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LATE CRETACEOUS DINOSAUR TRACKS FROM THE IRON SPRINGS FORMATION, IRON COUNTY, UTAH

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ABSTRACT

Located in Iron County, Utah, the Parowan Gap dinosaur track site contains over one hundred natural casts of non-avian dinosaur tracks preserved in sandstones and siltstones of the Late Cretaceous (≈83 Ma) Iron Springs Formation. For this study, the authors returned to the area to survey for and describe previously unidentified tracks. Many tracks from this new study occur as *in situ* casts found on the basal surfaces of sandstones deposited by braided and meandering rivers on the coastal plain of the Western Interior Seaway, with some specimens from fallen talus blocks. Over the course of two years, the research team identified and recorded a total of 31 specimens. The results comprise tracks that resemble a minimum of at least five ichnotaxa including *Caririchnium*, *Amblydactylus*, *Ceratopsipes*, *Magnoavipes*, and *Dromaeosauripus*. The most common and well-recognized ichnogenus recorded in the Iron Springs Formation is *Caririchnium*, which likely represents ornithopod dinosaurs. We also identified two *Ceratopsipes* tracks in a fallen sandstone block. The pair of tracks are significant because they are the second set from the ichnotaxa found at Parowan Gap. Together the Parowan Gap *Ceratopsipes* samples represent the oldest ceratopsian tracks in Utah. The potential *Dromaeosauripus* specimen represents a small theropod dinosaur. This specimen is of great interest because theropod tracks, especially dromaeosaur tracks, are less common in the Iron Springs Formation, with a total of seven tracks reported from previous studies. If this is an appropriate interpretation, it would make the potential *Dromaeosauripus* track the youngest dromaeosaur trace fossil in Utah.

KEY WORDS: Iron Springs Formation, Parowan Gap, Dinosaur Tracks, Cretaceous Fossils , Ichnology

INTRODUCTION

Parowan Gap, located in Iron County, Utah (Fig. 1) on ancestral lands of the Southern Paiute (Native Land, 2019), is named for a water gap cut by a now ephemeral stream from east to west through heavily deformed Jurassic-Eocene strata. Known primarily for the Parowan Gap Petroglyphs Site on the National Register of Historic Places, the area is also known for the Parowan Gap Dinosaur Track Site (Fig. 2). The Bureau of Land Management (BLM) manages both the main petroglyph and dinosaur track localities, with interpretive signage at each site. The dinosaur tracks appear within the Late Cretaceous (Santonian-Campanian) Iron Springs Formation, with a high concentration near the marked BLM interpretive site. A previous study (Milner *et al.*, 2006) identified approximately 90 unique tracks within 500 meters of the site. This project investigated additional, unstudied exposures of the Iron Springs Formation at Parowan Gap to locate and describe additional tracks. Most of the newly identified tracks occur *in situ* along exposed basal sandstone surfaces in the upper, terrestrial strata of the Iron Springs Formation, and include five distinct dinosaur ichnotaxa.

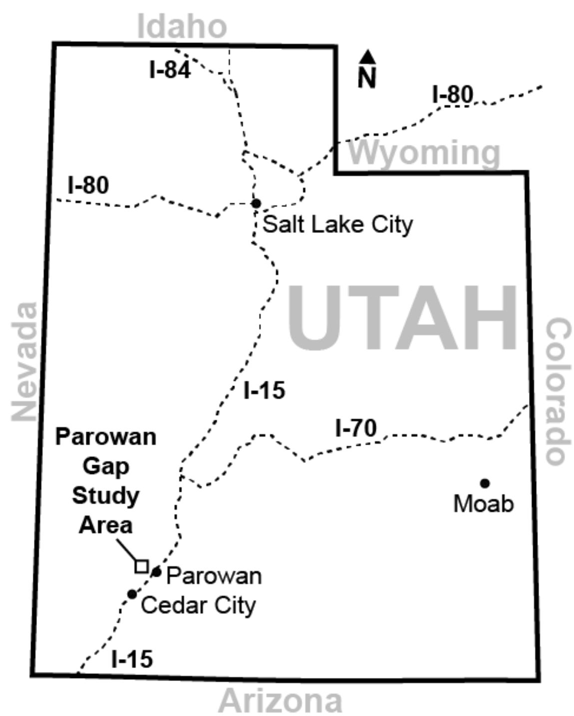


Figure 1. Location of the Parowan Gap study area in Utah, with interstate highways and some selected cities highlighted. Map generated by authors.

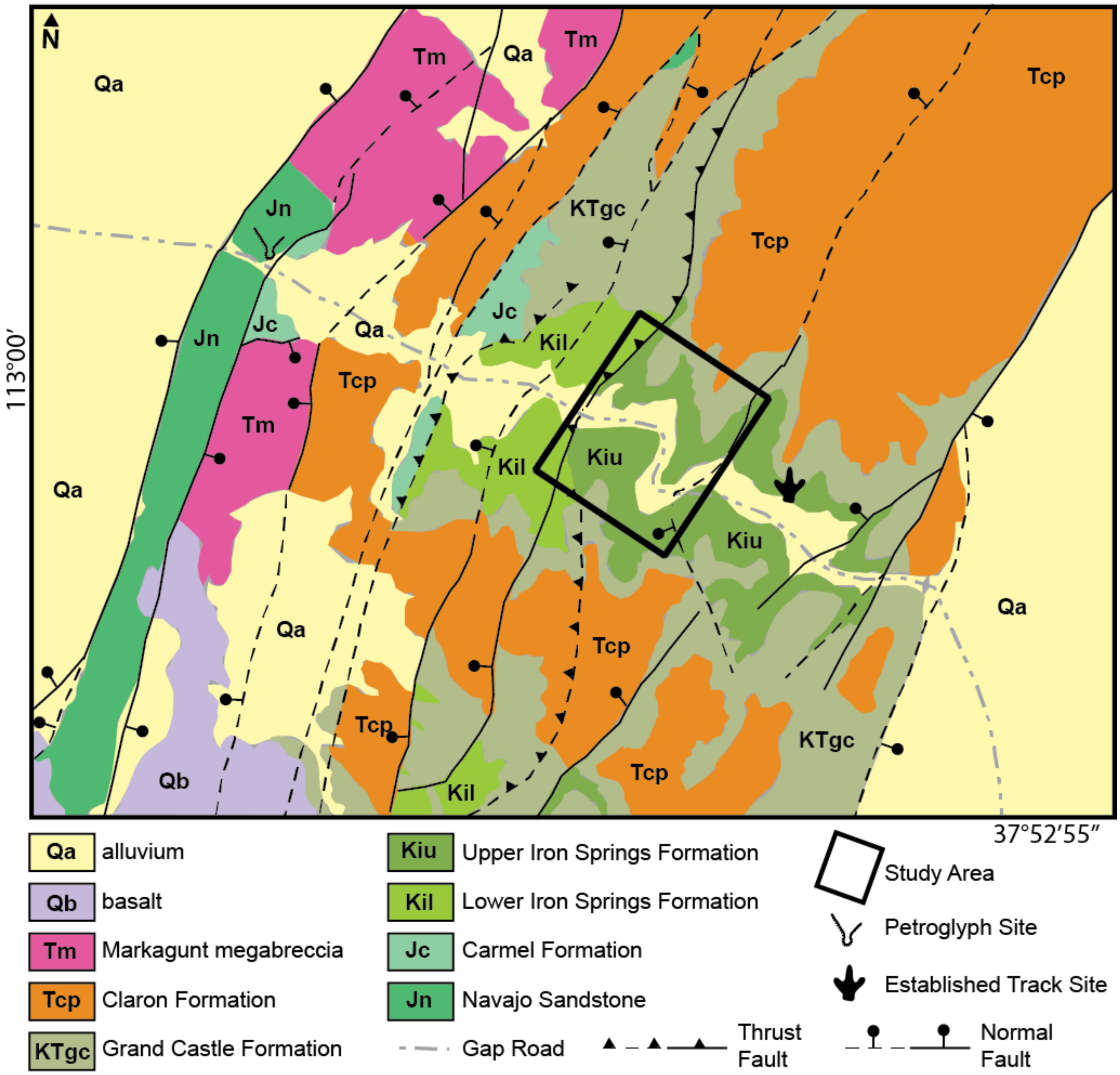


Figure 2. Simplified geologic map of Parowan Gap depicting Mesozoic and Cenozoic units, the location of the Parowan Gap petroglyphs and dinosaur track sites, and the study area, which is confined to the upper strata of the Cretaceous Iron Springs Formation. Map modified from Biek et al. (2015).

SEDIMENTOLOGY AND STRATIGRAPHY

The Iron Springs Formation of southwestern Utah is exposed in the Beaver Dam Mountains, the Pine Valley Mountains, and the northwestern portion of the Markagunt Plateau (Fillmore, 1991; Goldstrand, 1992).

There are only two locations that contain complete exposures of the Iron Springs Formation: Three Peaks and Gunlock, Utah in Iron and Washington counties respectively (Fillmore, 1991). Strata from the Iron Springs Formation were deposited in a northeast-to-east-directed fluvial braidplain with sediments that originated from the Wah Wah and Blue Mountain thrust sheets (Goldstrand, 1992). These sediments were shed into the proximal foreland basin from the Sevier thrust belt during the Turonian-Campanian. The lower Iron Springs Formation at Parowan Gap is similar in age to the Smokey Hollow and Tibbet Canyon members of the Straight Cliffs Formation (Fig. 3), and has been mapped as Straight Cliffs Formation by some authors based on oyster-bearing marginal marine calcareous sandstones interbedded with siltstones and coals (Anderson and Dinter, 2010). In contrast, the upper Iron Springs Formation contains Santonian to as young as earliest Campanian vertebrate index fossils (Eaton *et al.*, 2014), and is similar in character to the John Henry Member of the Straight Cliffs Formation (Peterson, 1969).

A thrust fault at Parowan Gap displaced the lower Iron Springs adjacent to or structurally above the upper Iron Springs (Fig. 2), and these faulted strata fall within the westernmost portion of the study area for this project. The Iron Springs Formation in the Parowan region rests unconformably on the Carmel Formation or the Cedar Mountain Formation, depending on its location. At Parowan Gap, the Iron Springs Formation rests unconformably on the Carmel Formation. The Iron Springs Formation is made up of 900-1200 meters of braidplain deposits (Eaton *et al.*, 2014), and the deposits represent channelized braided streams (Fillmore, 1991). The dominant rock types include sandstones, mudstones, limestones, and conglomerates with minor amounts of carbonates and coal (Fillmore, 1991; Goldstrand, 1990; Goldstrand, 1992). The most common rock type found in the formation is sandstone (Milner *et al.*, 2006). Quartz grains from the sandstones are fine- to very fine-grained and are typically well rounded with a frosted surface texture (Goldstrand, 1992). Overall, sediment grain sizes in the formation decrease toward the east and away from the Sevier thrust belt (Goldstrand, 1990).

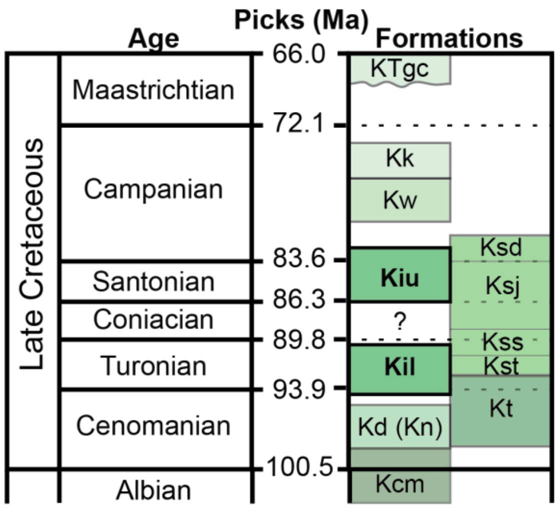


Figure 3. Late Cretaceous stratigraphy of southern Utah, with the Iron Springs Formation (Ki) in bold. In southwestern Utah, only the Tropic Shale (Kt), Straight Cliffs Formation (Ks), and Iron Springs Formation (Ki) are prevalent. Kcm: Cedar Mountain Fm., Kn (Kd): Naturita (formerly Dakota) Fm., Kt: Tropic Shale, Kil: lower Iron Springs Fm., Kiu: upper Iron Springs Fm., Kst: Tibbett Canyon Member, Straight Cliffs Fm., Kss: Smokey Hollow Member, Straight Cliffs Fm., Ksj: John Henry Member, Straight Cliffs Fm., Ksd: Drip Tank Member, Straight Cliffs Fm., Kw: Wahweap Fm., Kk: Kaiparowits Fm., KTgc: Grand Castle Fm. Based on data from Allen and Johnson (2010), Biek et al. (2015), Carpenter (2014), Eaton et al. (2014), Fillmore (1991), and Peterson (1969), with Cretaceous ages from Walker et al. (2018).

GEOLOGIC AGE AND FOSSIL CONTENT

According to Fillmore (1991) and Eaton *et al*. (2014) the age of the Iron Springs Formation is poorly constrained. Extensive research for dating the Iron Springs Formation has not yet been undertaken. The potential age of the formation covers a time span of about 28.4 million years, from the Cenomanian (100.5 Ma) to the Campanian (72.1 Ma) according to various authors (Goldstrand, 1990; Walker *et al*., 2018). The oldest Late Cretaceous rocks found in Parowan Canyon (near Parowan Gap) fall within the upper portion of the Iron Springs Formation, but an upper age for the formation has still not been determined (Fillmore, 1991; Eaton *et al*., 2001). In the Gunlock area, a maximum age of 80 Ma was suggested from bentonite zircons, which places the age of the formation in the Campanian (Fillmore, 1991; Walker *et al*., 2018). However, a palynomorph assemblage from shale strata found in the lower part of the formation in the southern Beaver Dam Mountains indicates a Cenomanian-

Turonian age, which is several million years older than was previously determined (Goldstrand, 1990; Fillmore, 1991). Evidence that further supports a Turonian age is an oyster-rich interval found in the Summit Canyon of the lower portion of the formation. This interval most likely represents an early Turonian transgression (Eaton *et al*., 2001). Eaton *et al*. (2014) further explain that brackish water faunas in the Pine Valley Mountains indicate a late Cenomanian age to an early Turonian age for the Iron Springs Formation because it provides evidence of a maximum transgression of the Cretaceous Western Interior Seaway.

Only Eaton *et al*. (2014) has obtained radiometric dates from the Iron Springs Formation. They reported an $^{40}Ar/^{39}Ar$ age of 83.1±1.1 Ma from a blue biotite ash found in Parowan Canyon, east of Parowan Gap. The biotite ash was located 133 meters above the base of the canyon floor and 231 meters below the upper contact of the Iron Springs Formation (Eaton *et al*., 2001; Eaton *et al*., 2014). The $^{40}Ar/^{39}Ar$ age places this part of the formation in either the late Santonian or early Campanian, based on the most recent time scale (Walker *et al.*, 2018).

The Iron Springs Formation contains a diverse assemblage of Late Cretaceous fossils including both trace and body fossils. Kirkland *et al*. (1998) reported on skeletal remains from hadrosaurs and a single ankylosaur from the formation. The hips, hindlimbs, and some of the caudal vertebral column of a hadrosaur were discovered in 1997 in Gunlock, Utah; however the bones are now unaccounted for due to poor excavation and documentation of the fossil site (Milner *et al.*, 2006).

Minimal paleontological research has been conducted in the Iron Springs Formation, especially within the Parowan Gap. Milner *et al*. (2006) were the first to thoroughly study, record, and publish their findings on the Parowan Gap dinosaur tracks. Their study site was constrained to a small section located at the modern dinosaur track interpretive site. Almost all of their recorded tracks occurred in fallen blocks. Their work resulted in the discovery and recording of over 70 recognizable tracks, many of which the authors attributed to hadrosaurid dinosaurs. They also recorded seven tracks belonging to theropod dinosaurs, which were more uncommon in the area. The rarest tracks Milner *et al*. (2006, fig. 5) recorded were a single left manus-pes set of ceratopsian tracks. They concluded this set of ceratopsian tracks were the oldest in North America.

Aside from dinosaur remains, other vertebrates are also present in the Iron Springs Formation, which include crocodiles, turtles, fishes, and several mammals (Milner, *et al*. 2006; Eaton *et al*., 2014). Invertebrates such as bivalves and gastropods are more abundant in the formation (Milner *et al*., 2006). Various conifer, angiosperm, and gymnosperm plant fossils are also found in the formation, though specimens have not been thoroughly studied.

The region has excellent potential for future track discoveries. The authors and several faculty members of Southern Utah University have observed dinosaur tracks from either the Straight Cliffs Formation (genetically related to the Iron Springs Formation) or Naturita Formation at two locations along the Thunderbird Gardens trail system in Cedar City, and another track from the Straight Cliffs Formation at the entrance to Ashdown Gorge, just to the east of Cedar City. A hadrosaur track from the Grand Castle Formation near the town of Parowan changed the age estimates for that formation from Paleocene to Cretaceous-Paleocene (Biek *et al.*, 2015). Lockley *et al.* (2018) also described an assemblage of Cretaceous dinosaur and crocodilian tracks from the underlying Naturita (formerly Dakota) Formation southeast of Cedar City, approximately 33 km south of the Parowan Gap track site.

MATERIALS AND METHODS

The team conducted this research under a Paleontological Resources Use Permit (form 8270) UT18-009S, obtained from the Bureau of Land Management (BLM). No materials were collected during this study. We recorded each track location using the Global Positioning System (GPS) on an iPhone 5S with the Avenza PDF maps application. Unfortunately, Parowan Gap dinosaur tracks located near maintained public trails have experienced vandalism and as such we will not give the exact locations of our specimens in order to protect the sites. We photographed each track using a

Nikon D3200 SLR for high resolution images or the iPhone 5S for lower resolution images when the tracks were less accessible due to limited space underneath *in situ* overhangs. The research team did not collect any physical specimens or casts of tracks, but digital data is on file with the BLM.

Each track site received a unique site number with the following nomenclature: PG for Parowan Gap, JKC for the lead author's initials, year recorded, and a sequential number for sites discovered. Some examples (PG.JKC.2018.06) have multiple tracks at the same location, with each unique track labeled alphabetically.

Track measurements (Fig. 4) were taken following Milner *et al.* (2006) using a metric tape measure recording track lengths and widths. Divarication angles were taken with a protractor between digits from a common midpoint at the heel. To measure track orientation, we used a Brunton Pocket Transit compass to determine azimuth direction based on the orientation of the middle digit. Azimuths are not corrected for minor structural deformation in the study area. Though portions of the Iron Springs Formation in Parowan Gap are heavily deformed, all of the *in situ* track sites in this paper come from nearly horizontal strata east of the major thrust fault and away from some smaller-offset normal faults that dissect the area.

Descriptive abbreviations used for tracks appear in Figure 4. We use the terms *left* and *right* digit for describing tridactyl tracks. The terms refer to what would have been the left and right side of the trackmaker's foot (or feet), not the right and left sides of the natural casts. This is not an interpretation of whether it was a left or right foot. That interpretation is only possible with PG.JKC.2018.01, due to the partial right digit, which would have been digit II on the left foot based on the interpretation described below. We include the Roman numeral designations for the digits in Figure 4.

DINOSAUR TRACK DESCRIPTIONS AND INTERPRETATIONS

Thirty-one previously unrecorded dinosaur tracks were recognized during this study (Table 1). Of the recorded tracks, 29 were tridactyl tracks (one probable didactyl) and two were tetradactyl tracks. Almost all of the tracks were found *in situ* with most tracks occurring in a northwest trending direction. Many of the tracks likely belong to hadrosaurid ornithopods, while theropod and ceratopsian tracks are less common. We were able to assign 21 of the better-preserved tracks to ichnogenera. Table 1 contains field measurements, with a final column for interpretations discussed below.

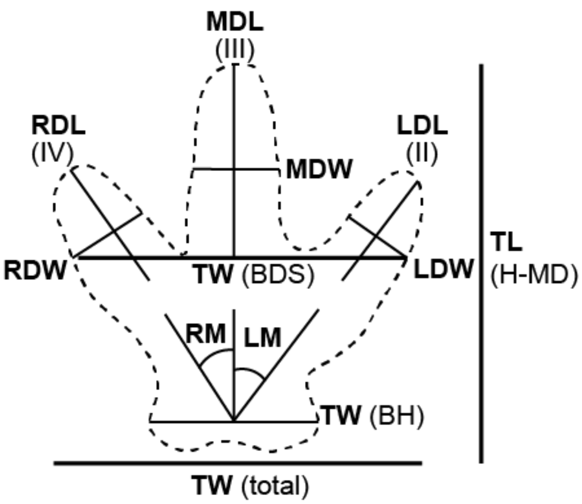
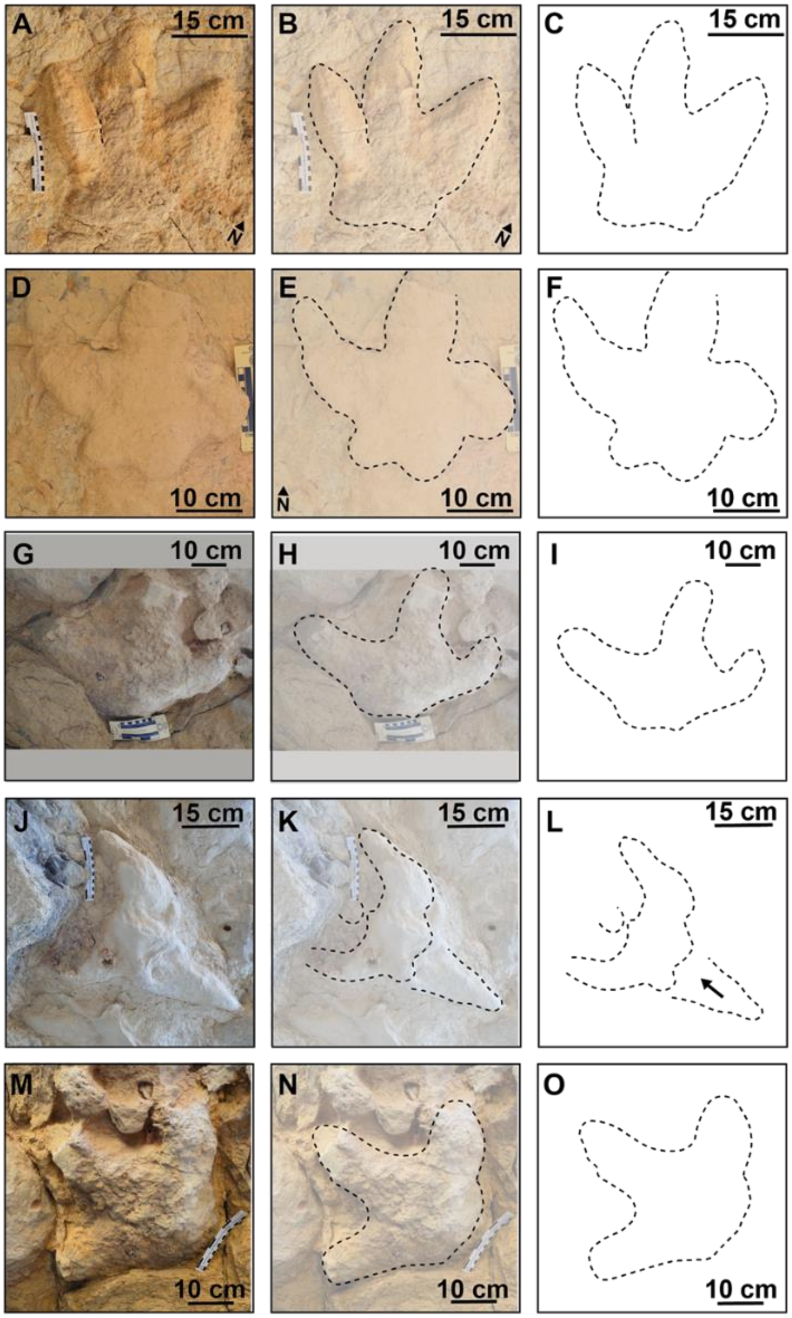


Figure 4. Depiction of track measurements and abbreviations. Modified from Milner et al. (2006). Tracks are not bilaterally symmetrical as illustrated in Figure 4, however the authors wanted to clearly indicate each track measurement in order to make it easier to visualize. The abbreviation measurement descriptions are as follows: track length (TL), track width (TW), track length from the heel to the middle digit (TL H-MD), track width of the base of the heel (TW BH), track width before digit separation (TW BDS), heel depth (HD), middle (III) digit length (MDL), middle (III) digit width (MDW), middle (III) digit depth (MDD), left (II) digit length (LDL), left (II) digit width (LDW), left (II) digit depth (LDD), right (IV) digit length (RDL), right (IV) digit width (RDW), right (IV) depth (RDD), divarication angle between the left (II) and middle (III) digits (LM-Div. angle), divarication angle between the right (IV) and middle (III) digits (RM-Div. angle), and track length (TL)/track width (TW) (L/W).

Morphotype A Track Description

The tridactyl casts categorized in Morphotype A share similar traits of at least two long digits of sub-equal lengths, with sufficient evidence or partial remnants of a third digit to calculate divarication angles. The range of divarication angles is between 45 and 120 degrees. These tracks lack discernable claw traces, and many of the specimens in this morphotype have a bi-lobate heel, as visible in Figure 5 A, D, and J. The majority of specimens were found *in situ*, as isolated tracks,



with the exception of a probable trackway consisting of three tracks.

These tracks are generally very robust with wide toe pads. The average track width before digit separation is about 18 cm. The tracks range in total length from 20-50 cm, with an average of 27.22 cm. There are several smaller specimens that cause a higher standard deviation of track length (8.96 cm). Track metrics are shown in Table 1 and examples are shown in Figure 5.

Figure 5. A selection of tracks interpreted as members of the Caririchnium ichnogenus. A-C: Long, wide tridactyl tracks, with heel impression, interpreted as the ichnogenera Caririchnium, and ascribed to hadrosaurid dinosaurs. PG.JKC.2018.06a. D-F: Another tridactyl track ascribed to Caririchnium and part of a trackway (Fig. 10) that includes A. Note the clear bilobate heel. Both the middle (III) and left digit (II) are broken off. PG.JKC.2018.06d. G-I: Tridactyl track, pictured at an angle, with wider divarication angles but similar digit morphology to A. The large size and equal length of the digits categorize this sample

with Caririchnium as opposed to Amblydactylus (Fig. 6) or Magnoavipes (Fig. 8). PG.JKC.2018.15. J-L: A tridactyl track with a deep digit drag cast at the posterior (direction of drag indicated with arrow in I). The actual middle digit (III) cast is absent. PG.JKC.2018.19a. M-O: A largely complete tridactyl track with large digits and similar wide divarication angles as G. PG.JKC.2018.16.

Morphotype A Interpretation: Hadrosaurid Ornithopod, similar to *Caririchnium* isp.

We interpret the tridactyl track type with long and relatively equal digit lengths found in the Iron Springs Formation as *Caririchnium* isp., representative of ornithopod tracks, likely produced by hadrosaurid dinosaurs. Characteristics that identify footprints belonging to hadrosaurids are wider than long, three digits that end bluntly (hoofed digits), and a wide, bilobed heel (Fiorillo *et al*., 2014). *Caririchnium* is a relatively common Cretaceous dinosaur ichnogenera throughout western North America (Lockley, 1987; Carpenter, 1992; Milner *et al*., 2006; Lockley *et al*., 2018). Milner *et al*. (2006) described over 80 similar ornithopod tracks in the Parowan Gap area which compare well with the ichnogeneric description provided above. They reported all as pedal tracks, although they also stated that some may be manus tracks, but were more difficult to differentiate. *Caririchnium* often preserve manus traces (Leonardi, 1984; Díaz-Martínez *et al*., 2015; Xing *et al*., 2015) so this is probably the case with the Iron Springs tracks.

The smaller specimens in this morphotype may represent juveniles or a level of sexual dimorphism within the dominant trackmakers, similar to the range of track sizes observed at the Denali National Park and Preserve tracksite from the Upper Cretaceous Cantwell Formation (Fiorillo *et al*., 2014). The Denali site contains tracks from four growth stages of hadrosaurid dinosaurs: early individuals, late juveniles, subadults, and adults which indicate these dinosaurs may have lived in multigenerational herds (Fiorillo *et al*., 2014; Ullmann *et al*., 2017). Other evidence for multigenerational herding behavior in hadrosaurs is present in the fossil record in both trace and skeletal remains. Lockley *et al*. (1983) infer from hadrosaur tracks from the Mesaverde Group that small and large tracks in the same area indicate multigenerational herds as well as parental care. Ullmann *et al*. (2017) suggested from their study of the Standing Rock Hadrosaur Site that such a high concentration of *Edmontosaurus annectens* subadult and adult bones in one area likely indicate the hadrosaurs may have lived and died together, providing evidence of gregarious behavior between the two age groups.

Sexual dimorphism is exhibited among the living relatives of dinosaurs (crocodilians and birds) and is strongly speculated in several dinosaur taxa, however a lack of adequate sample sizes makes demonstrating sexual dimorphism in the fossil record a challenge (Chapman *et al*., 1997; Barden and Maidment, 2011; Knell and Sampson, 2011; Mallon, 2017). Sexual dimorphism is an important aspect to consider in track diversity where different sizes of tracks may be attributable to males and females (Romano and Whyte, 2003). Sexual dimorphism may have manifested itself in different body size and shape, which has a possibility to be seen in the ichnologic record (Romano and Whyte, 2003). Because hadrosaurs are so abundant in Late Cretaceous strata, they are one of the most studied groups of dinosaurs and provide some of the best evidence of sexual dimorphism (Chapman *et al*., 1997). A notable example of a probable case for sexual dimorphism in hadrosaurs is reported from Dodson (1975), however recent studies question a lack of statistical evidence (Mallon, 2017). Although a possible explanation for the varying track sizes of Iron Springs specimens may be from a level of sexual dimorphism in hadrosaurid dinosaurs, no compelling evidence has been reported, so different growth stages is a more likely interpretation at this time. We recognize that differing sizes in our specimens can be a result of multiple variables, such as age, intraspecific variation, sexual dimorphism, and genetic and environmental factors, as discussed by Gangloff and Fiorillo (2010).

Morphotype B Track Descriptions

Tracks categorized in Morphotype B are also tridactyl casts similar to Morphotype A, but these tracks differ slightly in morphology.

Morphotype B tracks are short and wide when compared with *Caririchnium*, with an average width at the base of the heel of 12.7 cm. They are represented by at least four specimens. Most tracks lack claw traces. Morphotype B tracks have very round, short digits that end bluntly. These tracks lack a bilobed heel. Track metrics are shown in Table 1 and examples are shown in Figure 6.

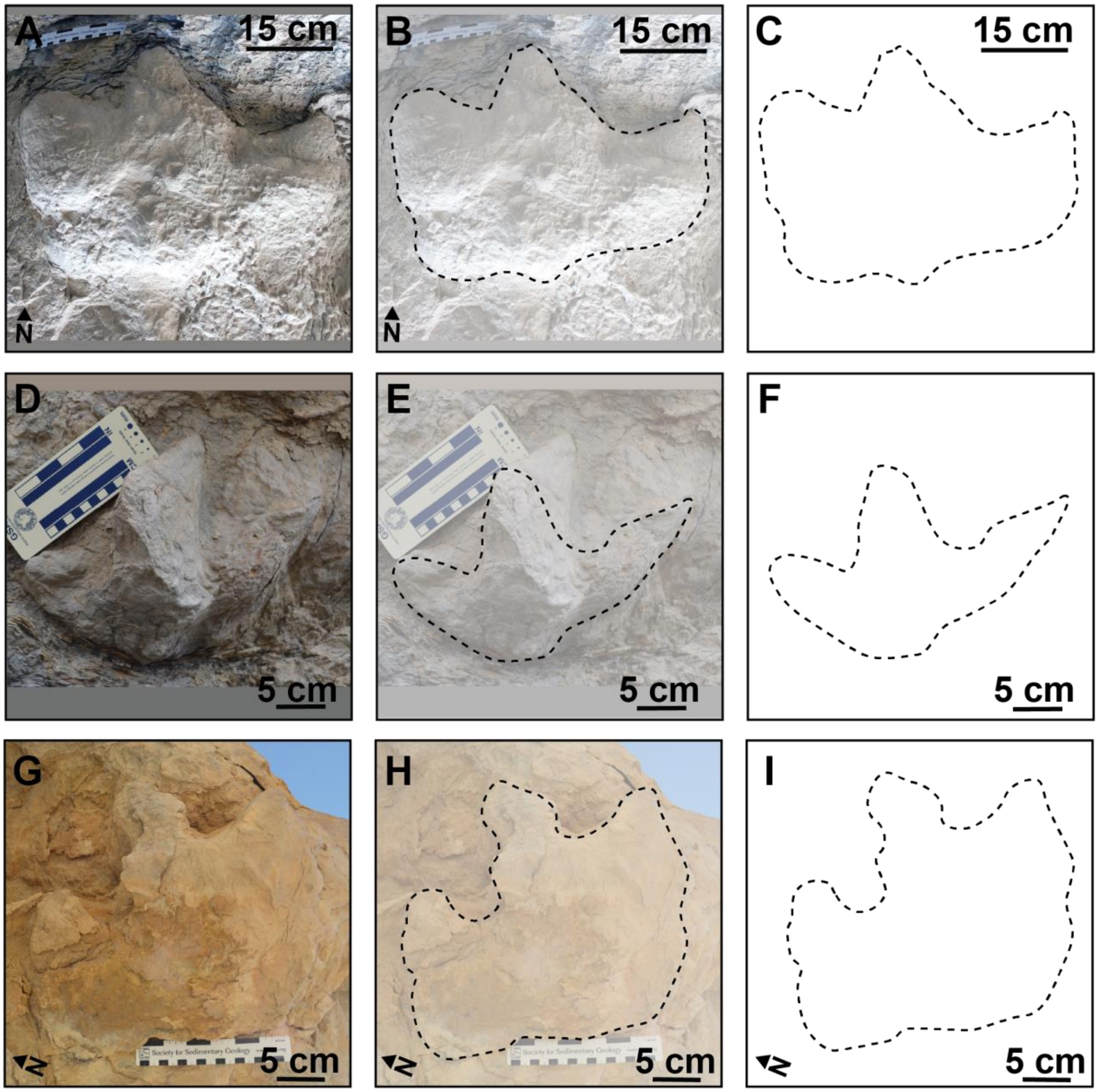


Figure 6. A selection of tracks attributed to the ichnogenus Amblydactylus. A-C: Short, wide tridactyl tracks interpreted as members of the ichnogenera Ambydactylus. Alternatively may represent Caririchnium lacking the toe impressions

of A-C. PG.JKC.2018.14. D-F: A deep cast of a tridactyl track with short digits and wide divarication angles characteristic of other Amblydacylus. Most of the digits may be missing. This photo is from an angle because there was insufficient space to crawl beneath the in situ cast, causing some distortion that underemphasizes the width of the heel. A claw impression appears visible on the left (II) digit. PG.JKC.2018.13. G-I: A wide, short tridactyl track similar to A. PG.JKC.2018.23.

Morphotype B Interpretation: Ornithopod, similar to *Amblydactylus* isp*.*

Ornithopod tracks are incredibly prevalent in Cretaceous age rocks, with several ichnogenera recognized (Lockley *et al*., 2014c). In North America, the most common ornithopod ichnogenera are *Caririchnium* and *Amblydactylus* (Joeckel *et al*., 2004). Although these two ichnogenera are similar, *Amblydactylus* pes tracks are much broader and lack a bilobed posterior margin (Joeckel *et al*., 2004). We interpret tracks categorized in Morphotype B as the ichnogenus *Amblydactylus*, likely associated with a hadrosaurid dinosaur. Tracks belonging to this ichnogenus are typically very large, tridactyl footprints with blunt digits (Weems and Bachman, 2015). An *Amblydactylus* track is about as wide or wider than the length of the track (Currie and Sarjeant, 1979; Currie, 1983). These track types usually have distinct phalangeal pads, such as specimen PG.JKC.2018.14 pictured in Figure 6 A-C (Currie and Sarjeant, 1979). Earlier interpretations of *Amblydactylus* tracks suggested the feet were webbed because they lacked well-defined hypices, however more recent interpretations by Lockley *et al*. (2014c) suggest this may have been due to sub-optimal preservation (Currie and Sarjeant, 1979). Early discoveries of *Amblydactylus* pes tracks were rarely accompanied by manus tracks (Joeckel *et al*., 2004; Lockley *et al*., 1992). This observation has led to the inference that *Amblydactylus* trackmakers were strictly bipedal, however Lockley *et al*. (2014c) doubt this interpretation and instead suggest that *Amblydactylus* may have been quadrupedal based on recent discoveries of trackways that appear to include manus prints. Many of our specimens were found as single pes tracks with a probable single manus track.

Morphotype C Track Descriptions

Two new tracks in a single trackway, and another manus-pes originally reported by Milner *et al*. (2006) are categorized into Morphotype C representing ceratopsian tracks. The new specimen was found on a fallen sandstone block, with the rear pes track more distinct and obvious than the leading pes track, which was very weathered (Fig. 7). We were not able to ascertain the original outcropping source of the trackway. The rear footprint has been iron-stained and is darker in color than the surrounding sandstone. Each footprint has four rounded digits. The rear pes track has a total track length of 20 cm with a width at the base of the heel of 15 cm. Each digit length ranges in size from 5-6 cm. The leading track also appears to have four-digit casts that left drag marks in the underlying sediment. Both pedal tracks appear to have overprinted the manus. Track metrics are shown in Table 1 and examples are shown in Figure 7.

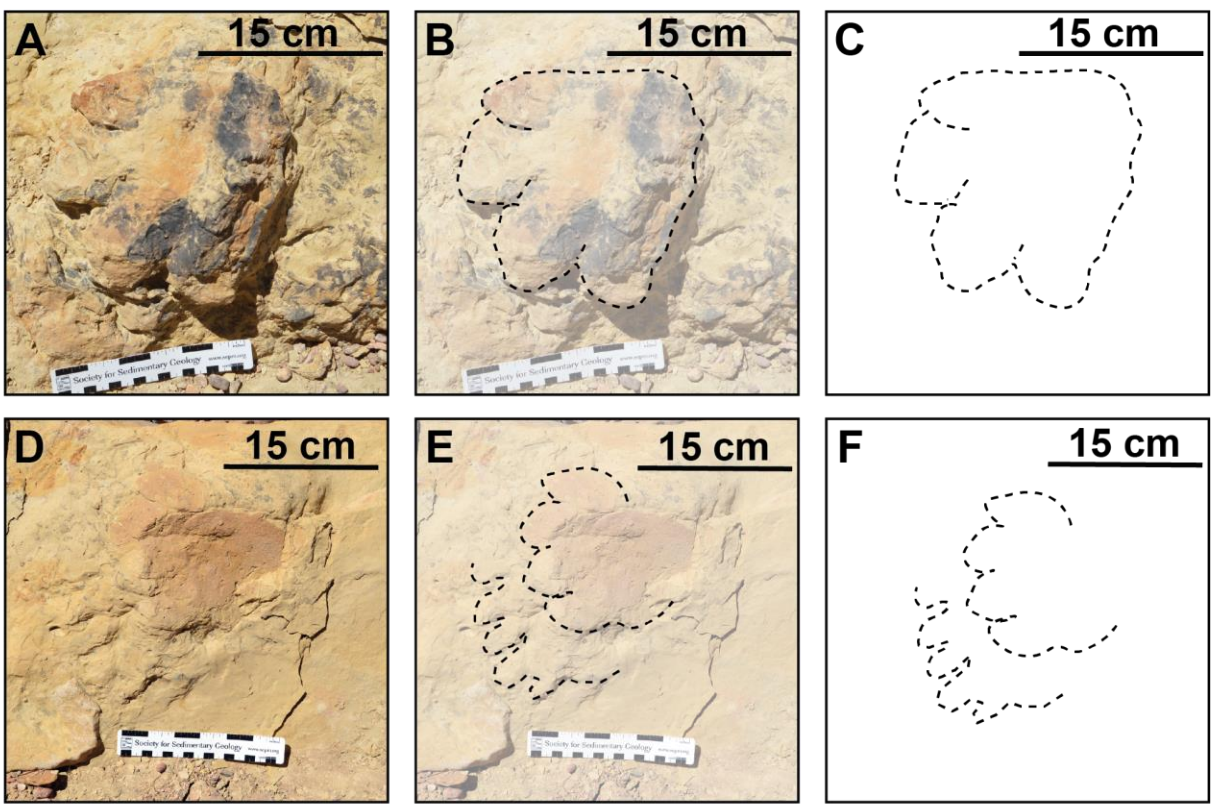


Figure 7. A-C: A selection of tracks interpreted as members of the Ceratopsipes ichnogenus. Tetradactyl tracks interpreted as the ichnogenera Ceratopsipes, and ascribed to a ceratopsian dinosaur, possibly juvenile due to the small size. PG.JKC.2018.18. D-F: Two overlapping tracks adjacent to A. Possible manus and pes of a ceratopsian dinosaur, with tetradactyl Ceratopsipes overlying a tetradactyl or pentadactyl track.

Morphotype C Interpretation: Ceratopsian Ornithopod, similar to *Ceratopsipes* isp.

Specimen PG.JKC.2018.18 likely represents a pair of ceratopsian manus-pes track casts in a trackway following Lockley and Hunt (1995), and their description of Laramie Formation ceratopsid tracks, previous descriptions of ceratopsian tracks from Parowan Gap (Milner *et al.*, 2006), and comparisons between probable ankylosaur *(Tetrapodosaurus*) and ceratopsian (*Ceratopsipes*) tracks in similarly aged Cretaceous rocks in Colorado by Lockley and Gierliński (2014). Ceratopsian tracks are unique among other quadrupedal dinosaur tracks because they have pentadactyl manus prints and tetradactyl pes prints. Ceratopsian tracks are similar to ankylosaur tracks, however Fiorillo *et al.* (2010) state that one of the main differences between the two track types are that ceratopsian tracks are symmetrical whereas ankylosaur tracks are not. Lockley and Gierliński (2014) discuss how tracks belonging to *Ceratopsipes* are associated with more derived ceratopsians with more robust feet that have shorter and wider phalanges and metatarsals. In ceratopsian feet the metatarsals are longer than the toes, which is reversed in ankylosaur feet (Fiorillo *et al*., 2019). The Parowan Gap tracks fit the criteria for being ceratopsian and we therefore propose the pes tracks belong to the ichnotaxon *Ceratopsipes*. Further evidence to support our proposal is a manus-pes set of *Ceratopsipes* tracks found in Parowan Gap previously described by Milner *et al*. (2006). Eaton *et al*. (2014) also describes a poorly preserved tooth from the Iron Springs Formation that possibly represents a ceratopsian tooth, providing more evidence of the presence of ceratopsians in the Iron Springs Formation.

The new Parowan Gap specimen is quite small compared to other ceratopsian pes tracks, however the size is similar to the recorded ceratopsian track measurements of Milner *et al*. (2006). Their recorded pes length is 25 cm and a width of 28.5 cm. Our specimen's recorded length (before digit separation) and width is 20 cm and 18 cm respectively, which is slightly smaller than the Milner *et al*. (2006) pes specimen. Lockley and Hunt (1995) reported ceratopsian pes track lengths ranging from 38 cm to 75 cm. They reported pes track widths of 46 cm up to 60 cm. A smaller specimen from Lockley and Hunt (1995) was reported to be 30 cm long and 35 cm wide (Lockley and Tempel, 2014). We hypothesize the contrast in track size may be attributed to differences in ceratopsian age, wherein our specimen may be a juvenile. Juvenile ceratopsian skeletal remains are known from various locations around the world, however no reports have been made on juvenile ceratopsian tracks (Lehman, 1989; Tokaryk, 1997; Hone *et al*., 2014). Since juveniles almost certainly existed in this ecosystem, and due to the other morphological similarities with larger ceratopsian tracks, *Ceratopsipes* is our favored interpretation.

Morphotype D Track Description

Tracks belonging to Morphotype D are tridactyl as well as Morphotype A and B, but differ in that each specimen has long, slender digits as compared to the short, wide digits of Morphotype A and B. The central digit is very long with wide divarication angles. At least three tracks are categorized into Morphotype D from the Parowan Gap. Three more probable tracks may also fall into this morphotype, but track details were insufficient. Track metrics are shown in Table 1 and examples are shown in Figure 8.

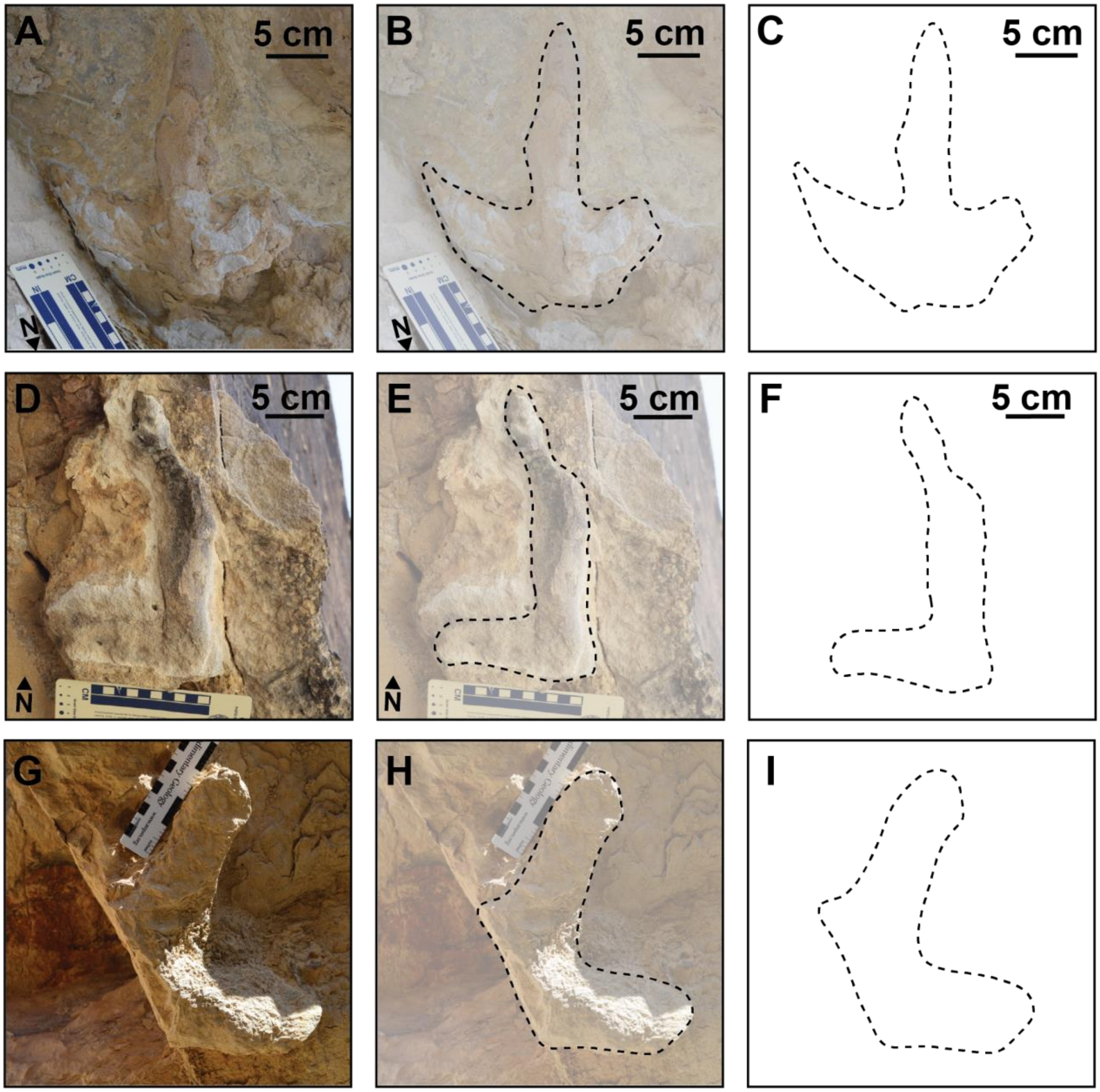


Figure 8. A selection of tracks interpreted as members of the Magnoavipes ichnogenus. A-C: A tridactyl track with very long central toe and wide divarication angles. Interpreted as Magnoavipes, from a theropod dinosaur. PG.JKC.2018.16. D-F: A partial track with elongated middle digit (III), similar to A, with a missing left (II) digit. PG.JKC.2018.07. G-I: Another partial track, this time with a missing right (IV) digit. The long middle digit (III) and wide divarication angle group this track with Magnoavipes. PG.JKC.2018.20.

Morphotype D Interpretation: Theropod, similar to *Magnoavipes* isp.

Magnoavipes is a non-avian theropod ichnogenus that appears in Cretaceous strata throughout western North America, including regionally in southern Utah (Lockley *et al*., 2018) and as far north as Alaska (Fiorillo, 2011). We interpret the tracks from Morphotype D as *Magnoavipes* isp. based on the narrow toes and wide divarication angles, as in Lockley *et al*. (2018) and similar to Lee (1997) and Lockley *et al.* (2001), and as described in McCrea *et al.* (2014) and Matsukawa *et al*. (2014). *Magnoavipes* tracks are tridactyl with long, slender toes that typically end in either a sharp point or a claw impression (Kappus and Cornell, 2003). The mean middle digit length for the four tracks we interpreted as *Magnoavipes* is 15.50 cm, which falls in line with similar tracks identified in the nearby Naturita (formerly Dakota) Formation (Lockley *et al*., 2018), but is slightly smaller than some Canadian examples from the Dunvegan Formation (McCrea *et al.,* 2014). Lockley *et al*. (2018) found that on average their *Magnoavipes* tracks were slightly wider than they were long. No hallux or heel trace is typically observed from *Magnoavipes* tracks (Lockley *et al*., 2006). One way to differentiate between *Magnoavipes* tracks and other tridactyl tracks is *Magnoavipes* tracks are elevated digitigrade while other tridactyl tracks such as *Caririchnium* are plantigrade (Kappus and Cornell, 2003).

Morphotype E Track Descriptions

Two tracks total are categorized in Morphotype E. Both were found *in situ*. Specimen PG.JKC.2018.01 (Fig. 9 A-C) is exceptionally well preserved and has claw marks on both digits. Tracks in this morphotype have two slender digits with a small divarication angle, both specimens are less than 50°. Both tracks are relatively small; PG.JKC.2018.01 is 21 cm long and PG.JKC.2018.05 (Fig. 9 D-F) is 15 cm long. Track metrics are shown in Table 1 and examples are shown in Figure 9.

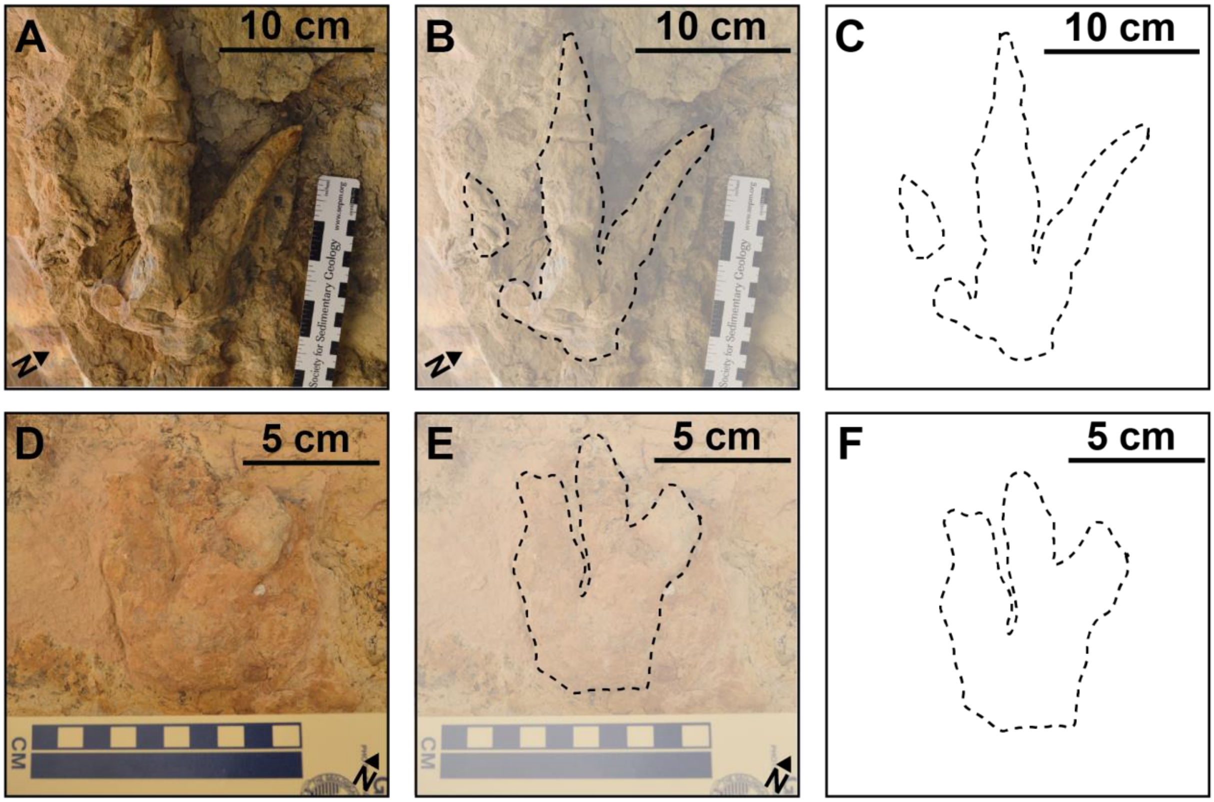


Figure 9. A selection of tracks interpreted as members of the Dromaeosauripus ichnogenus. A-C: Smaller, narrow tridactyl tracks interpreted as the ichnogenera Dromaeosauripus, and ascribed to a small dromaeosaur theropod. Most of the right toe (digit IV) is missing but there is enough to interpret the size. Claw impressions appear visible on the middle (III) and left (II) digits. PG.JKC.2018.01. D-F: A narrow, short tridactyl track, likely missing the ends of all three digits. Interpreted to be a smaller theropod, similar to Velociraptorichnus. PG.JKC.2018.05.

Morphotype E Interpretation: Dromaeosaurid or Ornithomimid Theropods, similar to *Dromaeopodus, Dromaeosauripus, Ornithomimipus* or *Velociraptorichnus*

Both samples from this morphotype appear marginally tridactyl, with a minimized digit II and an elongate middle digit. The narrow III and IV digits of PG.JKC.2018.01 end in distinct claw impressions, while digit II has a gap between the basal pad and a possible pad or claw impression (Figure 9, A-C). We interpret this trace as a cast of the left foot of a mediumsized dromaeosaur with a lifted sickle claw on digit II and ascribe it to the ichnogenera *Dromaeosauripus* isp. (similar to Li et al., 2007; Lockley *et al.*, 2016), though the 21 cm track length is smaller than *Dromaeopodus* described in Xing *et al.* (2018). We interpret the smaller PG.JKC.2018.05 (Figure 9, D-F) as a smaller theropod track, similar to *Velociraptorichnus* isp., a dromaeosaur ichnogenus identified from Early Cretaceous China (Li *et al*., 2007; Xing *et al*., 2009; Xing *et al*., 2013). The digits of PG.JKC.2018.01 are more curved than PG.JKC.2018.05, which lacks distinct claw marks, consistent with descriptions of *Dromaeopodus* and *Velociraptorichunus* in Li *et al.* (2007).

Dromaeopodus traces appear in a variety of global localities, including the type sections in China (Li *et al.,* 2007), numerous locations discussed in Lockley *et al.* (2016), and within the Late Cretaceous Campanian Toro Toro Formation of Bolivia (Apesteguía *et al.*, 2011). *Dromaeosauripus* tracks are known from Utah in the Early Cretaceous (Lockley *et al*., 2014a; Lockley *et al*., 2014b; Lockley *et al*., 2016), but there are no previously described examples from the Late Cretaceous in Utah. If our interpretations of these tracks as small, dromaeosauid theropods is accurate, that would make the tracks the youngest dromaeosaur traces in Utah. There are *Ornithomimipus*-like tracks from small theropods described by Lockley *et al.* (2011) in rocks of the Mesaverde Group of western Colorado, in similar Cretaceous deposits as the Iron Springs Formation. This is a possible alternative explanation. Given the Campanian-Santonian age of the Iron Springs Formation at Parowan Gap (Milner *et al.,* 2006), the authors of this study are not concerned about the age difference between the Early and Late Cretaceous dromaeosaurid track ichnogenera between the Utah and China sites, as there may only be a 10-20 million year gap in some cases. Eaton *et al*. (2014) report probable dromaeosaur teeth from the Iron Springs Formation elsewhere in Iron County.

Trackways

Almost all of the tracks recorded at Parowan Gap occur as single tracks, with the exception of two sets of trackways. The *Caririchnium* trackway was found *in situ* and contained three pes tracks (Fig. 10). Manus tracks were not observed. The *Ceratopsipes* trackway was found on a fallen talus block and consisted of two pes tracks with a possible manus track (Fig. 11).

Late Cretaceous ornithopod trackways are known throughout North America, Europe, and East Asia (Lockley *et al*., 2014c). Many of these trackways have been attributed to the ichnogenus *Caririchnium* and demonstrate that the trackmakers were quadrupedal animals (Lockley *et al*., 2014c). Milner *et al*. (2006) reported on two ornithopod trackways from the Iron Springs Formation. No measurements were obtained for one of the trackways because it was located underneath a ledge on a very high cliff face. The trackway they were able to obtain measurements for contained three tracks with a stride length of 60 cm. Our trackway also contained three tracks, however the stride length was 193 cm. No well-preserved Late Cretaceous ceratopsian trackways are currently known (Lockley and Tempel, 2014). Ceratopsians were quadrupedal animals and as Lockley and Tempel (2014) point out, ceratopsian trackways are more complicated to understand because the front footprints may have been overprinted and distorted by the hind footprints. Only one complete ceratopsian trackway has been reported, however in the last 20 years the trackway has become buried (Lockley and Hunt, 1995; Lockley and Tempel, 2014). Milner *et al*.'s (2006) ceratopsian track set consisted of a pair of left manus-pes tracks. Ceratopsian manus prints are more crescentic in shape compared to pes tracks and rotate outwards with the anterior digits pointing forwards (Lockley and Tempel, 2014). Based on Lockley and Tempel's (2014) description of manus prints, we interpret a possible manus print in our trackway that appears to have the left pes track overlap it.

Figure 10. Caririchnium trackway. This surface had many partial track impressions, but the three highlighted tracks appear to record the movement of a single hadrosaurid dinosaur (specimens PG.JKC.2018.06.a, PG.JKC.2018.06.b, and PG.JKC.2018.06.c). The total length between the first and last (right to left) track is 193 cm. The length between the first and second track (a to b) is 104 cm. The length between the second and third track (b to c) is 99 cm.

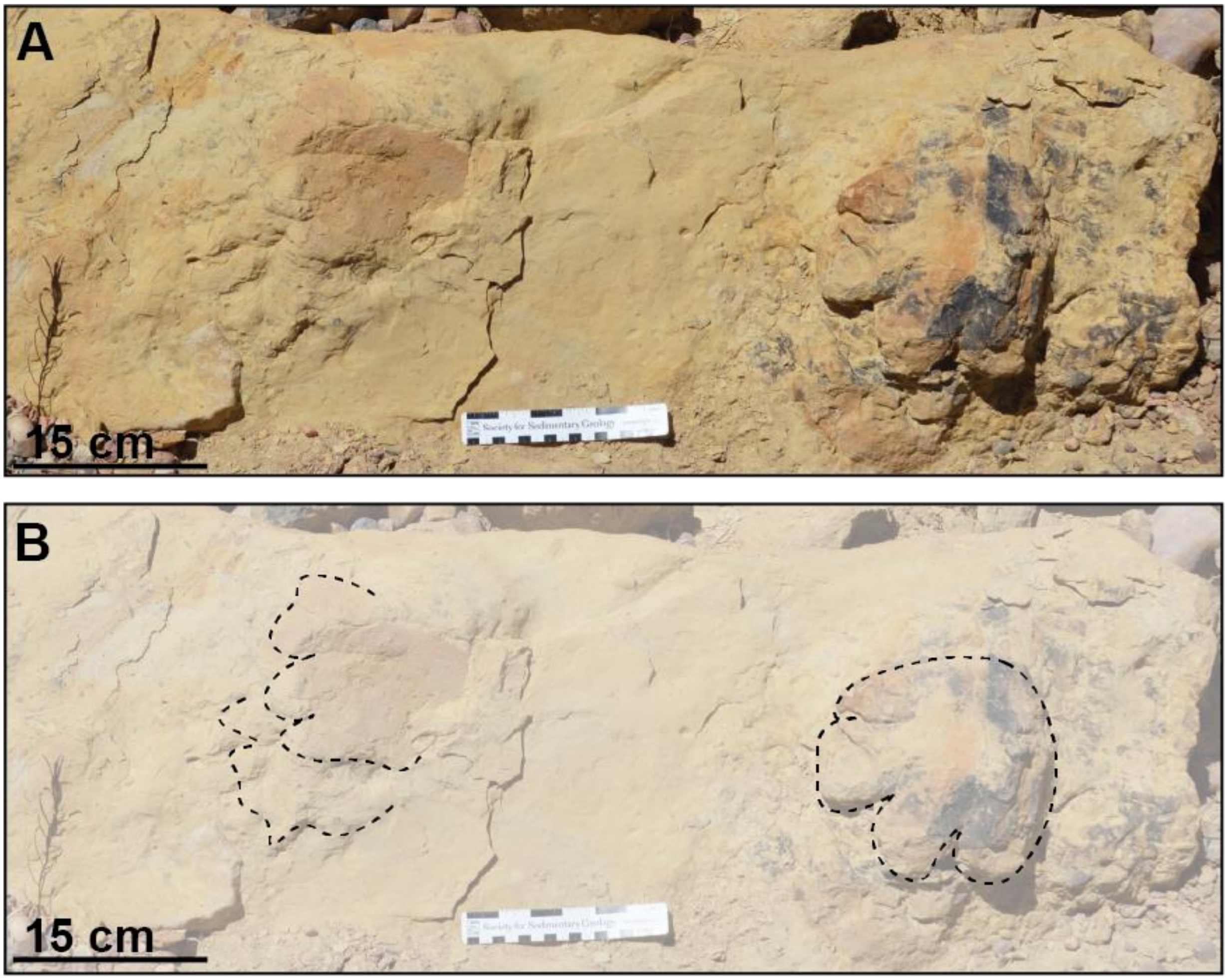


Figure 11. Ceratopsipes pes tracks from a fallen talus block that represent a likely ceratopsian trackway. PG.JKC.2018.18. The leftmost pes impression (left rear) appears to overlap a possible manus track (left front). The right pes track also appears in Figure 7.

DISCUSSION

The Upper Iron Springs Formation in Parowan Gap contains a considerable amount of Late Cretaceous age trace fossils, including an assortment of hundreds of poor to well preserved dinosaur tracks, many of which are preserved as natural casts. The formation consists of 900-1200 meters of mostly fine-grained sandstones interbedded with mudstone and shale layers representing a braidplain depositional environment (Eaton *et al.*, 2014). The Iron Springs Formation contains dinosaur tracks representative of at least five ichnotaxa including *Caririchnium*, *Ceratopsipes*, *Amblydactylus*, *Magnoavipes*, and *Dromaeosauripus,* with a possible *Velociraptorichnus*. This array of ichnotaxa indicates a diverse dinosaur community composed of various ornithischian and theropod dinosaurs. Our research is the first to attempt to ascribe the Parowan Gap tracks to ichnotaxa.

The Parowan Gap dinosaur track site is significant because it contains a variety of dinosaur ichnites that add to our understanding of the dinosaur fauna living in the southern Utah region during the time of the Western Interior Seaway. The most common tracks found in Parowan Gap are those that belong to ornithopods, represented by the ichnotaxa *Caririchnium* and *Amblydactylus*. This is to be expected considering how common ornithopod tracks are in mid- to high-latitude, coastal plain sediments of Eurasia and North America (Joeckel *et al*., 2004). We hypothesize during the Santonian-Campanian stages that hadrosaurs were very common in the Parowan Gap area and could have been gregarious due to the many different track sizes found in the same locale. Lockley *et al*. (1983) offers an explanation as to why hadrosaur tracks are so ubiquitous; they explain that hadrosaurs may have traveled together in herds because they lacked armor and were therefore mutually protected in herds, similar to moderate ungulates.

Less commonly found in Parowan Gap are *Ceratopsipes* tracks, with only a single left manus-pes set formerly reported on by Milner *et al*. (2006). The *Ceratopsipes* specimen described in this paper and the specimen described by Milner *et al*. (2006) likely represent the oldest ceratopsian tracks in Utah and possibly North America. Milner *et al*. (2006) states the Parowan Gap *Ceratopsipes* tracks are the oldest known because the previously oldest described ceratopsian tracks were reported from the Blackhawk Formation located near Price, Utah which had a reported radiometric age range of 82-77.5 Ma, making the Parowan Gap ceratopsian tracks slightly older at 83.1 Ma (Carpenter, 1992). To our knowledge, no further reports have been made contesting the age differences between the Parowan Gap and Blackhawk Formation ceratopsian tracks nor have any published works reported on any ceratopsian tracks older than the

Parowan Gap specimens. This makes our specimen incredibly important because it adds more to our understanding of Late Cretaceous ceratopsians living in southern Utah along the Western Interior Seaway.

Several theropod tracks are also present in the formation, however they are not common. The scarcity of theropod tracks compared to the abundance of ornithopod tracks further help us understand the dinosaur community living along the Western Interior Seaway because from this comparison, we can infer a typical predator-prey ratio of more herbivores than carnivores in the southern Utah area. Predator-prey ratios have been observed in the fossil record in both body and trace fossils and are critical to understanding paleoenvironments as well as dinosaur behavior (Bakker, 1975; Lockley *et al*., 1986). We compared the theropod tracks we recorded to several ichnotaxa, including *Magnoavipes* and *Dromaeopodus*. One specimen reported in this paper possibly represents a different morphotype than previously reported by other authors. Milner *et al*. (2006) described the most common theropod track morphotype as small, tridactyl, an elongate digit II, and a greater divarication angle between digits II and III. The different morphotype we report on has a small divarication angle and appears to be didactyl with an abbreviated digit. We associate specimen PG.JKC.2018.01 with the ichnotaxa *Dromaeopodus* or *Dromaeosauripus*, which would make this specimen the youngest dromaeosaur trace fossil known outside of Europe (Gierliński, 2007, 2008, 2009; Lockley *et al*., 2016). The second sample from the small theropod tracks is less definitive. We are the first to report the finding of a dromaeosaur track in the Iron Springs Formation, making the Parowan Gap track site even more unique for its diversity of dinosaur ichnofauna.

FUTURE RECOMMENDATIONS

The research team attempted some 3D analysis of tracks using photogrammetry, but the results were insufficiently accurate for publication. Through the use of traditional measuring techniques and digital photogrammetry, future researchers can record more precise and accurate morphological characteristics to better classify ichnogenera and analyze variation within groups at the site and in comparison with other Late Cretaceous track localities. The creation of 3D printed reproductions can be used for educational purposes as well. Falkingham *et al.* (2018) describes a standard protocol for data collection, presentation, and dissemination of ichnites using photogrammetry. As research continues, the array of track morphologies provides insight into the diversity of dinosaur populations and their behaviors along the western margin of the Western Interior Seaway during the Santonian-Campanian.

CONCLUSIONS

The Parowan Gap dinosaur track site is a prime location for the study of *in situ* tracks in Late Cretaceous strata of the Western Interior Seaway. The diversity of track ichnogenera and quality of natural casts support field identifications, shared published papers, and contributed significant suggestions and edits to the manuscript. We would also like to thank Southern Utah University interpretations of a diverse and vibrant coastal ecosystem during the Late Cretaceous. There is significant potential for additional track research, including photogrammetry. In addition to track surveys, future work within the Iron Springs Formation should include, but is not limited to, detailed descriptions of plant fossils and invertebrate ichnology, improved geochronology, and a detailed facies analysis of the stratigraphy for more expansive paleoenvironmental interpretations.

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Sample	Azimuth	TL (H-MD)	TW BH	TW BDS	HD	MDL	MDW	MDD	LDL	LDW	LDD	RDL	RDW	RDD	LM-Div	RM-Div	L/W ratio	Interpretation
PG.JKC.2018.01	297	21	4	9	3	12	0	3	17	0	3	9	0	3	35	35	5.25	*Ornithomimipus*
PG.JKC.2018.02	250	23		28	9										80	80		UNIDENTIFIABLE
PG.JKC.2018.03		13	10			7			8			7			60	90	1.30	UNIDENTIFIABLE
PG.JKC.2018.04		42	23				11		21	8					65		1.83	UNIDENTIFIABLE
PG.JKC.2018.05	170	15	7		3				13			12			50	40	2.14	*Ornithomimipus*
PG.JKC.2018.06.A	335	42	18		4	18	12		37	12		37	11		65	45	2.33	*Caririchnium*
PG.JKC.2018.06.B	284	37				20			26						50			*Caririchnium*
PG.JKC.2018.06.C		30	15		9	15									65	45	2.00	*Caririchnium*
PG.JKC.2018.06.D	298	27	16			10	11	7								60	1.69	*Caririchnium*
PG.JKC.2018.07		25	15	11	6	14	5	3				13	12	4		86	1.67	*Magnoavipes*
PG.JKC.2018.08		28	20	22		12	10	6	8	11	5	18	5	5	120	40	1.40	UNIDENTIFIABLE
PG.JKC.2018.09		30	28	35		12	12	7				6	12	7			1.07	UNIDENTIFIABLE
PG.JKC.2018.10		20	12	18		11	6	5	8	6	5				45		1.67	*UNIDENTIFIABLE: Ambydactylus (?)*
PG.JKC.2018.11		23	7	11		10	6	4	5	7	4				90		3.29	*UNIDENTIFIABLE: Magnoavipes (?)*
PG.JKC.2018.12		24	15	18		15	9	11.5	14	10	10	8	8	3	60	80	1.60	*UNIDENTIFIABLE: Magnoavipes (?)*
PG.JKC.2018.13		21	10	17		10	6	5				6	6	5		45	2.10	*Ambydactylus*
PG.JKC.2018.14.A		30	16	30		12	10	1	12	10	2	11	9	2	70	70	1.88	*Ambydactylus*
PG.JKC.2018.14.B		27							14	10	7							*Ambydactylus*
PG.JKC.2018.15		36	20	24		20	13	4	15	11	8	15	11	6	60	75	1.80	*Caririchnium or Ambydactylus*
PG.JKC.2018.16		22	6	9		15	6	2	4	6	2	15	7	2	60	75	3.67	*Magnoavipes*
PG.JKC.2018.17	125	17	8		1	8	7	3	5	7	3	5	6	3	115	115	2.13	*UNIDENTIFIABLE: Magnoavipes (?)*
PG.JKC.2018.18		20	15	18	1	6	7	3	5	6	5	5	6	3	100	60	1.33	*Ceratopsipes or Tetrapodosaurus*
PG.JKC.2018.19.A	352	50			10	30						32.5						*Caririchnium (with middle digit drag)*
PG.JKC.2018.19.B	352	40	35		15				34								1.14	*Caririchnium*
PG.JKC.2018.20a	125					17	5.5	3							90	90		*Magnoavipes (partial)*
PG.JKC.2018.20b	45					16	7	5.5										*Magnoavipes (partial)*
PG.JKC.2018.21	180	25	19	23	3	20	8	4	18	7	4	18	6	4	90	70	1.32	*Caririchnium*
PG.JKC.2018.22	37	20	10	10	6	13	10	5	10	9	5	6	5.5	5	50	80	2.00	*Caririchnium*
PG.JKC.2018.23		27	12	10	0	12	10	7	10	10	8	10	3	5	75	60	2.25	*Ambydactylus*
PG.JKC.2019.24																		*Caririchnium block*
PG.JKC.2019.25																		*Caririchnium block*
Averages	--	27.22	14.83	18.31	5.38	13.96	8.17	4.31	14.20	8.13	5.07	12.97	7.62	4.07	71.19	67.05	2.04	
STDev	--	8.96	7.33	8.15	4.35	5.20	3.08	1.82	9.28	2.94	2.40	9.01	3.40	1.49	22.6	21.1	0.93	

Table 1. Dinosaur Track Measurements and Interpretations

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