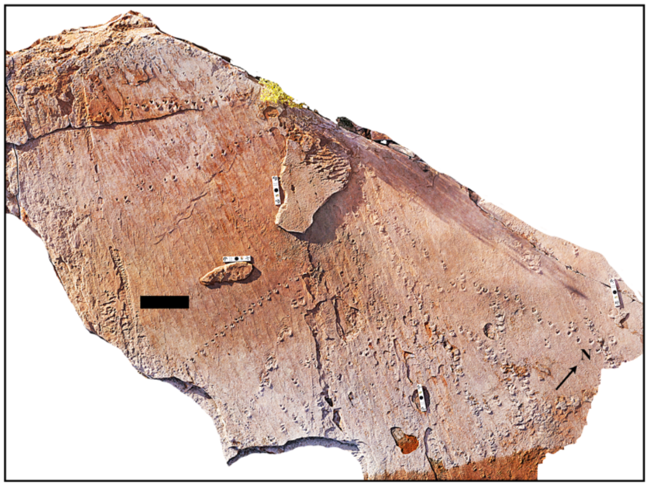

Figure 1.3 Orthomosaic model of GLCA #357, Santucci's Site from data collected in 2014. The scale bar is 50 cm.

In May 2022, GLCA #357 was revisited to obtain a second collection of images. After 8 years of large-scale weathering from wetting-drying processes and temporal sun exposure, the orthomosaic created from the 2022 data was unusable as most sedimentary features and ichnites had weathered away (Figure 1.4).

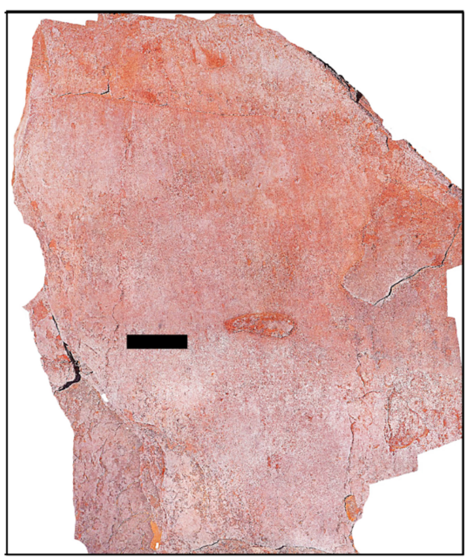

Figure 1.4 Orthomosaic model of GLCA #357, Santucci's Site from data collected in 2022. The scale bar is 50 cm.

Trackways	Total Tracks	Partial Tracks	Complete Tracks	Total Length (m)
A	12	7	5	0.86 m
B	18	5	13	1.36 m
C	12	1	11	1.69 m
D	13	1	12	1.63 m
E	28	6	22	1.53 m
F	4	3	1	1.01 m
G	8	2	6	0.19 m
H	4	2	2	0.55 m
I	17	1	16	1.80 m
J	10	2	7	0.86 m
K	11	11	0	0.58 m
Total	137			

Table 1.1 Eleven trackways of GLCA #357.

1.4 ORGANIZATION OF THESIS

This thesis is subdivided into 3 chapters that include the Introduction as Chapter 1 and Conclusion as Chapter 3.

Chapter 2: This chapter focuses on the 3D orthomosaic image of the track-bearing surface of a sandstone rock found in Navajo Sandstone named Santucci's Site, or GLCA #357. A total of eleven trackways were discussed and interpreted. An interpretation of the ichnites is made by analyzing the sedimentary structures, measuring the manus and pes traces, measuring individual trackways along the slip face, and calculating stride length and pace angulation. A rock sample was collected for lithologic and petrographic analysis of the Navajo Sandstone from the Early Jurassic. Identification of the ichnotaxa is made where available.

CHAPTER 2: Using Photogrammetry to Analyze the Morphology, Taphonomy, and Sediment Deformation of *Brasilichnium* Trackways on a Sloping Sand Dune from the Navajo Formation

2.1 INTRODUCTION

Vertebrate trackways can help aid in learning of an organisms' behavior within the environment it inhabits (Lockley, 1986; Lockley, 1998; Lucas et al., 2005; Lucas, 2007). A range of vertebrate trackways have been studied such as those of various dinosaurs including *Eubrontes* (Lucas et al., 2006), *Otozoum* (Lockley et al., 2023); pterosaurs such as *Pteraichnus* (Fiorillo et al., 2015); reptiles including *Chelinopus* (Lichtig et al., 2018); mammals like *Oplidcatylapes* (Mustoe and Hopkins, 2013), and *Musaltipes* (Lockley et al., 2022); and arthropods such as *Octopodichnus* (Lockley et al., 2022). This paper primarily looks at excellent examples of *Brasilichnium* trackways found on a track-bearing surface of an inclined sand dune foreset of the Navajo Sandstone in Glen Canyon National Recreation Area (GLCA) (Figure 2.1).

The ichnogenus, *Brasilichnium* (Leonardi, 1981), has been commonly found in dune field deposits from the vast Early Jurassic erg system that covered most of the western United States (Kocurek and Dott, 1983; Blakey et al., 1988). The coeval stratigraphic formations - Navajo, Nugget, and Aztec Sandstones - were part of the extensive eolian desert that stretched largely over the western United States. Each formation (names based on geographic location) has reported *Brasilichnium* trackways (Lockley and Hunt, 1995; Loope, 2006; Rowland and Mercadante, 2014; Engelmann and Chure, 2017). Despite being an arid and unfavorable environment, trackways like *Brasilichnium* are evidence that this ancient desert ecosystem was hospitable. *Brasilichnium* tracks are tetradactyl ichnites made by animals with broad feet and short, chubby digits (Fernandes and Carvalho, 2008) that walked both bipedal and quadrupedal

(Porchetti et al., 2017). The tracks display strong heteropody (Fernandes and Carvalho, 2008). They are often identified as having been made by small, synapsid animals with mammalian traits (Lockley, 2011; Porchetti et al., 2017; Leonardi and Carvalho, 2020). Due to the rarity of finding body skeletons in eolian desert sediments with low preservation capabilities, there are no existing published reports of the Navajo Sandstone producing body fossils of potential trackmakers. However, an eligible candidate is a tritylodontid, *Kayentatherium* (Kermack, 1982). This tritylodontid therapsid was discovered in the stratigraphic layer that underlies the Navajo Sandstone, the Kayenta Formation, known for its fluvial depositional system and interdune deposits (Winkler et al., 1991).

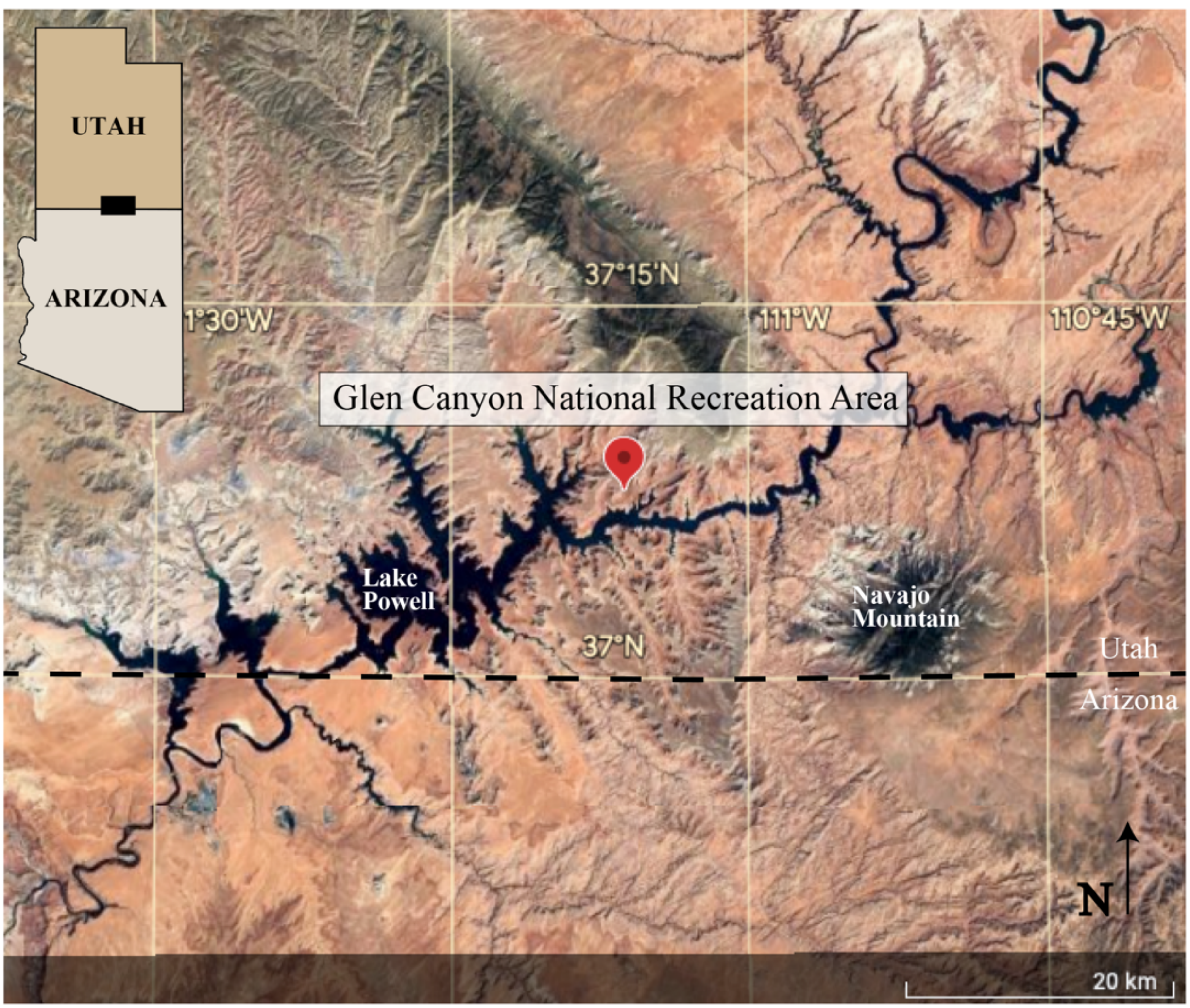

Figure 2.1 Google Earth satellite image of Glen Canyon National Recreation Area. Following federal regulations, the coordinates for this study will not be publicly disclosed.

2.2 STUDY AREA

The primary study area, Santucci's Site (GLCA #357), is located on the southern portion of the man-made reservoir called Lake Powell. This region lies within the federal boundary of Glen Canyon National Recreation Area (GLCA) on the Arizona/Utah border (Figure 2.1). In 2014, a group of National Park Service researchers were performing a wide-scale paleontological survey on a hot summer day when a researcher taking a dip in the lake stumbled upon this track-bearing slab. Named after Vincent Santucci (the chief of paleontological resources at the National Park Service), Santucci's Site was immediately noted as a highly significant site. Because of the lake's fluctuating water level, it was impossible to collect. The team performed structure-from-motion (SfM) photogrammetry, which provided the data used for this project.

The track-bearing surface of GLCA #357 strikes N22°E and dips 25° SE (Figure 2.2). In 2014, it measured 5.04 meters at its longest and had a width of 6.05 m. However, years of weathering from wetting and drying processes due to the dynamic lake levels of Lake Powell caused the brittle sandstone to break apart and erode. Upon returning in 2022, only about 3.5 m of the original dune was preserved. Locality GLCA #357 is only accessible by boat and about a 5 km walk on rocky terrain. It has an elevation of 1,109.4 m. When the site was first documented in 2014, the base of the track-bearing surface was at water level. However, in 2022, the water level was nowhere in sight as the lake level had receded to an elevation of 1,074.7 m (BOR, 2022).

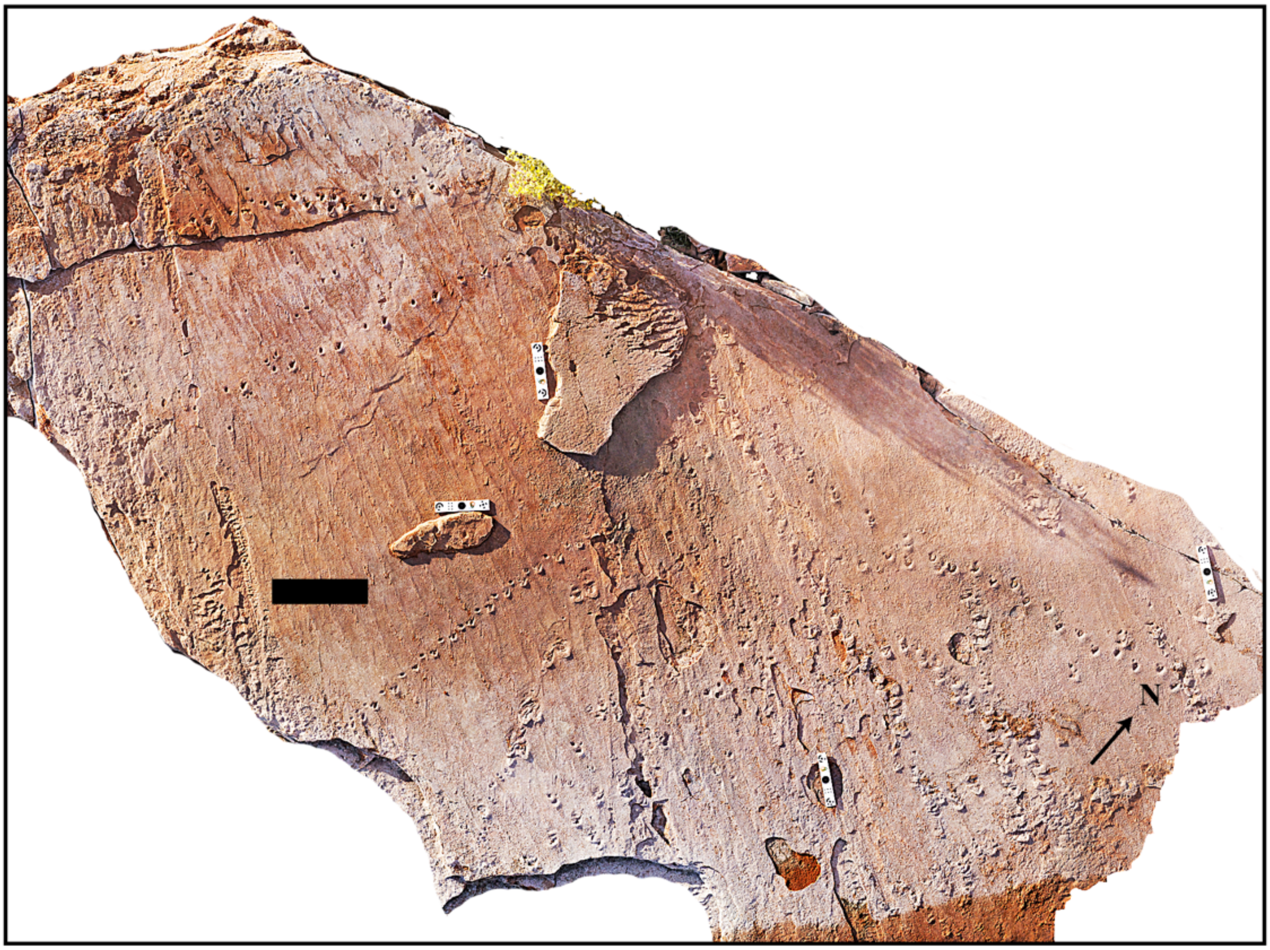

Figure 2.2 Santucci's Site (GLCA #357). The 3D orthomosaic model is from data collected in 2014. The scale bar is 50 cm.

2.3 PALEOGEOLOGICAL AND PALEOENVIRONMENTAL SETTING

The Navajo Sandstone (Gregory, 1917) is the most prominent formation from the Glen Canyon Group (Figure 2.3, 2.4) (Averitt et al., 1955; Lockley and Gierlinski, 2014). This formation is one of the best-preserved examples of an early Jurassic eolian paleoenvironment with large-scale, lithified sand dunes (Gregory, 1917; Kocurek and Dott, 1983; Blakey et al., 1988; Lockley and Gierlinski, 2014). This formation is composed of eolian cross-strata dipping southeast and an estimated maximum thickness of 677 m (Blakey et al., 1988). The Navajo Sandstone was deposited approximately 190 Ma (Pliensbachian - Toarcian; Peterson and

Pipiringos, 1979) (Figure 2.4) on the western coast of the supercontinent Pangea when it was positioned at approximately 10° - 17° N paleolatitude (Kocurek and Dott, 1983; Loope et al., 2001; Loope et al., 2004; Hassan et al., 2018). Loope et al. (2001) used sand slumps and micro faults found in the Navajo sandstone to estimate wind direction during sediment deposition. The dominant dune-driving winds were oriented northwest during the winter changing to a northeasterly direction during spring and fall (Loope et al., 2001). These winds created the massive dunes composed of southeast dipping cross-strata that the Navajo Sandstone is famous for.

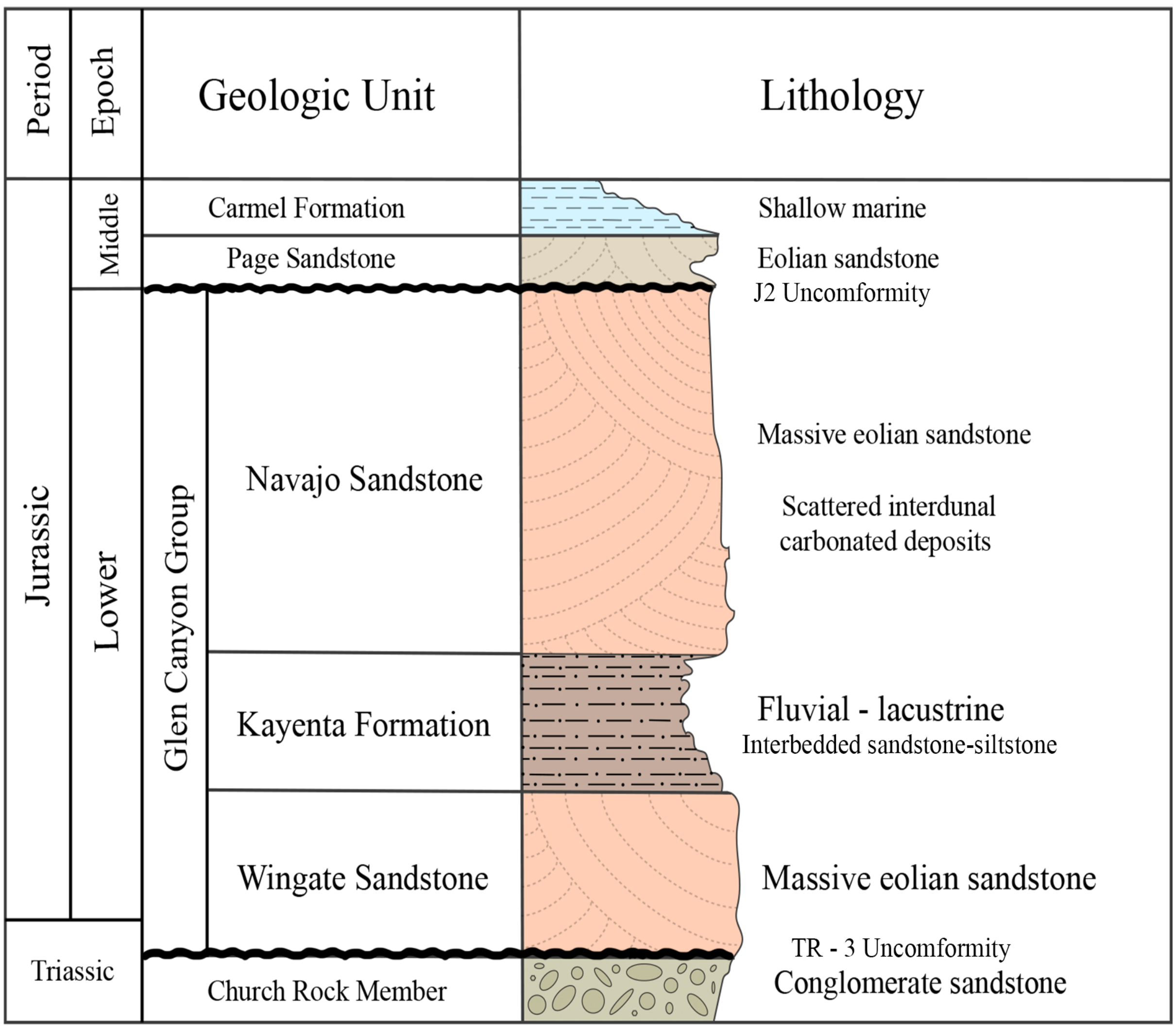

Figure 2.3 Stratigraphic sequence of Glen Canyon Group. (Modified from Kirkland et al., 2010)

The paleoenvironment of GLCA in the Early Jurassic period was equivalent to modern-day arid habitats but with intermediate monsoonal rains (Loope and Rowe, 2003; Hassan et al., 2018). The interchanging dominant winds created a weather pattern that is captured in the eolian southeast-dipping dunes (Loope et al. 2001). During the deposition of these massive windblown cross strata, annual monsoonal rains caused the collapse of dune slopes and sequential slump masses (Loope et al., 2001; Loope and Rowe, 2003). It is estimated that rainfall from these monsoons saturated the substrate as much as 40 cm in depth (Loope et al., 2001; Loope and Rowe, 2003). This monsoonal rain aided in preserving the sedimentary structures of *Brasilichnium* and other ichnites (Loope and Rowe, 2003). Based on the bioturbated zones and animal tracks, the presence of water in the dune-interdune strata was suitable for insects (like modern-day digger wasps, and crickets), arachnids, and relatively small animals like tritylodontids (Loope and Rowe, 2003).

2.4 STRATIGRAPHY

The Navajo Sandstone (Figure 2.4) intertongues and overlies the Kayenta Formation (Averitt et al., 1955; Hassan et al., 2018). The boundary between the Kayenta and Navajo formations is often regarded as the Kayenta-Navajo Transition Zone (Lockley et al., 2014; Hassan et al., 2018). It was previously referred to as the Todilto Formation (Gregory, 1917) before further research identified it as the contact boundary of an eolian environment transgressing over a fluvial depositional system (Averitt et al., 1955). The shared, and almost indistinguishable boundary, groups both formations into the Glen Canyon Group described by Averitt et al., (1955). Its composition is a pale red to dark-orange sandstone of fine- to coarsegrained sand and contains intervals of interbedded shale and siltstone (Vandiver, 1936; Averitt et al., 1955, Kirkland et al., 2010; Hassan et al., 2018). This sedimentological pattern and composition is the primary distinction between the two formations. The Kayenta Formation was deposited by fluvial depositional systems of braided and meandering streams that include small, ephemeral channels (Middleton and Blakey, 1983). Fossils are prevalent in the Kayenta Formation and the Kayenta-Navajo Transition Zone (Kirkland et al., 2010; Lockley et al., 2014). Discoveries of body fossils have been extensively reported (Lucas et al., 2005; Kirkland et al., 2010; Lockley et al., 2014). *Eubrontes* and *Grallator* are the most common tracks and trackways found in this formation (Lucas et al., 2005; Hunt and Lucas, 2006; Kirkland et al., 2010; Kirkland et al., 2011; Lockley et al., 2014).

In the vicinity of the study area, the Navajo Sandstone underlies the Page Sandstone (Averitt et al., 1955). The Navajo and Page Sandstones are divided by a layer of chert pebbles that mark the J-2 unconformity (Pipiringos and O'Sullivan, 1978). The unconformity is composed of small, scattered, and angular chert pebbles that range in size from 5 mm to 1.3 cm (Peterson and Pipiringos, 1979). Unlike the Navajo Sandstone, the Page Sandstone measures no more than 100 m in thickness and covers only a small area of the Colorado Plateau (Havholm et al., 1993). Its composition is reddish orange to reddish-brown, fine-grained, well-sorted sandstone (Peterson and Pipiringos, 1979). The Page Sandstone is represented by intervals of eolian sediment accumulation interchanging with periods of absence of sediment deposition (Havholm et al., 1993). No fossils have been reported in this formation except for petrified wood (NPS, 1999).

The Navajo Formation (Gregory, 1917) is the most prominent of the Glen Canyon Group (Averitt et al., 1955). It was part of a massive erg system that enveloped this area extending over

350,000 km^2 of the western United States (Kocurek and Dott, 1983; Blakey et al., 1988). This unit is lithologically similar to the Aztec and Nugget Sandstones, and all are tied to the same eolian depositional system. For this reason, these coeval formations are only differentiated by their geographic locations (Blakey et al., 1988). The Navajo Sandstone is a broad, cross-bedded sandstone that is responsible for the outstanding cliffs in the Circle Cliffs region of the southwestern United States (Davidson, 1967; Peterson and Pipiringos, 1979). It is composed of fine to medium, well-sorted grains of quartzose sandstone (Gregory, 1917; Davidson, 1967; Peterson and Pipiringos, 1979) ranging from white sandstone in the upper part to reddish sandstone nearest to the base (Peterson and Pipiringos, 1979). Thin interbedded carbonate and siltstone beds indicate ephemeral ancient playas within this eolian environment (Davidson, 1967). The context of this project is strictly from the Navajo Sandstone.

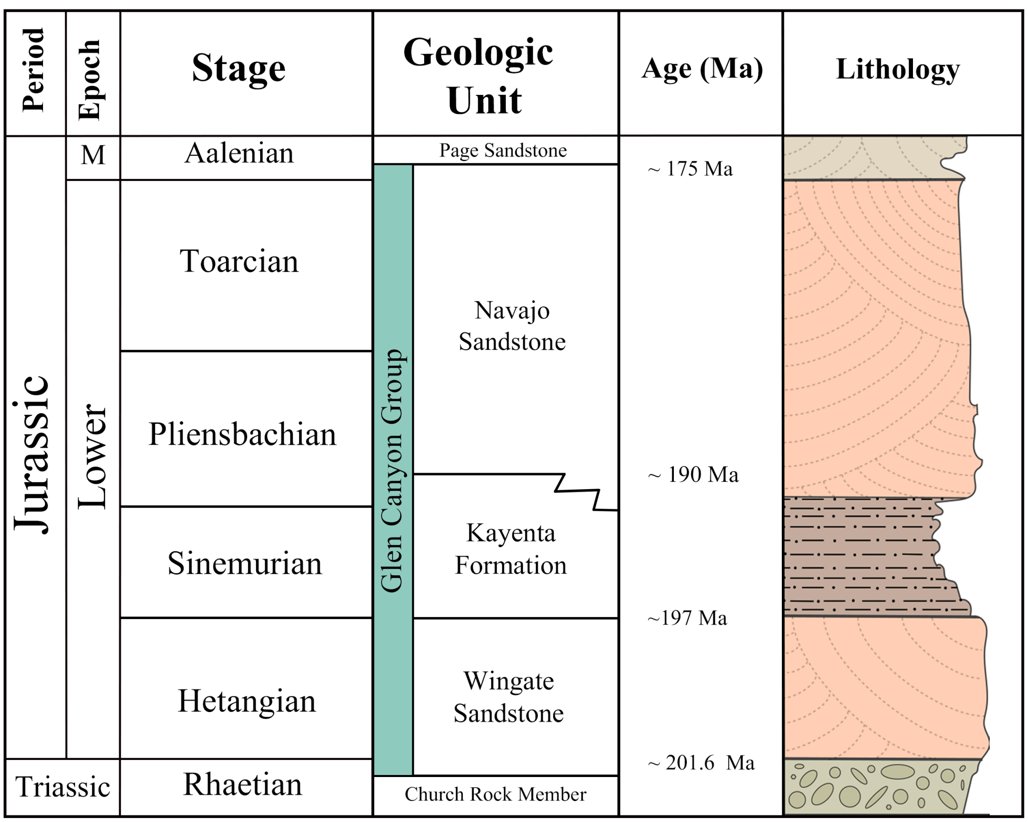

Figure 2.4 Geologic age of Glen Canyon Group.

2.5 *BRASILICHNIUM* AND ITS STRATIGRAPHIC DISTRIBUTION

The ichnogenus *Brasilichnium* was first introduced by Leonardi (1981) from a quarry found in southeastern Brazil. Thenceforth, it has been reported in Brazil (Leonardi, 1977), Paraguay (Leonardi, 1992), Mexico (Rodríguez de la Rosa et al., 2004), western United States (Engelman et al., 2010; Lockley, 2011; Lockley et al., 2011; Chure et al., 2014; Rowland and Mercadante, 2014), South Korea (Kim et al., 2017), China (Xing et al., 2018), and Africa (Contessi, 2013, including Namibia (Porchetti and Wagencommer, 2015), and the Democratic Republic of the Congo (Leonardi and Carvalho, 2021)). The stratigraphic distribution includes eolianites in sedimentary facies from the Early Triassic (Sadlock, 2019) to Late Cretaceous (Rodríguez de la Rosa, 2003). In the western United States, *Brasilichium* traces have been located within the same kind of massive eolian deposits of the Early Jurassic. Researchers have documented finds in the Nugget and Aztec sandstones (Hunt and Lucas, 2006; Reynolds, 2006; Chure et al., 2014; Rowland et al., 2014; Rowland and Mercadante, 2014; Engelmann and Chure, 2017). There have been a few ichnospecies introduced after Leonardi (1981) introduced the first ichnotaxa, *Brasilichnium elusivum*. Given their preservation, it is beyond the scope of this paper to identify the tracks in GLCA #357 to specific ichnospecies. For this reason, all tracks will only be referred to the ichnogenus, *Brasilichnium.*

2.6 MATERIAL & METHODS

2.6.1 Sedimentological Analysis

Brasilichnium tracks are found throughout the Navajo Sandstone of southern Utah and northern Arizona (Lockley and Hunt, 1995; Lucas et al., 2005; Hunt and Lucas, 2006; Lockley, 2011). In 2022, fragments of rock samples were collected from the track-bearing surface of

GLCA #357 and surrounding areas. This was done for lithologic and petrographic analysis of a thin section from the Navajo Sandstone.

2.6.2 Photogrammetry

Structure-from-motion (SfM) photogrammetry was used to create three-dimensional (3D) models for GLCA #357 in 2014 and 2022. This method of acquiring data has been used in research projects as a way to provide a less invasive procedure when studying paleontological resources, especially in federally protected lands (Wood et al. 2021). Dr. Vincent Santucci and his team of National Park Service researchers collected the first set of data images in 2014, using SfM photogrammetry. The equipment that was used is presently unknown. In 2022, Vincent granted the authors of this paper access to those images, 91 photographs in total. The images were transferred to Adobe Photoshop to enhance the image quality, increase the contrast, and remove shadows. To create the orthomosaic image, all final images were transferred to Agisoft Metashape Pro. This program created the final 3D photogrammetric model of GLCA #357 from the data 2014 collection. This 3D orthomosaic model was used for most of this project. All traces were measured in Adobe Photoshop using the ruler tool after calibrating the image to the scale bars in the orthomosaic model. Individual trackways, stride length, pace angulations, and track length/width were also measured in the same manner.

In May 2022, a science research permit (GLCA-2022-SCI-0013) was approved by NPS officials for data collection in Glen Canyon National Recreation Area. Santucci's Site, GLCA #357, was revisited. SfM photogrammetry was used to photograph the track-bearing surface of GLCA #357 using a handheld camera (Olympus TG-6). These images helped create a second 3D orthomosaic model for comparison. After eight years of weathering and exposure, this second model was deemed fruitless. Therefore, all data, unless otherwise noted, is from the 2014 orthomosaic model.

2.7 SEDIMENTOLOGY

The Navajo Formation is named after its relative proximity to the North American native lands of the Navajo (Diné) Nation and the native American reservation covering northeastern Arizona, southeastern Utah, and northwestern New Mexico (Kocurek and Dott, 1983). This study area has also been described as the Kayenta-Navajo transition zone (Lockley et al., 2014; Hassan et al., 2018). Both geological formations belong to the Glen Canyon Group (Averitt et al., 1955) and are known to researchers as track-rich sites. There have been no published reports of body fossils discovered within these two formations inside GLCA (Lockley and Hunt, 1995; Lucas et al., 2005; Lockley, 2011). The Kayenta formation is described as mostly fine-grained sandstone, siltstone, and mudstone from fluvial depositional systems, whereas the Navajo Sandstone is quartz sandstone, dune deposits (Lucas et al., 2005; Hassan et al., 2018). Due to this contrast in lithology, it is not difficult to distinguish either sedimentary layer.

2.7.1 Lithology

Petrography for Navajo Sandstone was evaluated using plane-polarized light (ppl) photomicrographs of a thin section from the track-bearing surface (Figure 2.5). The results of the thin section analysis demonstrated the sediments as grain-supported, medium to upper fine grains that are well-sorted and rounded to subangular. Ninety percent of the grains are 0.25 mm in size with only 1% of them being larger than 0.5 mm.

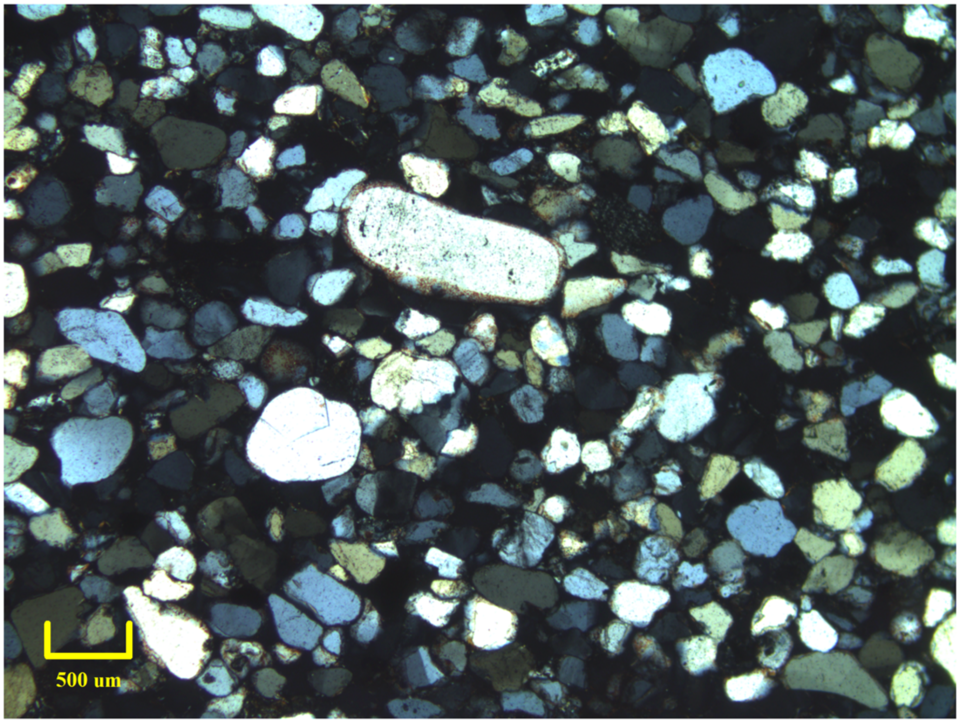

Figure 2.5 PPL Photomicrograph of GLCA #357.

2.8 RESULTS

GLCA #357 - Santucci's Site Trackways

GLCA #357 contains 11 trackways found in different orientations (Figure 2.6). They are listed as trackways A - K. Some trackways are found complete and isolated, whereas others intersect with another. In addition to the eleven trackways, a few sedimentary structures are present. Two sets of wind ripples are present throughout the track-bearing surface, one truncating the other. Additionally, an enigmatic sedimentary structure of possible biological origin will be discussed. The trackways have deteriorated over time. A site visit conducted during 2022 only shows clear impressions of the large and medium trackways: Track B is the best and, Tracks C and D are more poorly preserved. However, the smaller and shallower tracks of trackways A and E - K, are now almost non-existent. Each individual track was measured for both length and width. These measurements were taken from two points of ground disturbance; track length was measured parallel to the direction of movement and track width was measured perpendicular to it. Due to the large grade weathering of the brittle sandstone, the poorly preserved traces were disregarded due to the inability to obtain accurate measurements.

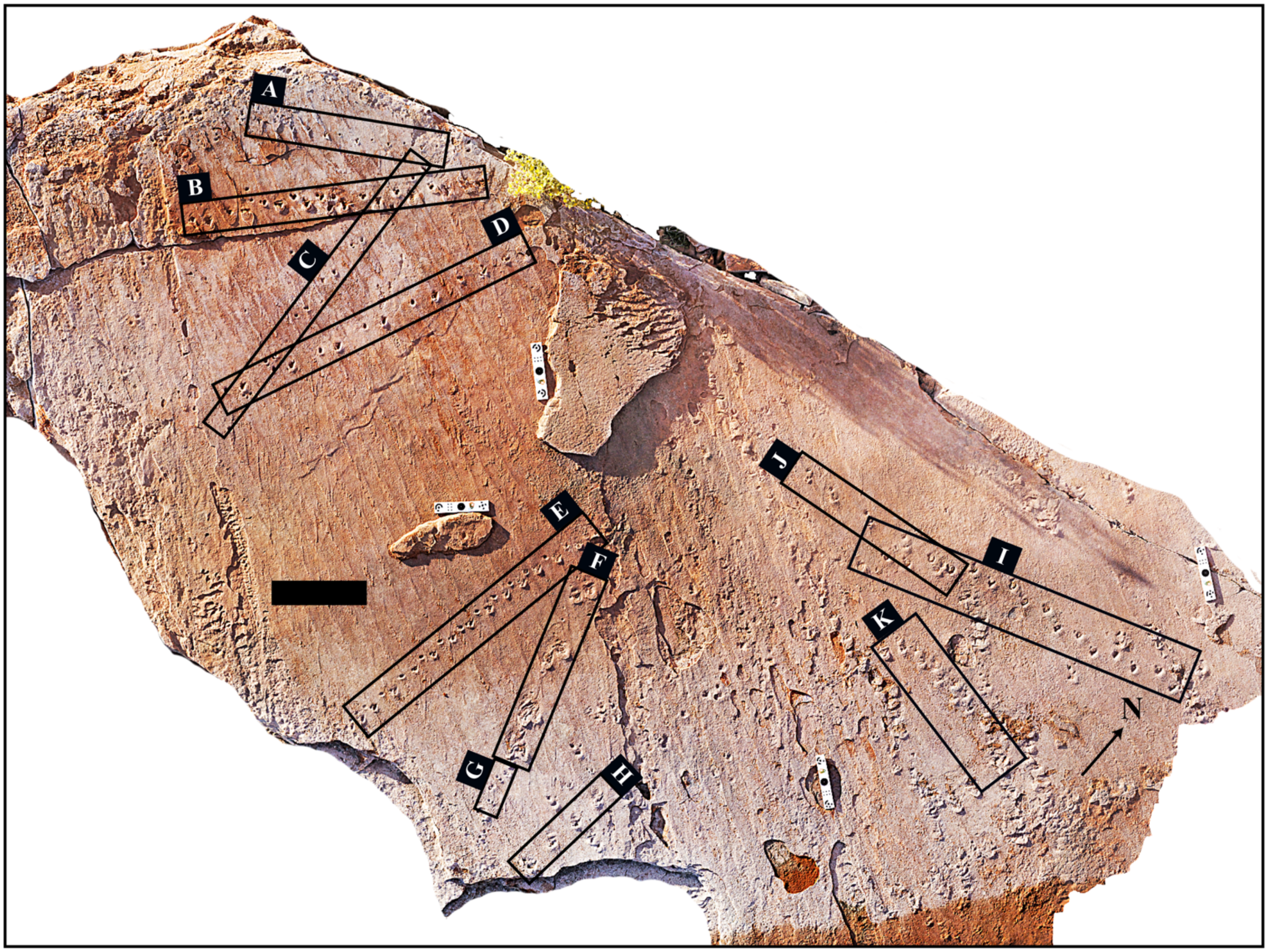

Figure 2.6 GLCA #357 trackways. The scale bar is 50 cm.

2.8.1 Trackway A

Trackway A of GLCA #357 is found on the northernmost section of the dune face (Figure 2.7). The total length of Trackway A is 86.3 cm, and the traces are in concave relief. Twelve tracks extend from left to right and each is relatively small in nature. There is a lack of detail in any of these tracks, and their spherical shapes vary. Most of the tracks are oval (similar to a deflated football) in shape with the exception of two, A3 and A5, whose shapes are almost-perfect circles. Two tracks, A6 and A7, are each associated with a smaller depression in front of the larger depression. These are faint traces of a poorly preserved manus track and are the only ones seen in Trackway A. This manus print at A6 has a width of 9.9 mm and a length of 8.3 mm. The average length and width of an individual pes trace is 1 cm and 1.3 cm, respectively. Due to weathering, tracks A8-A12 are indistinguishable. Therefore, length and width measurements were disregarded for those respective tracks. Although very faint, tracks A2, A4, A6, and A7 all show grain flows on the downslope side of the traces. Based on the location of the grain flow of A6, direction of motion is easterly.

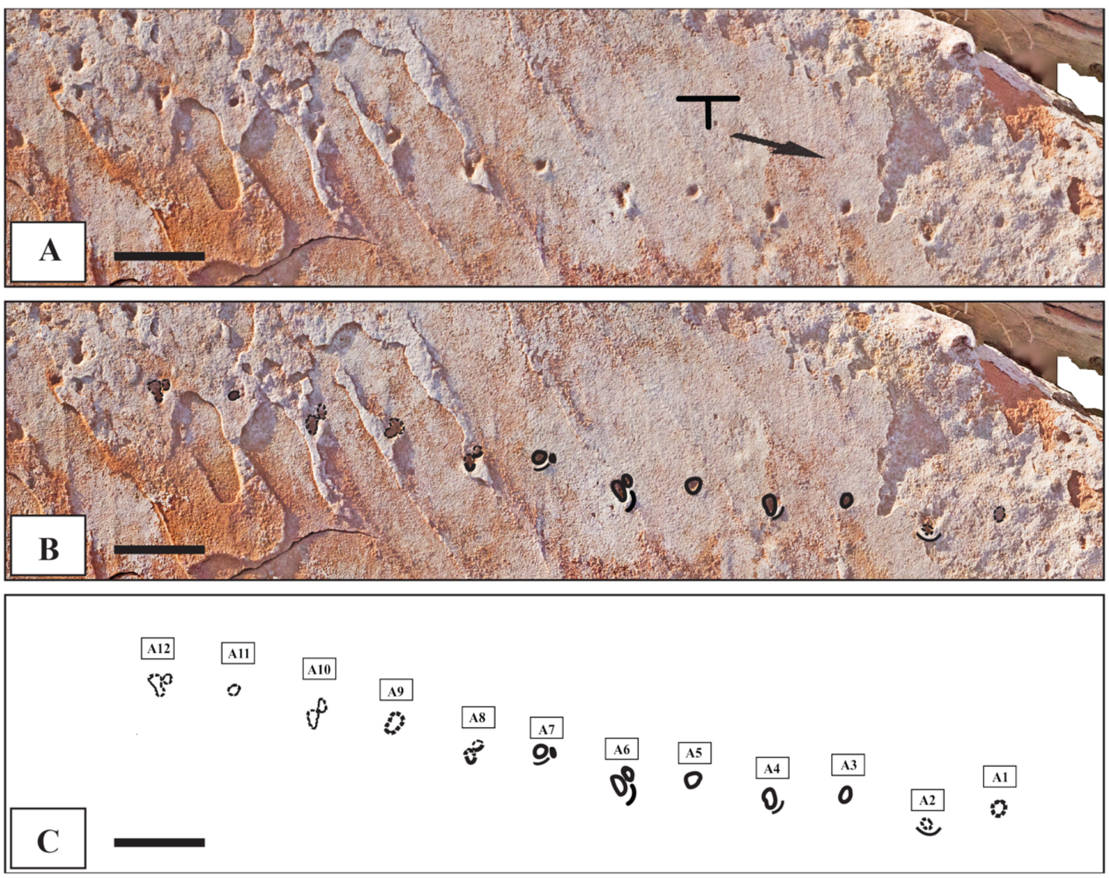

Figure 2.7 Trackway A. Scale bar is 10 cm. A. Original picture of Trackway A. Black arrow indicates the direction of forward movement. B. Original Picture with outline of tracks. C. Outline of Trackway A.

2.8.2 Trackway B

The most prominent trackway on GLCA #357 is Track B (Figure 2.8). Track B is also located in the uppermost section of the dune slipface, and it has a concave surface. It is oriented east to west, which mirrors its direction of movement (from right to left on the map). The entire length of the trackway measures 1.36 meters with at least 18 consecutive tracks. Most of the tracks in Track B are pes traces, although some tracks are followed by sedimentological features of ambiguous manus prints. Manus and pes prints were measured whenever they were distinguishable. The average length of the manus traces is 1.1 cm and the average width is 1.3 cm. The average width of the pes traces is 3.2 cm, and the average length of the pes traces is 2.4 cm. Only five (tracks B5, B7, B11, B13, and B18) of the eighteen tracks display distinct digits. All these tracks are left-foot traces and were on the downslope side of the duneface. Track B5 illustrates a left footprint with four digits, I, II, III, and IV (Figure 2.9a). Track B7 includes digits II, III, and IV. In addition, this trace extends beyond the phalangeal impressions. Track B7 contains a metatarsal impression towards its posterior area. This detail is not seen in any other trace in Trackway B (Figure 2.9b). Both tracks, B11 and B17, show only the fourth digits clearly. Track B13 has impressions of a large external digit IV, but all other digits are indistinguishable due to a small-scale slump located uphill from the trackway. Ten of these tracks have attached grain flows located on the downslope side. They vary in size, although most of the larger grain flows are located under the left pes prints. The most prominent grain flows were also observed in the 3D images taken in 2022. Tracks B13 and B15 were distinguishable after eight years of exposure. Upon returning to GLCA #357 in 2022, a new, never-seen grain flow was found under Track B18 (Figure 2.10). In the interim period, an overlying layer of sandstone had eroded to expose the sand crescent under this trace.

Figure 2.8 Trackway B. The scale bar is 10 cm. A. Close-up view of Trackway B. Black arrow show the direction of forward movement. B. Original image overlined by a black outline. C. Outline of Trackway B. Dashed markings indicate uncertainty of trace structure.

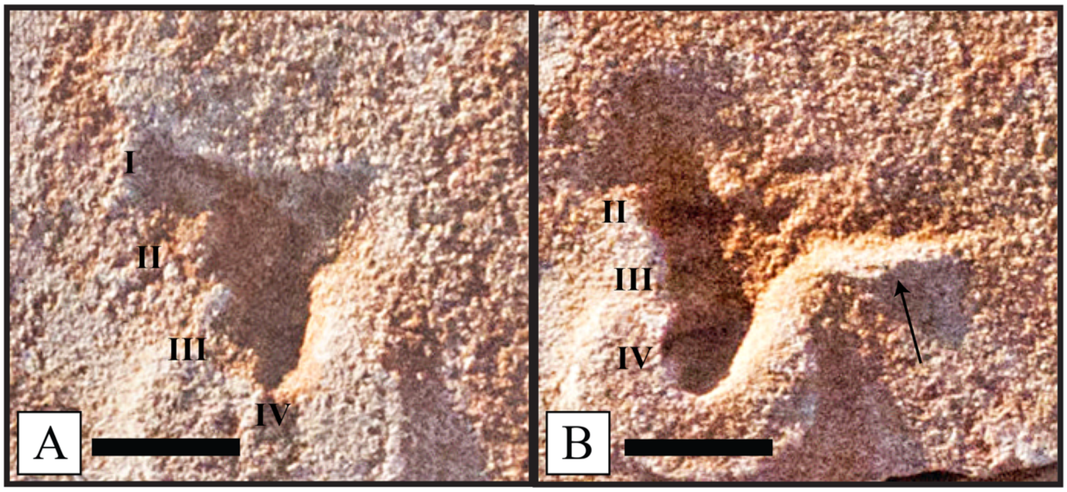

Figure 2.9 Close-up images of tracks B5 and B7. Scale bars are 2.5 cm. A. Track B5 shows digits I, II, III, and IV. B. Track B7 showing digits II, III, and IV. The black arrow indicates a metatarsal trace.

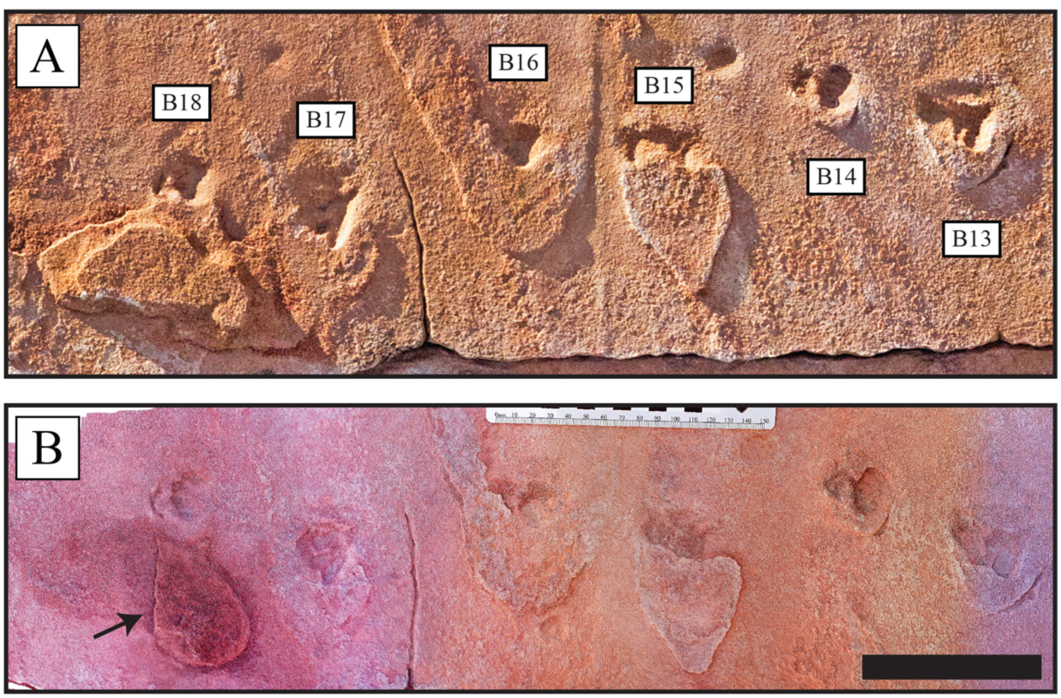

Figure 2.10 Close-up of the distal end of Trackway B from data collected in 2014 and 2022. From left to right, Track B13 and B18 are shown. A. Image of Trackway B from data collected in 2014. B. Image of the same section from data collected in 2022. Arrow indicates a new grain avalanche. The scale bar is 10 cm.

2.8.3 Trackway C

The longest trackway of GLCA #357 is Trackway C (Figure 2.11). Trackway C is longer than Trackway B, but only contains twelve pes tracks and three manus traces. This trackway meets Trackway B intersecting at Track C3 (Figure 2.11c). The entire length of the trackway measures 1.69 m. Six of the traces are left footprints, and six are right footprints. All three manus traces are left-sided impressions. The average length of a manus trace is 1 cm with an average width of 1.3 cm. The average length of pes impressions is 1.5 cm, and the average width is 1.8 cm. Except for C12, the tracks are consecutive in order. This trace runs northeast to southwest, and it extends obliquely to Trackways B and D. Individual tracks in Track C are less distinct. They lack any type of details such as the impressions of digits. Preservation of Track C is poor, although shallow grain flows are seen under most traces. All manus traces are devoid of the crescent-shaped sand structures, which is also true of the footprints C7, C9, and C12. Beyond the immediate area where most tracks are concentrated is Track C12, which is isolated from the rest of the tracks and located at the southwest end of the trackway. The reason for its separation is unknown. Like Trackway B, Trackway C was more easily seen in the 2022 photogrammetric data.

2.8.4 Trackway D

Trackway D (Figure 2.12) is the second longest trackway in GLCA #357. Its longest dimension is 1.63 m, and its orientation is from northeast to southwest. The ichnites are found in concave relief and consist of 13 tracks. The average lengths of individual tracks are 2.5 cm and the width average is 2.6 cm. The ratio of widths to lengths of footprints of Trackway D is close in range because of the metatarsal impressions. The metatarsal impression adds to the track's length, thus increasing the average length. The average track length of traces found without metatarsal traces is only 1.6 cm. Track D10, located on the far-left side of Trackway D, nearly intersects with Trackway C. Although both trackways are on the same slipface, there does not seem to be any connection shared between the trackways. Grain flows are seen on all the tracks except for D5, D7, D9, D11, and D13. All tracks devoid of grain flows are right pes impressions that are located on the upslope side of the trackway. Those on the left side of the trackway are embedded deeper in the sandstone, whereas the right tracks are only weakly impressed. This gives the illusion of the left pes traces being larger than the right ones. Like trackways B and C, Trackway D was discernible in the 3D images taken in 2022.

2.8.5 Trackway E

Trackway E consists of 28 consecutive tracks, making it the longest single trackway (Figure 2.13). The total length of this trackway is 1.5 m. Each footprint is asymmetrical to its respective counterparts. Except for E1, a track that is badly weathered, all left foot traces are heart-shaped depressions. In contrast, all right foot impressions are almost complete spheres or are bean-shaped. For this reason, width and length measurements for each track were separated based on their right or left positions. The right foot impressions have an average length of 2.3 cm and an average width of 2 cm. Left-foot impressions have an average length of 4 cm and an average width of 3.4 cm. Sixteen of these tracks are associated with grain flows. Like Trackway D, tracks on the left side are more deeply impressed into the sandstone, and almost all initiated an avalanche. Except for E12, E14, E16, and E20, all grain flows are downslope below the left-foot impressions. Trackway E is oriented northeast to southwest and it is aligned almost parallel to Trackway D (Figure 2.6).

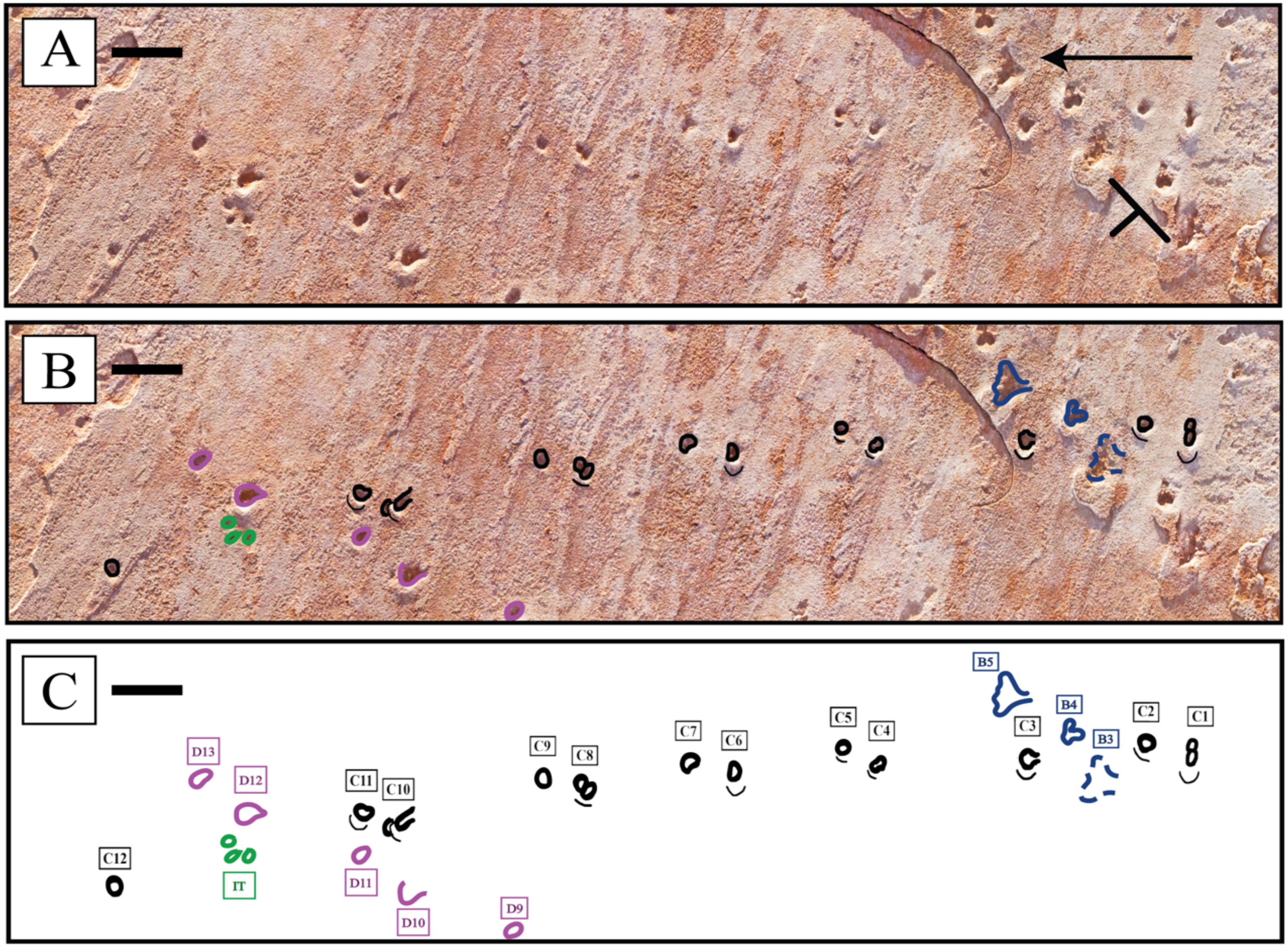

Figure 2.11 Trackway C. Scale bar is 10 cm. A. Close-up view of Trackway C. Black arrow indicatesdirection of forward movement. B. Black outline of Trackway C imposed over original image. Note: Trackways B (blue) and D (pink) intersecting with Trackway C. C. Outline of Trackway C. IT = Isolated trace.

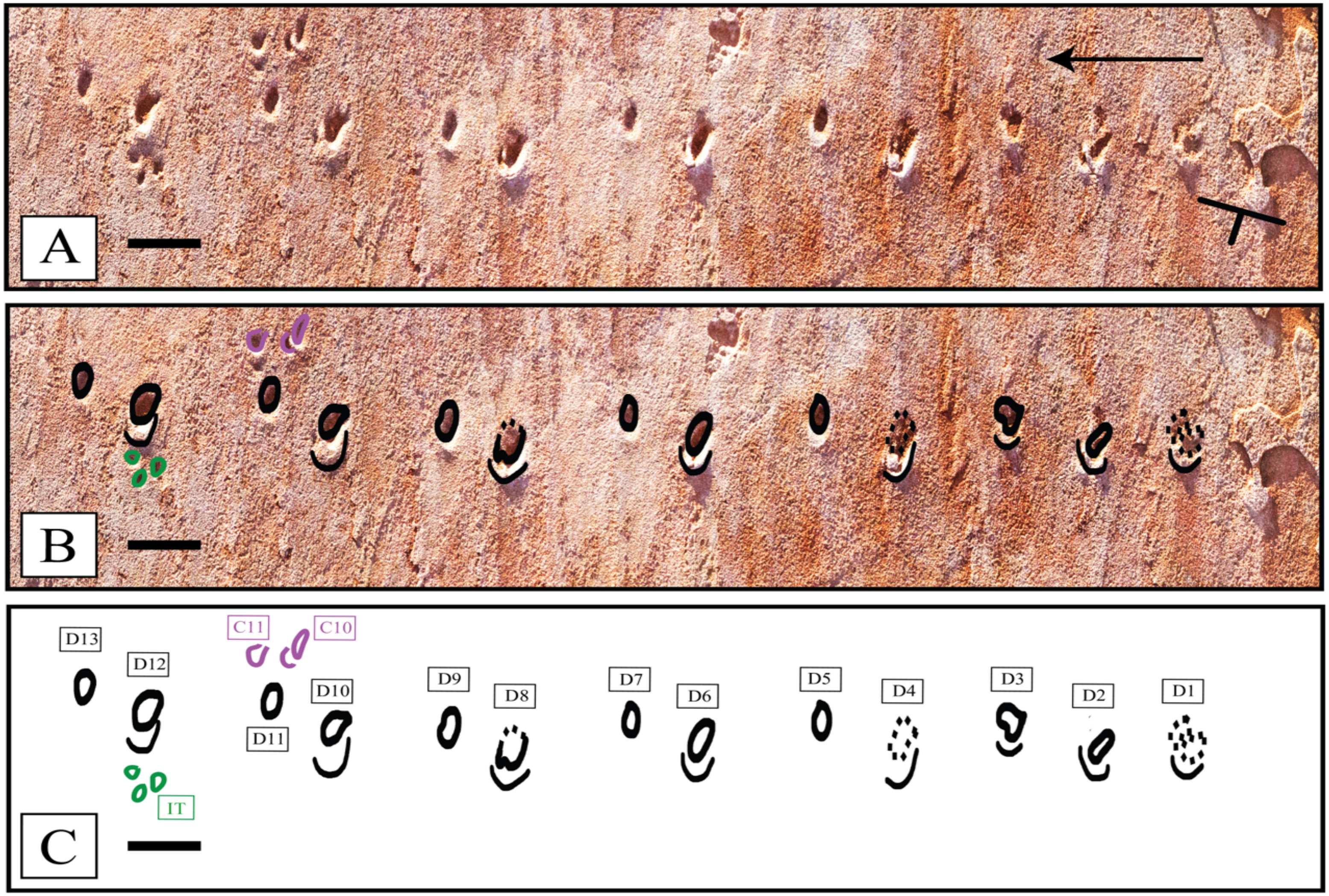

Figure 2.12 Trackway D. The scale bar is 10 cm. A. Close-up view of Trackway D. The black arrow indicates direction of forward movement. B. Original image overlain by drawn outlines. Trackway D is shown in black, tracks C10 and C11 are shown in pink, and the isolated trace is shown in green. C. Black outline of Trackway D. Dashed lines indicate uncertainty of trace structures. IT = Isolated trace.

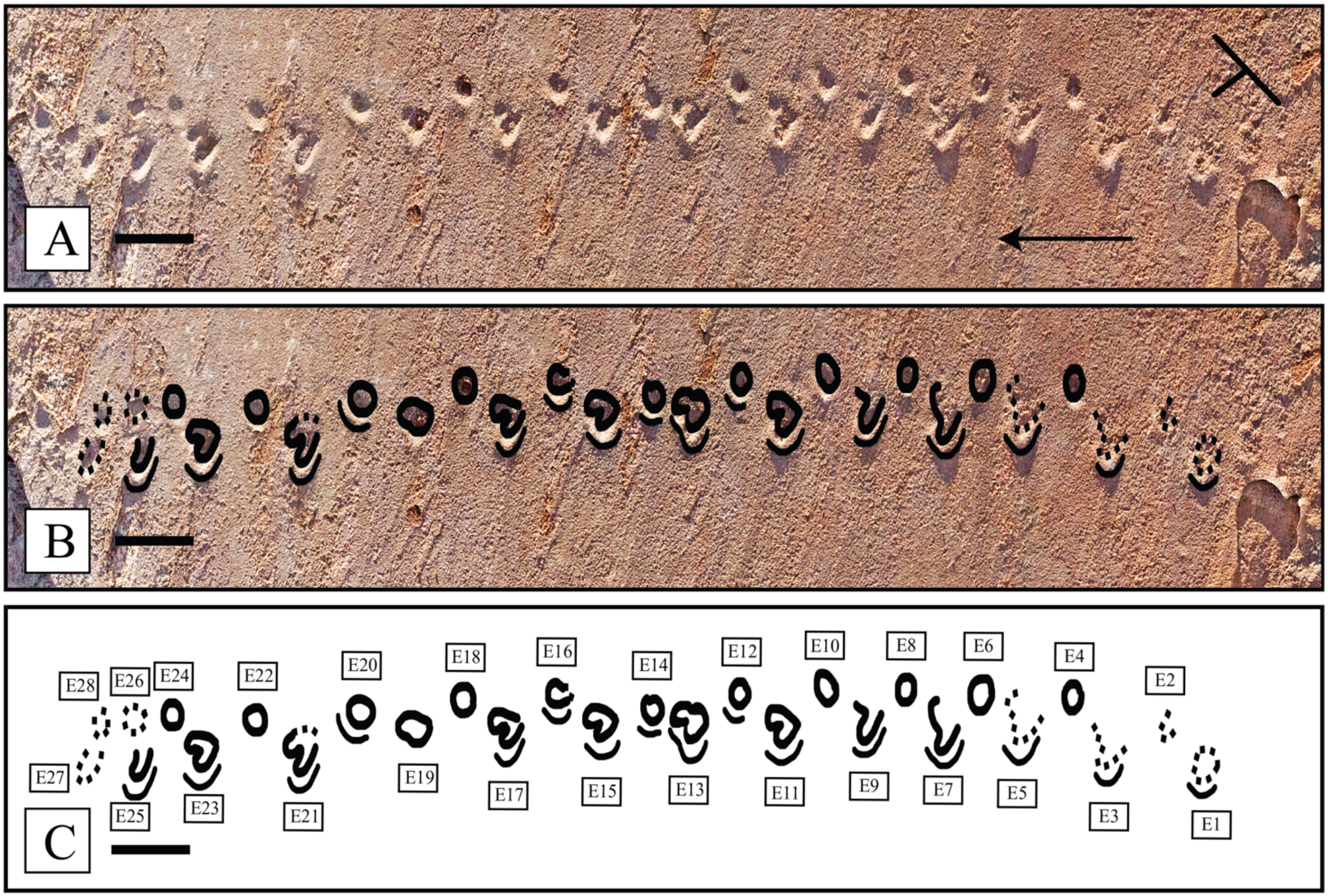

Figure 2.13 Trackway E. Scale bar is 10 cm. A. Close-up view of Trackway E. The black arrow indicates direction of forward progression. B. Original image overlain by black outline of tracks. C. Black outline of Trackway E. Dashed lines indicate uncertainty or missing trace structure.

2.8.6 Trackway F

Trackway F comprises only four tracks, all of which are associated with grain flows (Figure 2.14). These four consecutive traces are oriented from northeast to southwest. Tracks F1, F2, and F4 are poorly preserved. On the contrary, Track F3 is the only trace with discernible features (three distinct digits - II, III, and IV) clear enough to produce reliable measurements. Length and width measurements of F3 are 10.8 cm and 9.8 cm respectively. The entire length of this trackway is 1.01 m. Trackway F is significant as it is superimposed over Trackway G. This is unique to GLCA #357. After the four tracks were impressed, Trackway F disappears when it intersects with Trackway G and disappears completely from the dune slip face.

2.8.7 Trackway G

There is one intersection between trackways F and G, which are both oriented on the same path on the track-bearing surface (Figure 2.15). Trackway G is noticeably smaller than Trackway F (Figure 2.15c). It includes four well-preserved pairs of traces that seem to be overlapping, congruent circles. The circles have an average length of 2.01 cm and an average width of 4.08 cm. The total length of the trackway is 19.07 cm. Similar to Trackway F, the orientation of Trackway G is from northeast to southwest. Miniscule grain avalanches are observed beside every circular-shaped depression, and the two circles of each pair encroach upon each other. Thus, the two overlapped congruent circles produce the odd shape of the trace overall. Trackway G shows a unique feature in that Track G3 is perpendicular to the longitudinal axes of the other three traces. This trace is oriented at a 71° angle from Track G2 and at a 76° angle from Track G4. No other discernible characteristics are observed.

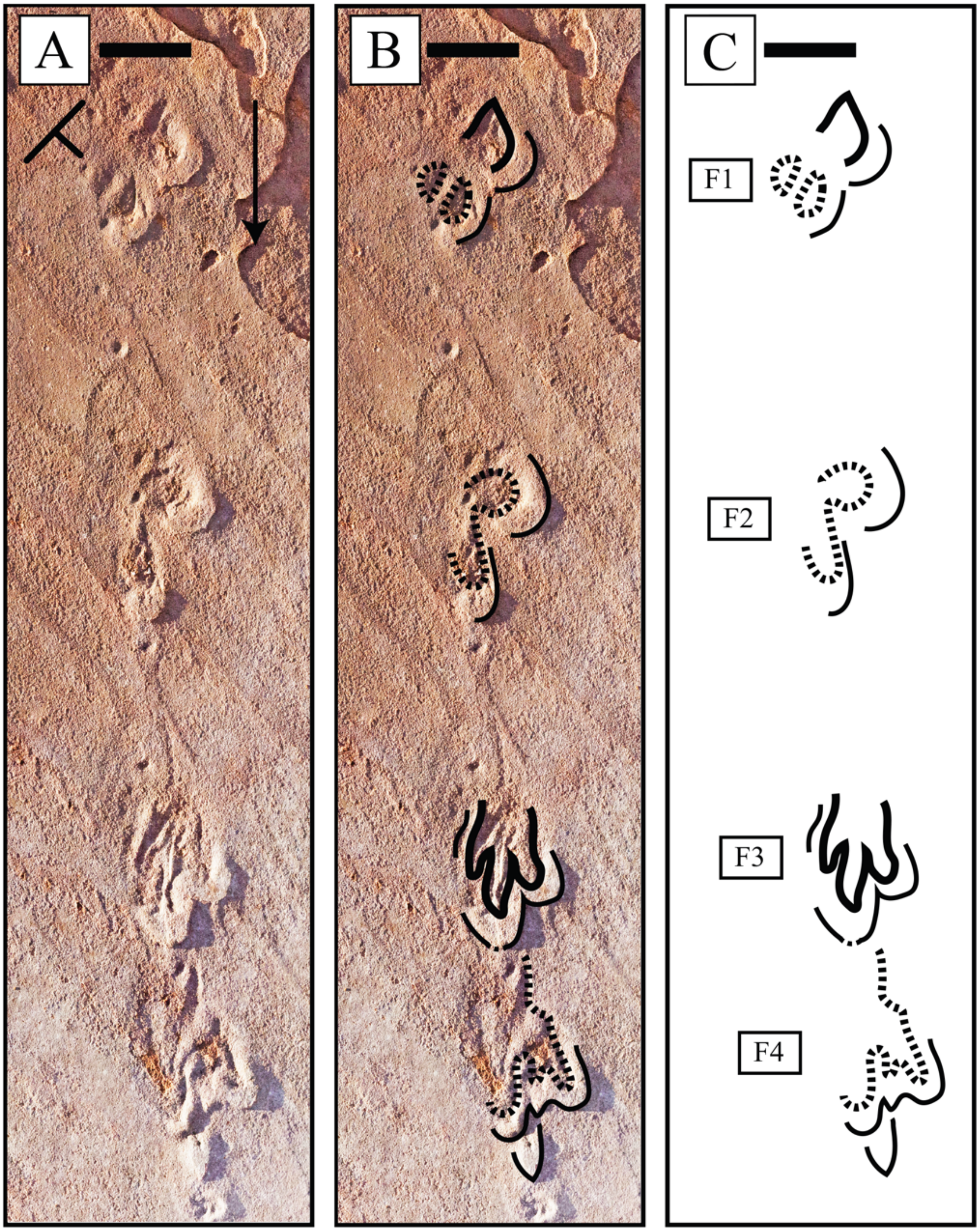

Figure 2.14 Trackway F. The scale bar is 10 cm. A. Close-up image of Trackway F. Black arrow points to the direction of forward movement. B. Original image overlaid by a black, drawn outline of traces. Dashed lines indicate the uncertainty of the trace profile. C. Outline of Trackway F.

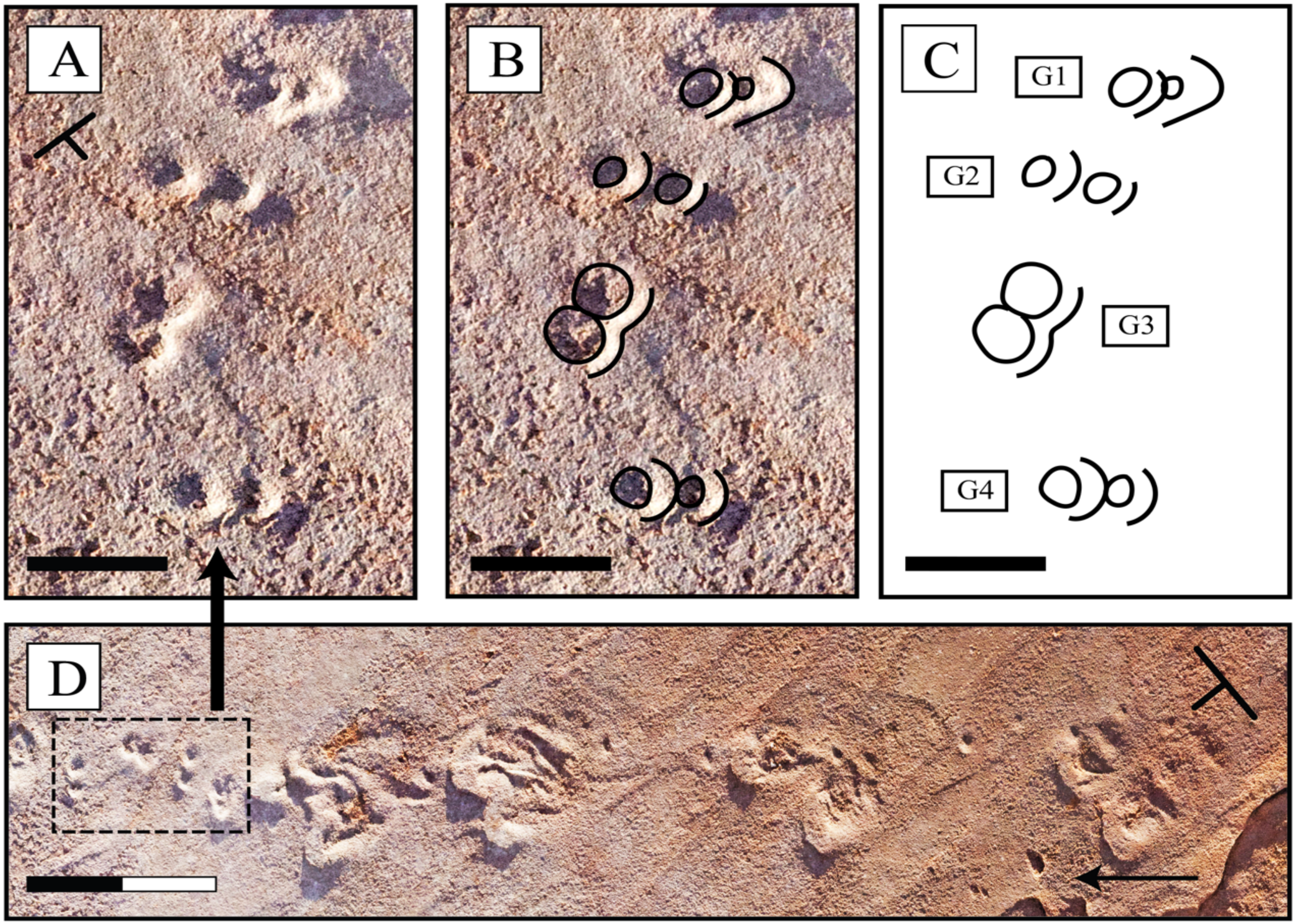

Figure 2.15 Trackway G and F. Scale bars for 15A - 15C are 5 cm. Scale bar for 15D is 20 cm. A. Close-up image of Trackway G. B. Original image overlain by drawn outline of traces and grain avalanches. C. Outline of Trackway G. Note: The orientation of G3 is facing at 71° from G2 and oriented 76° from G4. D. Close-up image of trackways F and G. Black arrow indicates direction of forward movement of Trackway F. There is no clear evidence to indicate direction for Trackway G.

2.8.8 Trackways H

Downslope from Trackway G is another relatively small trackway with few clear features. Trackway H (Figure 2.16) consists of four consecutive tracks, each with two digits. These didactyl traces are elongated, and the individual digits curve slightly inward. All tracks show associated grain flows. Track H3 has two sand crescents located on either side of the trace (upslope and downslope). The didactylous characteristic is strikingly clear in Track H3, whereas it is only faint in tracks H1, H2, and H4. The lengths of the digits of H3 are 5.09 cm for the downslope depression and 3.9 cm for the upslope depression. These two digits differ only by 1.1 cm in their lengths. The average length of all tracks is 6.6 cm with an average width of 4.9 cm. The total length of Trackway H is 55.8 cm.

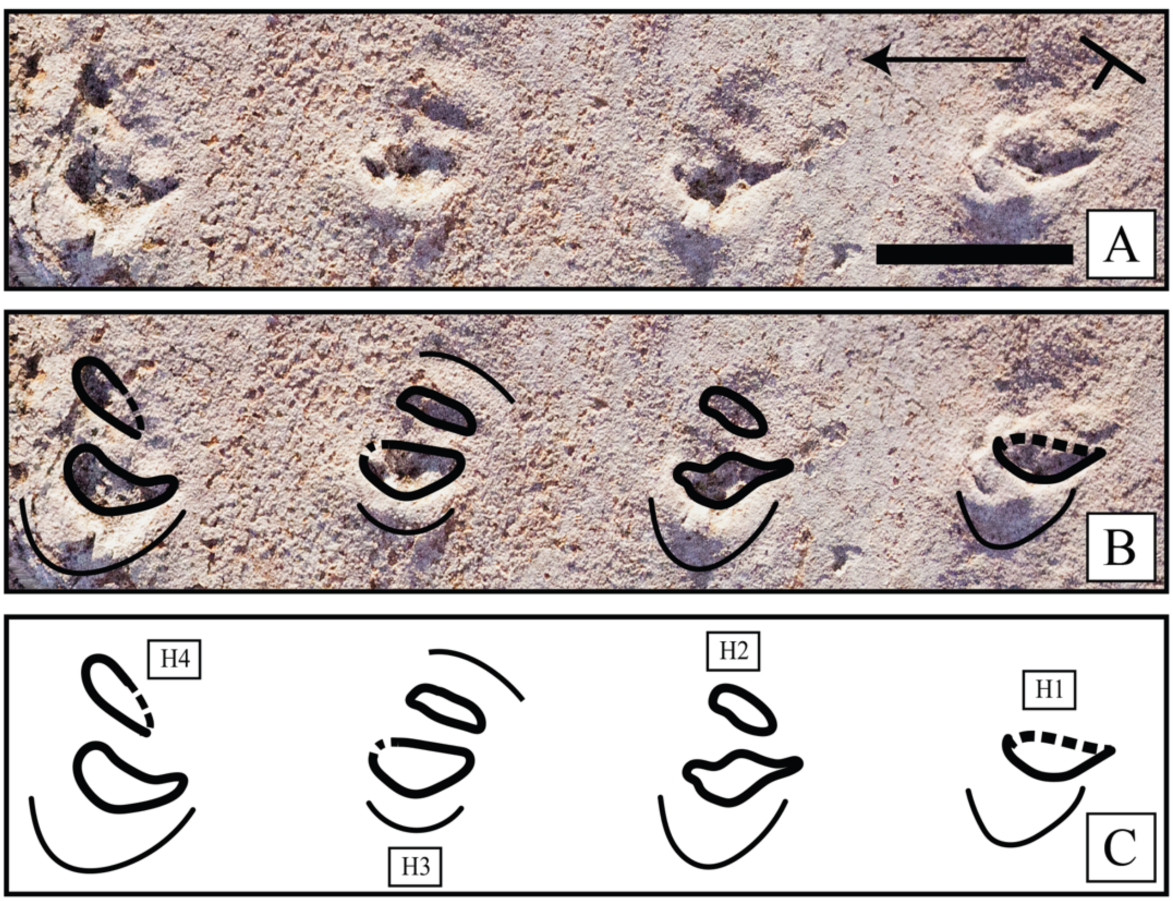

Figure 2.16 Trackway H. The scale bar is 10 cm. A. Close-up view of Trackway H. Black arrow points to the direction of forward movement. B. Original image of Trackway H with an overlain black outline of the traces and grain flows. Dash markings indicate uncertainty of traces. C. Outline of Trackway H. Note: H3 is the only trace with an upslope and downslope sand crescent.

2.8.9 Trackways I, J, K

In addition to trackways A - H, there are many other trackways found on GLCA #357. However, due to weathering and poor preservation, the bottom right corner of the track-bearing surface (SE corner) is difficult to describe and account for details. Much of the rock has been spalled off the uppermost layer, revealing the surface below. This makes it problematic to distinguish trackways, track morphology, collect measurements, or determine their orientation. In addition, some are seemingly deeper undertracks from a surface layer above this track-bearing surface. Tracks in this portion of the slab are also superimposed on each other and there is a lack of detail preserved.

One trackway shows the same distinctive sediment grain flows such as those seen on the previous trackways, but with a few unique features. This trackway, Trackway I (Figure 2.17) lacks fine detail, but the most distinguishing features are the grain avalanches located downslope of the traces, the change of direction, and the horseshoe-shaped depressions. The first feature unique to this trackway are the depressions left by the trackmaker on this sandy surface. There is a displacement and forward movement of sand, seen on Trackway I, that leave behind horseshoe-shaped depressions. This peculiar shape is the first of its kind seen on GLCA #357. Seventeen traces comprise Trackway I; 9 right-sided and 8 left-sided tracks. All tracks have a sandy avalanche with exception for I4 and I12. Another interesting detail of Trackway I, is the orientation. This trackway begins running west to east, however, about two steps in (two

Figure 2.17 Trackway I. The scale bar is 15 cm. A. Close-up image of Trackway I. Black arrow indicates direction of forward and descending movement. B. Outline of traces over the original image. C. Outline of Trackway I.

right, one left), the change of progression changes course towards a southeasterly direction as it descends the slipface. By doing so, the grain flows shift their location - from directly underneath the trace's U-shaped cavity to then shifting to the right side of the U-shape trace. The horseshoe shape changes its silhouette as the trackway begins to descend the dune face. As seen on Tracks I7, I9, I11, I13-15, and I17, a protrusion emerges at the bottom of the U-shape (Figure 2.18). This knob is perfectly visible on Tracks I11 and I17. The total length of Trackway I is 1.8 m with traces of an average length of 3.67 cm and an average width of 3.06 cm.

North of Trackway I is a smaller trackway, Trackway J (Figure 2.19). This trackway intersects with Trackway I at Track J9 (Figure 2.19c) but is oriented on a route that is at a much steeper angle. Trackway J consists of ten paired traces: 5 right-sided and 5 left-sided traces. Weathering has affected the preservation of fine detail, however, grain flows are visible on the downslope margin. Due to the inability to gather accurate measurements of individual traces, calculations were made from each paired trace. The total length of this trackway is 86.8 cm. The average length of a pair is 7.8 cm with an average width of 6.4 cm. Length of Track J9 and J10 were excluded from the average calculations as their orientation differs from the other pairs. Tracks J9 and J10 sit at a 94° angle from Tracks J7 and J8. Unlike the other pairs, both traces sit side by side like two congruent circles as seen in Trackway G. After Trackway J meets Trackway I, it disappears from the dune slipface.

The most ambiguous and unintelligible trackway of GLCA #357 is Trackway K (Figure 2.20). The only visible feature on this trackway are the grain flows protruding from the bottom of each trace. Eleven grain avalanches account for Trackway K with a total length of trackway at 58.3 cm. The movement of forward progression begins with the first eight grain flows that take on an ascending route, but thereafter, make a sharp-left direction. In this section of the track-bearing surface, traces are cryptic and uncertain. Weathering has affected the ability to document any details, however in Tracks K9 through K11, there are shallow and faint depressions akin to a foot trace.

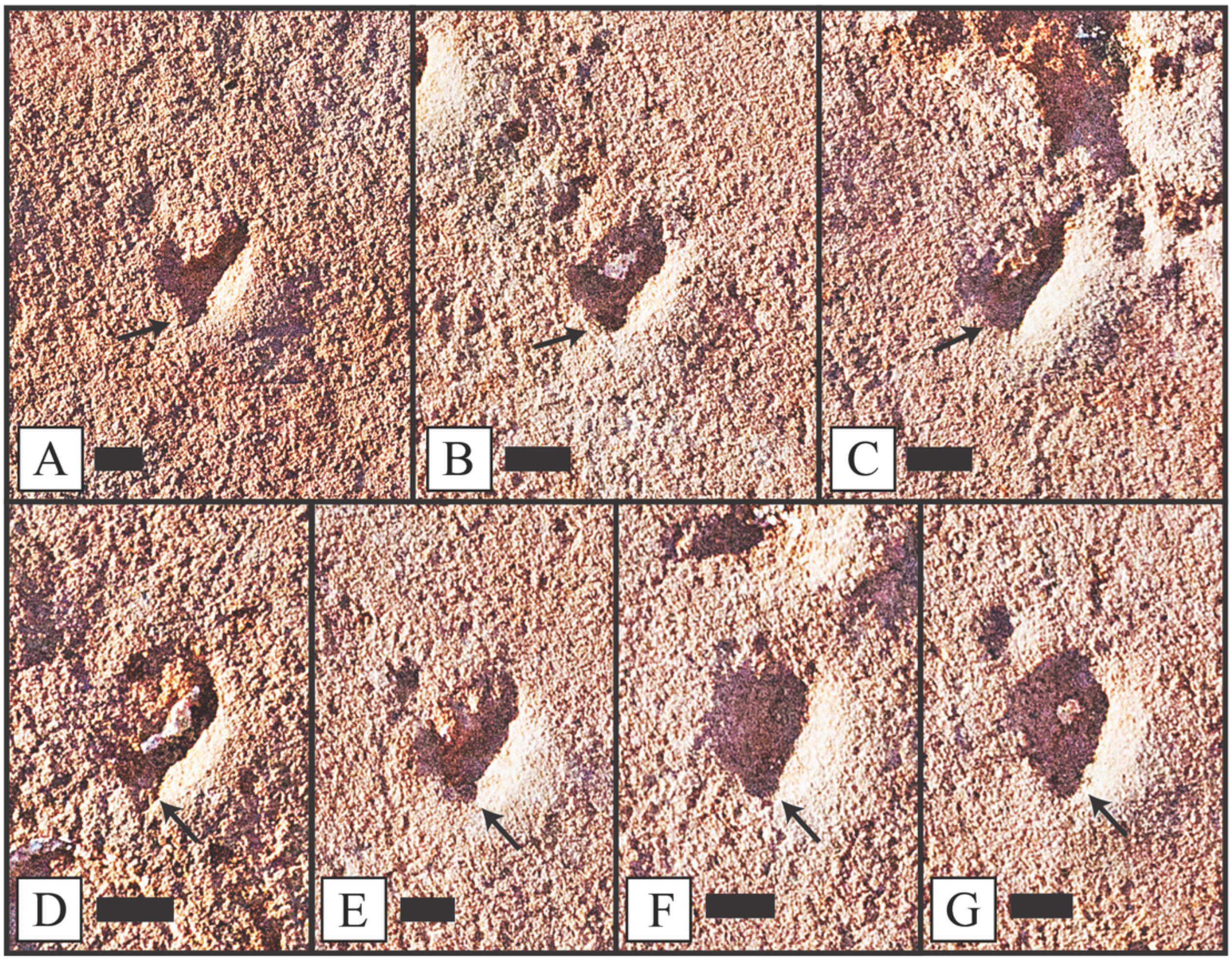

Figure 2.18 Horseshoe-shaped tracks with nodule trace from Trackway I. Arrow points to distinct nodules. Scale bars are 2 cm. A. Close-up image of Track I-7. B. Close-up image of I-11. C. Close-up image of I-17. D. Close-up image of I-9. E. Close-up image of I-13. F. Close-up image of I-14. G. Close-up image of I-15.

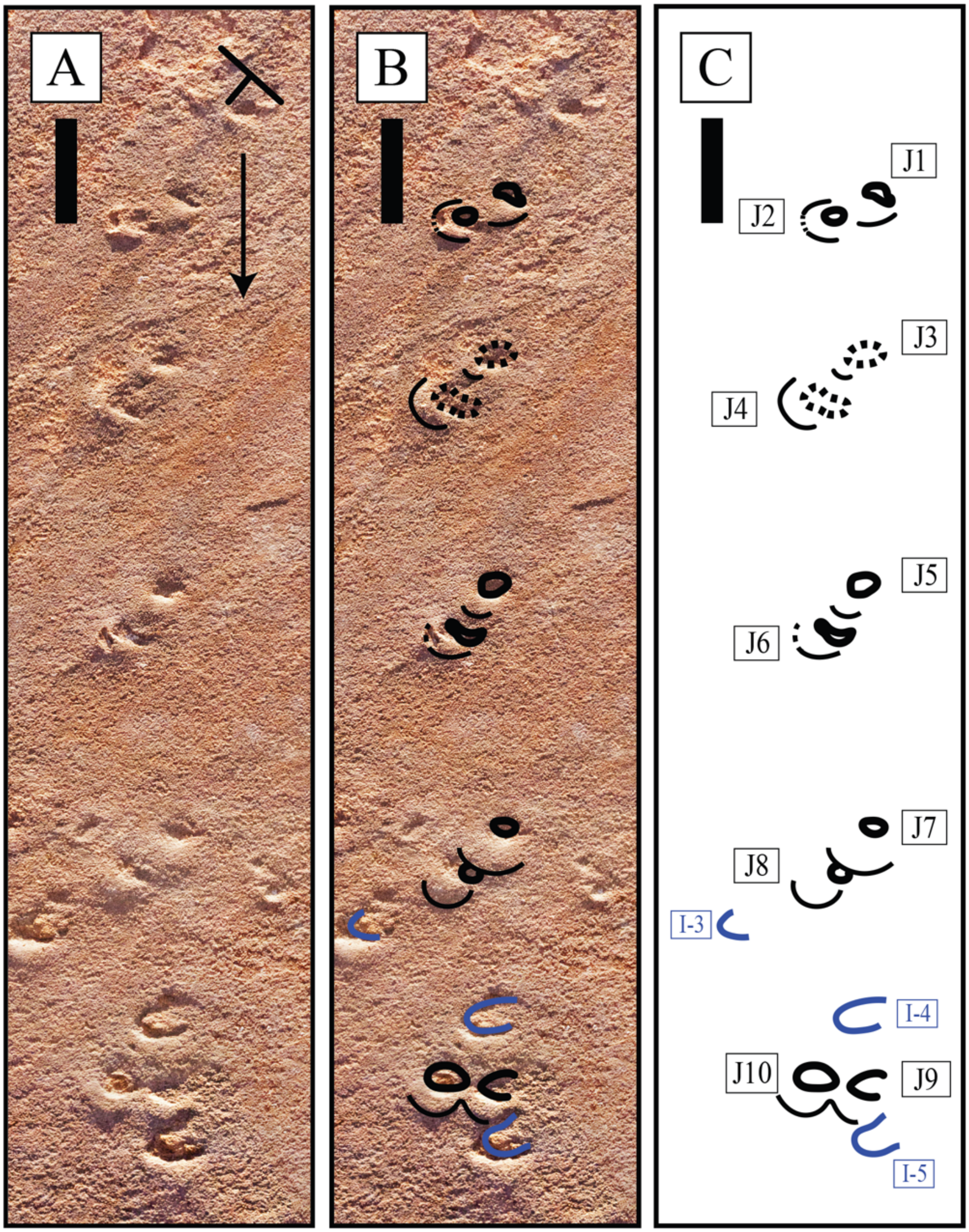

Figure 2.19 Trackway J. The scale bars are 10 cm. A. Close-up image of Trackway J. Black arrow points to the direction of forward movement. B. Original image with outline of traces from trackways I (shown in blue) and J (shown in black). Dashed lines indicate uncertainty of trace structure. C. Outline of traces from trackways I and J.

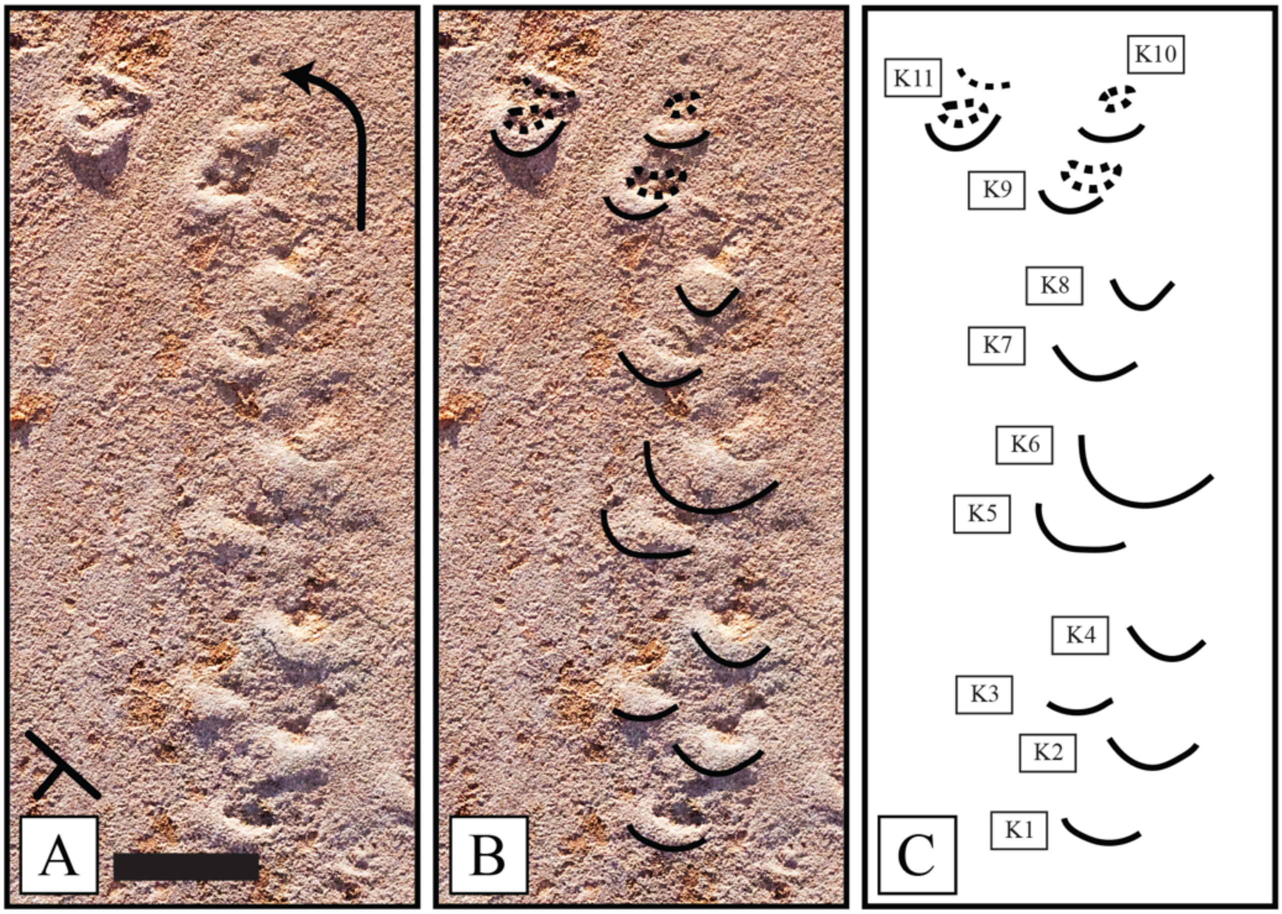

Figure 2.20 Trackway K. The scale bar is 10 cm. A. Close-up image of Trackway K. Black arrow indicates the direction of forward progression. B. Original image with overlain outlines of grain flows. Dashed lines indicate the uncertainty of trace structures. C. Outline of Trackway K.

2.8.10 Other Traces

In addition to trackways A through K, there are isolated tracks found in random orientations throughout the track-bearing surface. Six tracks, or trackways, are in random areas of this track-bearing surface that hold no continuous pattern to be grouped as a trackway (Figure 2.21). One unique structure is found between trackways D and E (Figure 2.21E). This structure is a discontinuous, sinuous track that displaces sediment on either side, creating ridges above and below the linear figure. This structure measures 1.2 m in length and has a width of 10.7 cm at its widest opening. It is oriented northeast to southwest. The ridges are very shallow compared to the traces found around the structure but are deep enough to be intriguing.

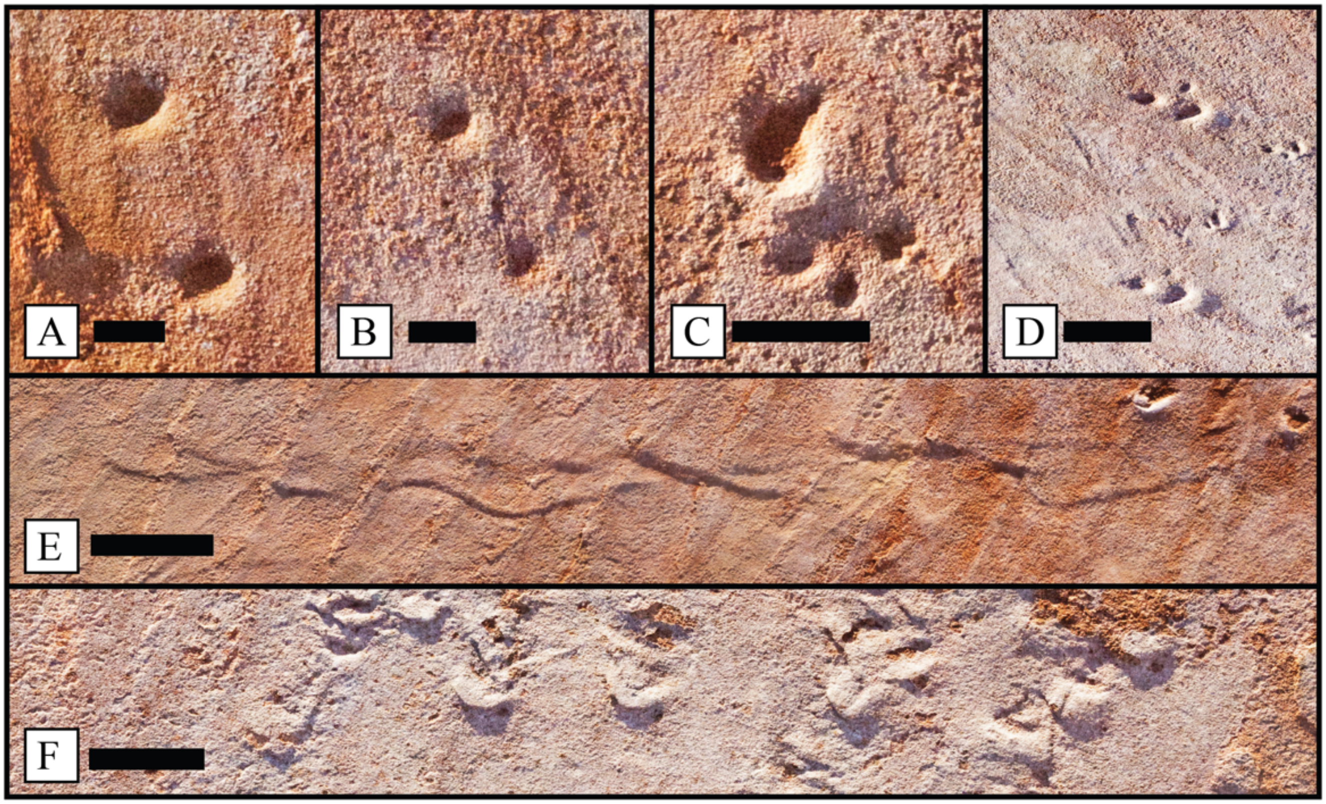

Figure 2.21 Isolated traces and trackways. A. Isolated trace located north of Trackway B. Scale bar is 2.5 cm. B. Isolated trace found between trackways B and C. Scale bar is 2.5 cm. C. Unknown trace found below Track D12. Scale bar is 5 cm. D. Isolated trace found north of Trackway H. Scale bar is 15 cm. E. Ambiguous trace located between trackways D and E. Scale bar is 15 cm. F. Enigmatic trace found south of Trackway K. Scale bar is 10 cm.

2.8.11 Physical Sedimentary Structures

Two sets of low-amplitude wind ripples are found on GLCA #357 (Figure 2.22). The primary set of these ripple crests is more pronounced across the surface than the second. They are straight, long, with parallel crests, and seemingly asymmetrical. The symmetry of the ripple crests is based on the weathering patterns visible on most ridges. The right side of the summit point is devoid of the overlying layer of rock. The opposite is said of the left side of the summit point where the overlying rock is notable on most ripple profiles. However, due to the sediment degradation, the symmetry of the crests is difficult to determine. A cross-view section of the track-bearing surface is required for accurate analysis. Though faint, the second set of wind ripples are seen to truncate the original ripples before the process of lithification began. The first set of wind ripples, the most pronounced set, are oriented 26° to the dip direction. The second set of wind ripples is parallel to the dip direction. For reasons unknown, they are most prominent on the left side of the track-bearing surface. It is important to mention that both ripples are trampled on by the trackmakers. Figure 2.22c shows tracks from Trackway E step over the ripple crests. Reineck and Singh (1975; Table 4) label these structures as small wave ripples due to the ripple length measuring less than 0.6 m. The direction of wind ripples and grain avalanches seen in the trackways help orient the track slab to its original position. It is without question that GLCA #357 is dipping in the position of when the secondary set of wind ripples were deposited.

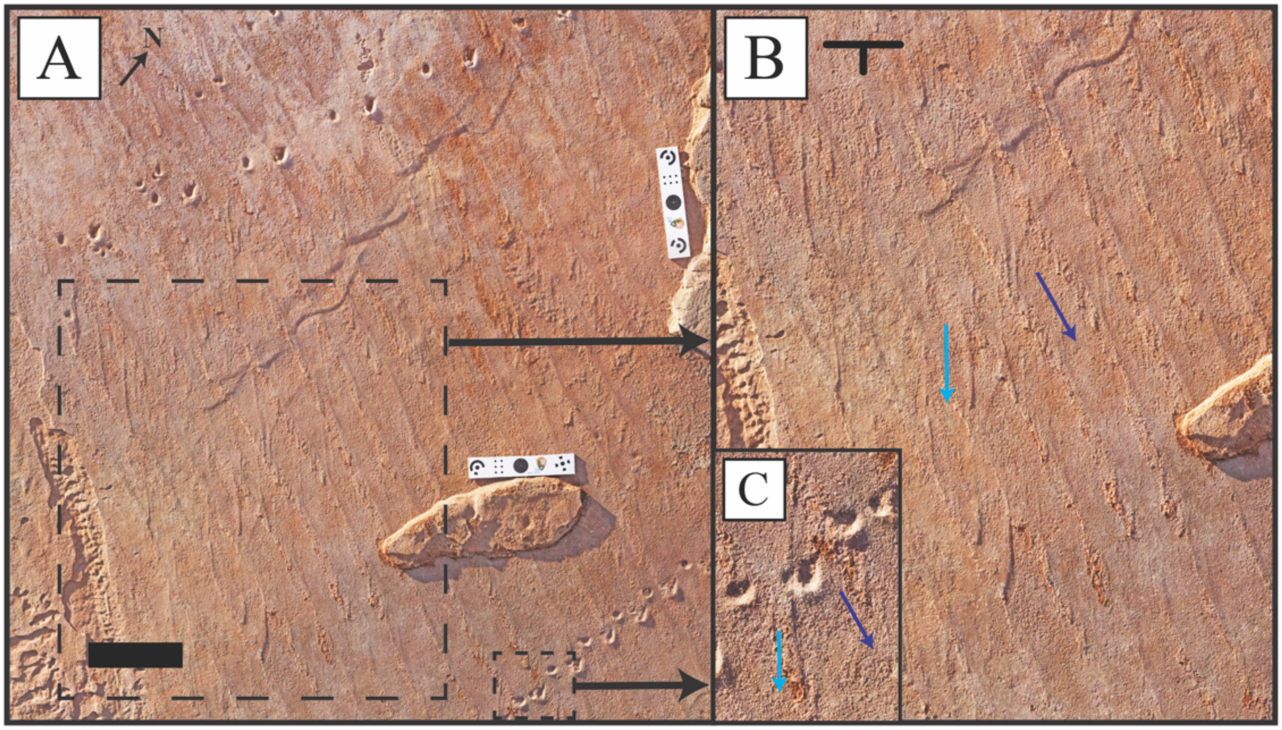

Figure 2.22 Wind ripple structures across GLCA #357. A. Two sets of wind ripples on track-bearing surface. The scale bar is 25 cm. B. Close-up view of the two sets of wind ripples. Directions of the parallel ridges from both sets of wind ripples are shown as arrows. The primary set of ripple crests is shown with a dark blue arrow and the secondary set is shown by a light blue arrow. C. Trackway E oversteps both sets of wind ripples.

2.8.12 Stereonet – Orientation of Bedding Plane and Trackways

A stereonet (Figure 2.23) was made to display the orientation of Trackways A through K. The results of the stereonet determined the animals' pathway at an angle of no greater than 40 degrees from horizontal, and 7 of the 11 trackways are 30 degrees or less. Notably, trackways F, G, J, and K, which are the steepest ascents, also suggest a pronounced hopping in their tracks.

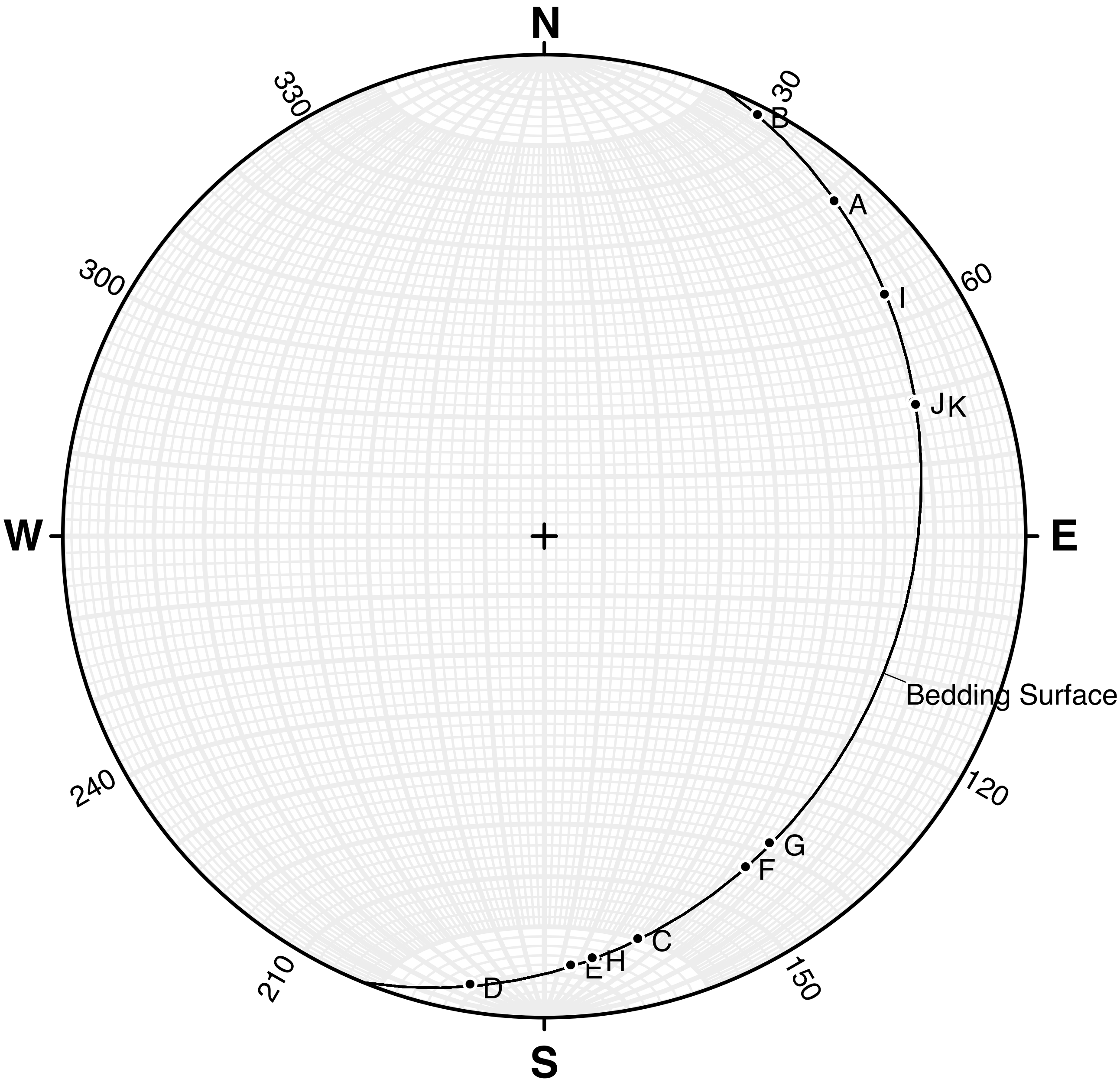

Figure 2.23 Stereonet showing orientation of Trackways A through K.

2.9 INTERPRETATION

GLCA #357, Santucci's track slab, records during a short moment of time the ichnofauna found within the eolian deposits of the Early Jurassic Navajo Sandstone. The track-bearing surface of this dune slip face offers a glimpse of active animal behavior and locomotion prevalent in the massive erg system of the Early Jurassic period. Traces, like the ones discussed, depict several animals, not only surviving but thriving in this arid ecosystem. The angle of repose of dry sand is about 33° (Webster, 1919; McKee, 1944). The dip of GLCA #357 is 25°, which makes the substrate stable for track impressions without the risk of collapsing. The Mesozoic tetrapod ichnofossil assemblage associated with the Lower Jurassic Navajo Sandstone includes *Brasilichnium* and *Grallator* (Lockley and Gierlinski, 2014). This correlates with the ichnotaxa found on GLCA #357. Most of the documented trackways show sub-optimal preservation due to the sloping slip face of a sand dune. This level of preservation makes it difficult to classify certain trackways and traces. Therefore, the taxonomy and identification of tracks will be reliant on the singular and faint details observed. Most trackways suggest that they were made on the same stratigraphic layer of the dune slipface. However, the most difficult trackways to discern, notably Trackway K, are presumably under tracks from an overlain sandstone layer hence the lack of detail. Therefore, some of our taxonomic assignments hinge upon indistinct morphological characteristics and their similarity to other traces found in this erg system.

According to Leonardi and Carvalho (2020), the orientation of trackways can be detected by observing the crescent-shaped displacement of sand and the midline of the trackway. Trackways can be identified as uphill, downhill, or vertically (diagonally) across the foreset. In addition, the placement of pes rotation, either symmetrical or asymmetrical, can help identify the gait typology (Porchetti et al., 2017). In GLCA #357, four types of movement of forward progression are seen of *Brasilichnium*-like traces and a few have a change in locomotion. Walking, running, half-bounding, and skipping gaits are visible. These categories of locomotion are based on trackway slabs seen in Porchetti et al., 2017 (Fig. 4, Fig, 6, Fig. 7, and Fig. 10). The other trackways not attributed to *Brasilichnium*, *Grallator*-like, and the unknown trace also depict a forward motion of movement. Those descriptions will also be discussed below.

2.9.1 Trackway A

Although small in nature, Trackway A is most likely a *Brasilichnium*-like trackway (Figure 2.7). These football-shaped tracks are wider than they are long consistent with *Brasilichnium* tracks in Leonardi and Carvalho, 2020. No digits or other visible characteristics are found in this trackway. The trackmaker is seemingly walking in the most typical stance seen with *Brasilichnium elusivum* (Fernandes and Carvalho, 2008; Lockley, 2011; Porchetti et al., 2017; Leonardi and Carvalho, 2020). According to Porchetti et al., 2017, a walking gait in a *Brasilichnium* trackway is defined by various patterns of symmetrical or asymmetrical pes rotation on its direction of forward movement. Trackway A shares this characteristic. The lack of digits and grain avalanches located on each right-sided trace located at the anterior of the trace indicates the trackmaker was walking slightly downhill and across the dune foreset.

2.9.2 Trackway B

The most prominent trackway that is easily identifiable is Trackway B. Most notable of this trackway are the distinct digit impressions with the reputable large outer thumbprint that *Brasilichnium* is known for (Lockley, 2011). This trackway's lateral movement is depicted with grain flows and digit impressions. Trackway B is the only trackway with digit impressions deep enough to also be detected in the 2022 3D digital images (Figure 2.10). This suggests the depth of this trackway was deeper than the other trackways on this slipface making it resistant to the large-scale weathering that occurred in the span of eight years. In addition, this animal's orientation is east to west, and moving at walking speed according to Porchetti et al., 2017. Traveling direction is evidenced by the grain flows found on the downslope of each footprint. As the animal was walking westward, the depressions made by the foot created small landslides of sand flowing downslope. These grain flows are consistent with an inclined sandy surface pulling the displaced sand downwards, like a minuscule avalanche. Each forward step on the left side of each trackway contains an avalanche. In addition, each left foot is sunken noticeably deeper than the right foot. This detail helps explain the uneven distribution of the weight of the trackmaker as it balanced itself on the inclined surface of the sand dune. These factors illustrate how most of the animal's weight is set on the left side of the animal, towards the downslope side. This uneven balance of the trackmaker's weight assisted with stabilization while walking on the sloping, uneven surface of the slip face. Another indication of the direction of progression is the manus impressions facing west on the anterior of the footprint. The manus prints seen on Trackway B (Figure 2.23) are consistent with the walking gait of *Brasilichnium* (Porchetti et al., 2017). Consequently, Trackway B is a trace of an animal walking across an inclined surface parallel to the strike of the dune slipface. As mentioned above, Trackway B intersects with Trackway C, but there is no relationship between both traces.

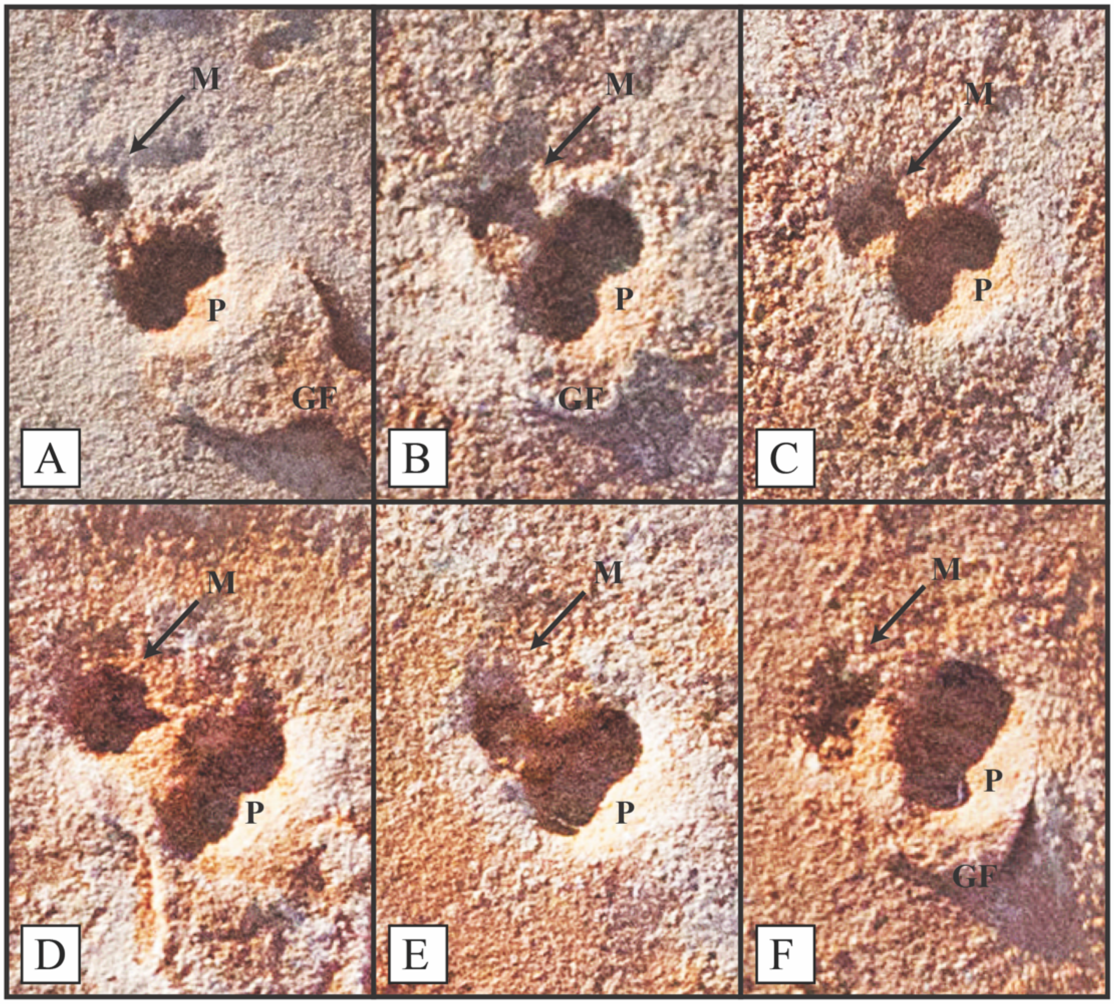

Figure 2.24 Manus traces found on Trackway B (M = Manus, P = Pes, GF = Grain flow). A. Close-up image of track B2. B. Close-up image of track B4. C. Close-up image of track B6. D. Close-up image of track B10. E. Close-up image of track B12. F. Close-up image of track B14.

2.9.3 Trackway C

Not often seen in *Brasilichnium* trackways are the trackmakers' footprints as it descends downhill. The only reported downhill trackways of this trackmaker on Early Jurassic sediments are reported in Engelmann and Chure (2017) and Porchetti et al. (2017). Trackway C has an orientation northeast to southwest and due to its proximity to Trackway B, it is presumed a

Brasilichnium trackway, but this is held with great uncertainty. This trackway is traversing diagonally across the dune slipface. A downslope running gait is defined as a track with little or no digit traces (Engelmann & Chure, 2017) with a long stride, high-pace angulation, and manus traces located close to the pes traces (Porchetti et al., 2017). All manus traces on Trackway C are overlain by the pes trace consistent with the above description (Figure 2.11). The stride length is an average of 24.61 cm, which is one of the largest found on GLCA #357. Pace angulation calculated from available traces was an average of 163°. Lastly, the lack of digits and the grain flows located at the forefront of almost all of the left pes impressions signify the trackmaker running diagonally downhill. Although Trackway C intersects with both, trackways B and D, there is seemingly no connection between any of the three trackways.

2.9.4 Trackway D

The fourth *Brasilichnium*-like trackway is Trackway D (Figure 2.12). The football-shaped traces are more bulbous in shape than previous trackways but are still notably wider than they are long just like *Brasilichnium*. Stride length is an average of 27.6 cm and average pace angulation of 173°. There are no evident digits found on this trackway and most of the grain avalanches are located on the downslope side of the trackway. These details are consistent with the trackmaker running diagonally across as it descends the dune slipface. As the animal dug each left footprint into the sandy surface, it left behind grain flows that are typical on a sloping surface. The direction of movement of the trackmaker is also indicative by the lack of digits due to the irregular dislocation of sediment. Average stride length depicts the trackmaker descending the slip face in a running motion. The same type of running gait is seen on Engelmann and Chure (2017) (Figure. 5). The unusual shape of Track D2, a horizontal, long, teardrop-shape (Figure

2.24a), can be related to the trackmaker's foot digging into the sandy substrate although this is uncertain and needs to be looked at further.

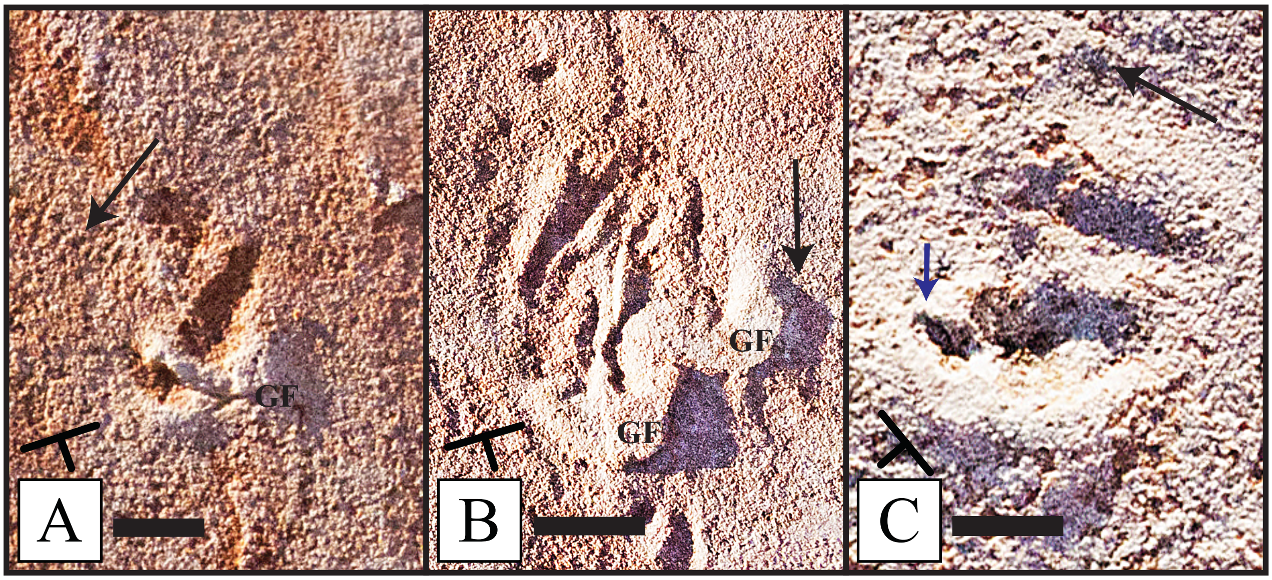

Figure 2.25 Close-up of tracks D2 (A), F3 (B), and H3 (C) and their distinctive details. Black arrows show the direction of forward movement. A. Track D2 shows a teardrop-shaped structure with an attached grain flow. The scale bar is 2.5 cm. B. *Grallator*-like track, F3, displaying tridactyl shape and subsequent grain flows. GF = Grain flow. The scale bar is 5 cm. C. Didactyl trace, H3, with a possible claw impression (blue arrow). The scale bar is 2.5 cm.

2.9.5 Trackway E

The third descending trackway in GLCA #357 is Trackway E. These asymmetrical, heart- and bean-shaped depressions are unique to this track-bearing surface. Currently, no documentation of traces like these is found in published literature. Therefore, no taxonomy will be registered to Trackway E. However, one track in the aforementioned trackway, Trackway A, shares the same heart-shaped trace, but it is found to be more elongated. Track A6 is a heart-shaped ichnite, but its orientation is eastward; opposite of the traces in Trackway E where orientations are westward (Figure 2.25). Nevertheless, the lack of digit impressions and grain flows signifies this trackway descending the dune slip, heading southwest towards the base of the slip face. Stride length is short with an average length of 10.9 cm. Due to the narrow stride length, Trackway E is discerned as a walking gait. Another unique feature of Trackway E is the placement of left-sided and right-sided traces. Relative to the movement of progression, the orientation of left and right traces face outward. This trait may be due to the action of stabilizing the trackmaker's weight as it descended the sloping sand dude as hypothesized by Porchetti et al., 2017.

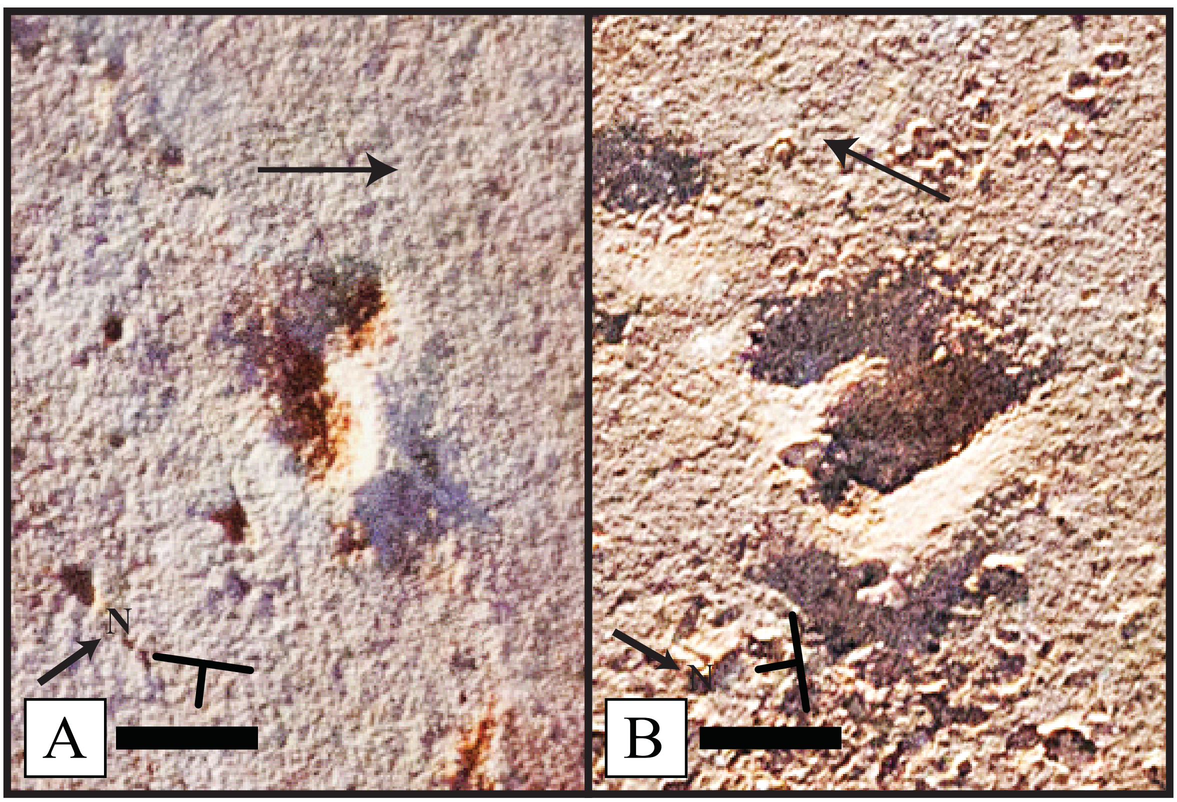

Figure 2.26 Side-by-side comparison of tracks A6 and E23. The black arrow shows the direction of forward movement. The scale bar is 2 cm. A. Track A6 is oriented eastward. B. Track E23 oriented west. Note: Both tracks have similar heart-shaped depressions and corresponding grain flows.

2.9.6 Trackway F

The only trackway on GLCA #357 that can potentially be attributed to a dinosaur is Trackway F. This *Grallator*-like trackway is the only one of its kind on the track-bearing surface. Only one of the four traces, Track F3 (Figure 2.24b), has distinct details of a tridactyl impression as the other three traces are badly weathered. The ichnotaxa, *Grallator* (Leonardi and Lockley, 1995), is commonly found in many Early Jurassic eolian ichnofaunas (Lockley et al., 1994; Lucas et al., 2005; Hunt and Lucas, 2006a; Hunt and Lucas, 2006b; Lockley and Gierlinski, 2014), most notably, alongside *Brasilichnium* traces (Lockley et al., 1994). It is attributed to a relatively small, bipedal, carnivorous theropod dinosaur (Hunt et al., 1998). In 2014, Lockley and a team of researchers found and reported an inclined sand dune foreset on Navajo Sandstone that shows both ichnotaxa within GLCA (Lockley et al., 2014). This validates the probability that Trackway F is a *Grallator* trackway. Loope (2006) has documented grain flows on *Grallator* traces in the Navajo sandstone. In Trackway F, grain flows nearest to the impression of the tridactyl digits (on the anterior side of the foot) depicts the trackmaker descending downslope on this slip face. Tracks F1 - F3 show a stride length relatively longer than F3 - F4. Due to poor preservation, an accurate measurement of stride length proves difficult. The differences in stride length indicate the trackmaker changing from a running gait to a walking gait. Yet, this illustration remains a theory as the termination of the tracks and any continuation of forward motion disappears.

2.9.7 Trackway G

The unique trace of Trackway G is noted in Porchetti et al., (2017: Figure 6) where the authors identify this as a half-bounding gait. As so, Trackway G is made up of four different pairs of two symmetrical circles that sit perpendicular to the midline of the trackway (Figure

2.15). They total eight traces. These two circles sit perpendicular to the midline of the trackway. with visible grain flows are emplaced. The traces show no digit impressions, and each pair has one circle that overlaps its counterpart trace. Besides Trackway G, only two other track-bearing surfaces are documented with the same gait pattern (Leonardi and Sarjeant, 1986; Porchetti et al., 2017) (Figure 2.26). The traces (symmetrical and spherical in shape) are described as a "galloping track" in Leonardi and Sarjeant (1986). Unlike the aforementioned published reports, manus traces in this traceway are absent. This is inconsistent with the definition of a half-bounding gait as releasing more energy to the ground during landing thus needing the support of stabilization provided by the upper limbs (Porchetti et al., 2017). The authors of the published reports identify the taxonomy as *Brasilichnium* therefore the taxonomy of Trackway G is identified as *Brasilichnium*-like. Both trackways, F and G, follow the same route on GLCA #357 (Figure 2.15d). It may be fun and easy to envision a larger theropod (*Grallator*) chasing a smaller reptile (*Brasilichnium*) on this track-bearing surface. However, based on the traces alone, there is no connection tying both trackways to a possible predator-prey hunting event. Additionally, further research is required to determine the direction of forward movement and to explain why Track G3 is found almost perpendicular (71° - 76° angle) to the other traces.

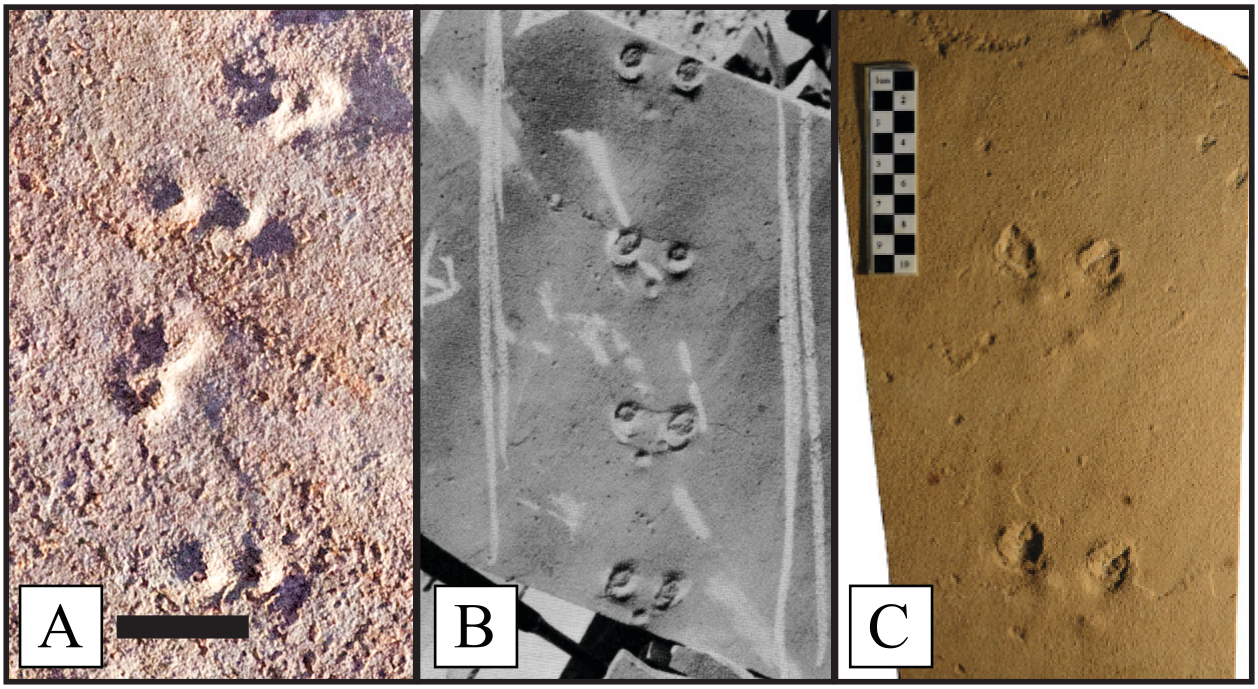

Figure 2.27 Trackways with half-bounding gaits. A. Trackway G from GLCA #357 in Navajo Sandstone (Lower Jurassic). Scale bar is 5 cm. B. "Galloping" trace from São Bento quarry from the Botucatu Formation (Upper Jurassic-Lower Createaceous) (As seen in Leonardi and Sarjeant, 1986). Scale unknown. C. Half-bounding trackway, URCR 23, from the Botucatu Formation as seen in Porchetti et al., (2017). Scale bar is 10 cm.

2.9.8 Trackway H

The only didactyl trace on GLCA #357 is Trackway H (Figure 2.16). Ichnofossil assemblages commonly found with *Brasilichnium* traces (Lockley and Gierlinsky, 2014) allow for a few hypotheses for the taxonomy of this trackway. The first assumption for Trackway H is a sunken, very deep impression of *Brasilichnium* with the half-bounding gait seen in Trackway G. The biggest problem with this idea is the lack of detail found on these traces. They are also horizontally longer and not as bulbous in shape as prior *Brasilichnium* traces. A second presumption is a trace of partial *Grallator*. Its proximity to Trackway F could make this idea a possibility. A small feature in Track H3 (Figure 2.24c) resembles a claw mark impression and can be interpreted as so. However, unless this theropod was missing a digit or was didactyl, the probability of it producing four consecutive, two-digit tracks is very low. Additionally, *Grallator* trackways are known to have large digit diverication with an elongated digit III that noticeably surpasses digits II and IV (Lockley et al., 2014). Based on measurements taken of Track H3, both digits are almost conjoined, and digits are only 1.1 cm apart in length. The claw mark impression can be disregarded as an erosional feature. Due to the uncertainty of this trackway, Trackway H is acknowledged as a trace with unknown origins. Based on the direction of travel and location of grain flows, Trackway H is regarded as a downslope walking trace with a half-bounding gait.

2.9.9 Trackway I

The most notable features of Trackway I are the U-shaped traces made by the trackmaker as it stepped into the sandy substrate. The horseshoe-shaped depressions (and those with an additional nodule) are unique to GLCA #357 (Figure 2.17; 2.18). The nodule, seen on Tracks I7, I19, I11, I13-15, and I17, can be attributed to a large, protruding exterior thumb typical of *Brasilichnium elusivum* (Leonardi and Carvalho, 2020). In this trackway, there is also a change in direction of forward movement. The gradual downturn of the trackmaker's route illustrates the agility of the animal. There is no doubt that descending a sloping sand dune parallel to the dip direction is a steeper route than traversing the surface parallel to the strike of the slip face. This trackmaker's decision to stroll to the base of the dune face by traveling this steeper route created deeper depressions in the sediment. The action of stepping into the sloping sediment and then lifting the foot led to a displacement and forward movement of sand. The sediment disturbance and the deeply embedded grain flows in the latter part of the trackway are the results of this type of locomotion on an inclined surface (Loope, 2006; Porchetti et al., 2017; Engelmann and Chure, 2017; Leonardi and Carvalho, 2020). No manus traces are observed in this trackway so consequently these traces are regarded as pes traces.

2.9.10 Trackway J

Trailing behind Trackway I is a smaller, bipedal trace listed as Trackway J (Figure 2.19). The placement of pes traces suggests this trackway is a bipedal *Brasilichnium* trace with a skipping gait as described by Porchetti et al. (2017). Trackway J intersects with Trackway I at tracks J9 - J10 but follows a descending route that is at a much steeper angle. This helps explain the relatively broad distance of the stride length between each step. The average stride length is 20.47 cm. It is evident that the trackmaker of Trackway J was presumably left-step dominant as it descended the steep slope as a single pace is relatively short in length and no digit impressions are visible in the anterior area of the trace. The direction of the forward movement of Trackway J is a descending route. This is opposite of the skipping gaits seen in Porchetti et al. (2017) where the authors describe it as an uphill gait. Due to the sub-optimal preservation, no accurate measurements of pace can be collected.

2.9.11 Trackway K

Although Trackway K lacks striking details, one characteristic feature that is different is the grain avalanches that follow the ascending route and its change of gait movement (Figure 2.20). This trackway shows forward movement changing from walking to skipping pace. This trace depicts the animal climbing upslope as proven by the short stride length that is outlined by the grain avalanches. Additionally, their location on the downslope side of each step (the posterior area of the foot) is consistent with the trackmaker's route ascending the dune face with a walking gait then making an abrupt left turn, with a skipping gait, until it disappears into a badly weathered section of the track-bearing surface. The trackmaker only skipped for two forward steps, but this skipping motion is visible from the sand crescents located on the downslope side of each step. This example closely resembles a track slab seen in Porchetti et al., 2017 (Figure 7A) that changes gait from a walking to skipping motion. This trackway is almost identical to other ascending *Brasilichnium* trackways in published reports (Rowland and Mercadante, 2014; Lockley et al., 2014, Figure 5B). Therefore, the taxonomy of Trackway K is *Brasilichnium*-like.

2.9.12 Others

Included in this ichnofauna party is the enigmatic, slithering, wavy sedimentary structure between Trackways D and E (Figure 2.21e). This seemingly apodous trace is analogous to two snake-like traces overlapping each other. A discernible "S" shape can be seen descending (or ascending) on the sandy substrate. Seen on this snake-like trace are the uplifted ridges outlining its route. The direction of progression is difficult to interpret as both ends of this trace disappear abruptly from the dune face. Its preservation can be perceived as a limbless animal in locomotion on the sandy substrate. The idea that an apodous trackmaker sliding down the same track-bearing, slip-face surface as mammal-like reptiles and carnivorous theropods is probable. The Candeleros Formation (Late Cretaceous) in northern Patagonia is evidence of squamates and theropods sharing and inhabiting the same eolian paleoenvironments (Palci et al., 2013; Halupczok et al., 2017; Garberoglio et al., 2019). Tracks from an ornithischian dinosaur were found in the same eolian depositional system with body fossils from the limbed snake, *Najash rionegrina* (Palci et al., 2013; Halupczok et al., 2017; Garberoglio et al., 2019). The earliest documentation of squamates in the fossil record is from the Bathonian, Middle Jurassic, and, in North America, the earliest report is from the Kimmeridgian, Upper Jurassic (Caldwell et al., 2015). Around this study area (Arizona/Utah), the first documented snake in Utah is from the Cedar Mountain Formation dated Early Cretaceous (Cifelli and Nydam, 1995). Although body fossils of squamates are found in older rock units than the Navajo Sandstone, the origin and early evolution of snakes would have occurred before the evidence in the geological rock record. Therefore, the sinuous track is interpreted as a possible, but inconclusive biogenic structure of an apodous-like animal.

2.10 DISCUSSION

The preservation of multiple tetrapod trackways in an eolian environment is extraordinary, to say the least. Eolian environments are dynamic due to the constant migration of sand dunes and the unconsolidated substrate (Loope et al., 2004). The preservation of these 11 trackways was produced by multiple forces, including strong surface winds, monsoonal rains, and concurrence of multiple trackmakers traversing the same lee face of one sand dune. Loope (2006) argues the avalanche side of a sand dune, the lee face, is the least likely to erode. This in turn makes this surface the preferred area for tracks to lithify and preserve. The presence of the massive cross strata observed on the Navajo Sandstone asserts the notion of its high preservation abilities (Loope, 2006). Thus, creating the perfect setting for GLCA #357 to exist.

On this dune face, the trackmakers are seen running, walking, fast walking, skipping, and half bound-skipping on the sandy substrate. The grain avalanches, depending on their relative location, helps indicate the direction of forward progression and their route of descending or ascending on the sloping substrate (Loope, 2006; Porchetti et al., 2017; Engelmann and Chure, 2017). There doesn't seem to be any explanation to why different trackways show different gait patterns. The walking trackways (trackways A, B, D - F, H, I, K) have nothing in common. Most of the trackways are traversing diagonally across the dune face with the exception to trackways I and K. These traces are seen abruptly turning, (right and left, respectively) to ascend and descend the slip face. The only running trackway, Trackway C, shows the direction of forward movement as downward until it disappears on the surface due to weathering. There is no clear explanation why this trackmaker was running down the dune's slope. Undoubtedly, the most odd-looking trace is Trackway G. The trackmaker responsible for these traces had a unique way of prancing on the sandy sediment. Its location explicitly on the same route as Trackway F, makes it even more bizarre. Due to the discontinuation of both trackways, not enough details can help explain the relationship between both. Lastly, the only half-bounding trackway seen on GLCA #357 is Trackway J. Like the other traces, very little detail is known about the progression of forward movement from these ten footprints; however, the galloping stride is seen as another method of descending the dune surface.

The track-bearing surface on GLCA #357 also illustrates the occurrence of the trackmakers' preferred route on a dipping slip face. Some trackmakers stroll crosswise (trackways A, B), others diagonally (trackways C - I), and two little animals chose an almost vertical path when they descended (Trackway J) and ascended (Trackway K) the steep incline. They all leave grain avalanches that show their direction of progression and preferred method of roaming this dune face. In some instances, the trackmakers change the direction of forward movement. These two trackways do not seem to have any relationship to each other as one is going down the slope by making a right turn (Trackway I) and the other is going up making a left turn (Trackway K).

The sloping surface and the sandy sediments affect morphology and stride. In GLCA #357 footprints belonging to the same trackway show variation of sizes, shape, and appearance. The morphology of tracks is affected by the small sand slumps occurring immediately after the removal of the trackmaker's limb, correlating with Loope (2006). In one trackway (Trackway I), one can still detect the infill sediment inside the wide hole the trackmakers left after lifting their foot off the sediment. Furthermore, the infill deters the ability to distinguish the morphology of the footprint since the slumping of sediment disturbs the trace's structure. Differences in left and right shapes are notable in many trackways, but it is very profound in Trackway E. In this trace, all right-footed tracks produced circular depressions on the sediment as opposed to the left-sided tracks that are heart-shaped. The reasoning behind this may be the position of the left foot located on the downhill side of the slope. There are a few examples of Brasilichnium traces with the sand crescents in the same region e.g. Engelmann and Chure, 2017. However, there are no current published reports of a *Brasilichnium* trackway resembling the circle and heart-shaped depression seen on Trackway E. Porchetti et al. (2017) suggests that the difference in foot morphology between both pes impressions is due to the trackmaker sliding forward the downhill foot to compensate for the sloping dune face.

As is common with mammal gaits, trackways of *Brasilichnium* often vary from a bipedal pattern to a quadrupedal (Lockley, 2011) trace. Santucci's track slab is no different. Many of the trackways documented show an absence of manus prints. However, in some trackways noted here, there is an interchange from bipedal to quadrupedal gaits, most notably in Trackway B. The common construct is that much of the gaits of *Brasilichnium* trackmakers were quadrupedal, however, often, the manus prints are overstepped by the hindfoot. This explains why it is difficult to distinguish the trace of a manus from a hind foot imprint. Some of the traces can even be explained as soft sediment deformation and not tracks as identified above. It should also be noted the level of biased taphonomy of sandy surfaces on the lee face of a sand dune. Many of the eleven trackways are devoid of digits or essential characteristics necessary for identification. This research is solely focused on the grain avalanches created by the placement/displacement of the sandy sediment and the general structure of the traces left behind by the trackmakers. The level of weathering that GLCA #357 has undergone is unfavorable to further research.

2.11 CONCLUSION

Variations of gait patterns of *Brasilichnium* and *Grallator*-like trackmakers are seen on GLCA #357. Walking, skipping (or galloping), half-bounding, and running are the many ways these desert trackmakers migrate on sloping sand dunes. The diversity of traces illustrates a glimpse of the eolian paleoenvironment in the Early Jurassic. The animal's behavior is a theoretical construct. However, the concept of analyzing the locomotion of tetrapod trackways illuminates the association between animal-substrate interactions. There are currently no published reports of a *Brasilichnium* track slab in the Navajo Formation depicting all four gaits. Furthermore, the inclusion of a *Grallator*-like trackway located on the same track-bearing surface should be regarded as an uncommon occurrence. The major question that remains is the discovery of a potential trackmaker. Researchers continue to debate whether the animal is of mammalian origin or therapsid. Without the findings of a body fossil, one can only guess the animal responsible for the ichnites. Studying the ichnofauna of arid environments, like *Brasilichnium,* can aid in understanding the process of track making on sloping foresets.

CHAPTER 3: CONCLUSION

Despite the many documentations of *Brasilichnium* traces found all over the world (Leonardi and Carvalho, 2020) there are currently no published reports of *Brasilichnium* showing various gaits on the same track surface layer. GLCA #357, Santucci's Site, is the first occurrence of *Brasilichnium* trackways in four different gaits: walking, running, skipping, and half-bounding gait. The rarest of the four gaits, the half-bounding gait (Trackway G), marks only the third discovery in *Brasilichnium* literature. Using a single 3D orthomosaic model, these variations of movement were investigated and documented. The reported exertions were observed ascending, descending, and traversing the sloping dune face at different intervals. Track morphology changed based on the selected gaits and direction of forward movement. The presence of the many sedimentary structures gives insight into the animal-sediment interaction on the lee face of a sand dune in an eolian environment. The sub-optimal preservation of GLCA #357 on the sandstone sediment lacked many details generally seen on other substrates. Nonetheless, it is recognized that there is no preference for gaits on any upward, downward, or diagonal forward movement by the trackmaker.

The Navajo Sandstone is not commonly known to host body fossils; therefore, the discovery of these tetrapod ichnites is highly significant to this formation. Structure-from-motion (SfM) photogrammetry allows for a more sustainable, less invasive way to preserve *in situ* paleontological resources that are deemed not salvageable by government officials. Additionally, this method is advantageous for the preservation of trace fossils as it digitally collects information on these non-renewable resources. As evident by the level of degradation of GLCA #357 observed in May 2022, SfM photogrammetry was pivotal for this project.

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