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Running Title: Morphometric Analysis of Dinosaur Tracks from Southwest Arkansas

Abstract

Dinosaur trackways were discovered in Cretaceous De Queen Limestone strata in Howard County, Arkansas, in June 2011. Multiple trackways with variably sized tridactyl tracks were exposed in a commercial quarry, suggesting multiple theropod species or adult and juvenile tracks of a single species. Results of morphometric analyses of 32 plaster casts from selected trackways are reported in an effort to identify the specific track-making dinosaurs and differentiate large and small tracks. Track measurements included length and width of each track, the lengths and widths of each digit impression, and the angular spread (divarication) between digit impressions. Twenty-nine plaster casts were of tridactyl theropod tracks whereas three casts were of poorly preserved tracks of a presumed but unknown tetradactyl (and possibly tetrapod) organism. Plaster casts of tridactyl theropod tracks ranged from 0.36 to 0.61 m long and 0.22 to 0.54 m wide. The longest digit impression on each track was the second, or middle, digit (range = 0.15 – 0.35 m long) with total digit divarication ranging from 31 - 57 degrees. The Arkansas track measurements were compared to tracks (*Eubrontes glenrosensis* Shuler 1935) preserved in the correlative Glen Rose Formation, Texas and attributed to the large Early Cretaceous carnosaur, *Acrocanthosaurus atokensis*. The *E. glenrosensis* track measurements from Texas plotted within the Arkansas data range, suggesting affinity of the Arkansas tracks to *E. glenrosensis*. Relatively poor preservation of tetradactyl tracks precluded morphometric analysis, but visual comparison to known Cretaceous crocodilian tracks is suggestive of affinity to such organisms.

Introduction

Open-pit quarries and mines in Howard County, Arkansas (Fig. 1) have long been known to expose dinosaur tracks and trackways (Pittman and Gillette 1989). In June 2011, continued excavation unearthed a new trackway site exposing innumerable sauropod tracks and trackways similar to those described by Pittman and Gillette (1989), but also the first-reported occurrence in Arkansas of tridactyl tracks and trackways of theropod dinosaurs and three poorly preserved tetradactyl tracks of uncertain origin.

Figure 1. Arkansas Map showing Howard County (shaded). From http://upload.wikimedia.org/wikipedia/commons/thumb/8/85/Map_of_Arkansas_highlighting_Howard_County.svg/200px-Map_of_Arkansas_highlighting_Howard_County.svg.png)

The theropod tracks occur in multiple trackways up to 40 m long and individual tracks are of several distinct size classes suggesting multiple individuals responsible for trackways and potentially representing different species or a single species in different stages of development (adults versus juveniles). The largest theropod tracks are morphologically similar to large tridactyl tracks (*Eubrontes glenrosensis* Shuler 1935; Lockley, 2000; Lockley et al. 2000; Adams et al. 2010) preserved in the Glen Rose Formation in Texas and attributed to the early Cretaceous carnosaur, *Acrocanthosaurus atokensis* (Farlow 2001). Smaller theropod trackways observed at the Howard County site may represent juvenile *Eubrontes glenrosensis*, or a different ichnospecies of *Eubrontes*, or another ichnospecies altogether. Morphological differences among theropod tracks observed at this site are described in detail below. Brief mention is also made regarding morphology of the three enigmatic tetradactyl tracks, though ichnospecies identification and attribution to a particular trackmaker was difficult due to poor preservation of these tracks.

The purpose of this investigation was to assess how the observed theropod track morphologies related to one another, and how they related to other Albian-aged theropod tracks from Texas and Australia. It was not known if the Arkansas tracks represented a single unknown ichnospecies, a single known ichnospecies, several unknown ichnospecies, or some combination thereof. Morphometric data detailed below were obtained from 32 plaster casts from the Arkansas trackway site and compared to similar tracks observed in correlative strata of Texas (Farlow et al. 2012, Farlow 1982) and a known track site of similar age from Australia (Romilio and Salisbury 2011). An attempt to identify the tetradactyl tracks was also made, but this attempt was based strictly on visual comparison to known Cretaceous tetradactyl tracks, owing to the small number and poor preservation of these tracks.

Previous Work

Shuler made the first published report of dinosaur tracks from the Gulf Coast region in 1917 (Shuler 1917). This report described sites along the Paluxy River in Somervell County, Texas. Reports of other sites in the region began in 1922 and have continued to this day (Pittman 1989). Much of the early work on dinosaur footprints in Texas comes from Roland T. Bird, who described, mapped, and even excavated sauropod and carnosaur tracks from the Paluxy River (Bird 1939 and 1941). Sauropod tracks and trackways in Arkansas were thoroughly described by Pittman and Gillette (1989) and compared to similar tracks and trackways exposed in the correlative Glen Rose formation of Texas (Forgotson, 1957; Langston 1974).

Dinosaur tracks and trackways provide crucial evidence of biomechanics (movement and locomotive behavior) of dinosaurs (Farlow et al. 2012). For example, Gulf Coast sauropod tracks proved that the leg structure of this group of very large dinosaurs was of sufficient design and strength to permit walking on land, though it is also evident from some trackways the animals were wading in shallow water, and even controversially suggest they were partially swimming in shallow water but being propelled forward using only their front feet (Gillette and Lockley 1991, Bird 1944, Lee and Huh 2002, Henderson 2004, Lee and Lee 2006; contra Lockley and Rice 1990, Hwang et al., 2008). Carnosaur tracks coincident with sauropod tracks provide evidence of predator-prey relationships that body fossils do not (Gillette and Lockley 1991). Farlow (1981) and Alexander (1991) also outlined the uses of dinosaur tracks for determining the mechanics of walking dinosaurs, their speeds, and their weights.

Geologic Setting

Dinosaur tracks and trackways in Arkansas are known exclusively from the De Queen Limestone (Pittman 1984). The formation as a whole is exposed in southwest Arkansas (Sevier, Howard, and Pike Counties) (Pittman 1984, Pittman and Gillette 1989) and generally consists of interbedded claystone, gypsum, and limestone (Fig. 2). It is correlative to the Glen Rose Formation (Trinity Group; Forgotson, 1957) of Texas.

Figure 2. The wall of the Howard County, Arkansas open-pit quarry showing gypsiferous claystone and limestone of the Early Cretaceous De Queen Limestone correlative to the Glen Rose Formation, Texas (Trinity Group; Forgotson, 1957). Dinosaur track-bearing limestone at top of section (arrows). Scale bar is approximately 5 meters.

The unit is assigned to the Albian stage (Early Cretaceous) based on presence of *Douveilliceras* ammonites and the foraminiferan, *Orbitolina texana*. (Pittman 1984, Loucks and Longman 1982).

Sedimentary structures observed at the site and by Pittman (1989) indicated that the tracks were made close to the shoreline of the Cretaceous Gulf Coastal Plain. The presence of gypsum and molds of hopper crystals of halite (sodium chloride) in gypsiferous mudstones are indicative of hypersalinity associated with intense evaporation of broad coastal mudflats that were episodically inundated by marine waters.; an environment remarkably similar to coastal sabkhas of the southern Persian Gulf today (Wilson 1975, Bathurst 1975, Tucker and Wright 1990).

Regionally, this tracksite is part of a broad suite of Cretaceous dinosaur track-bearing strata that occur in near-shore deposits from Arkansas to south-central Texas along the Lampasas Cutplain and the Edwards Plateau (Hawthorne 1990). These near-shore deposits form an Albian-aged ring of sediment along the southern continental margin of North America (Fig 3).

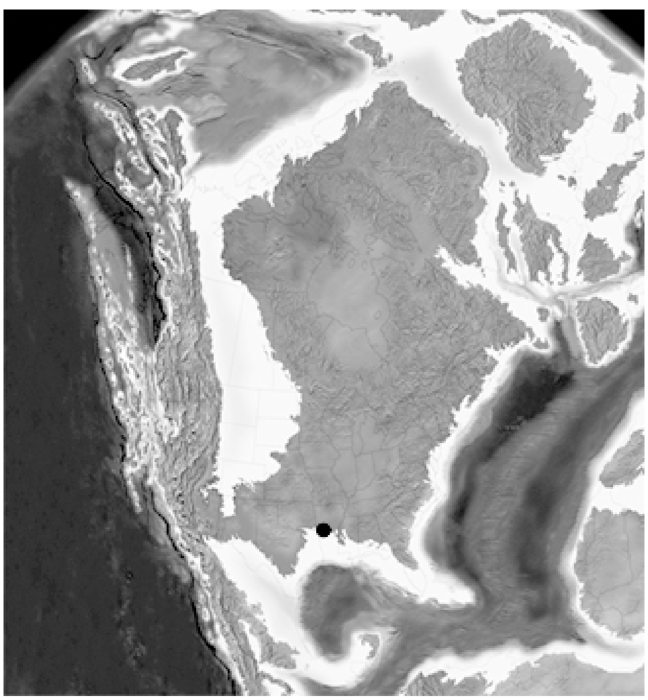

Figure 3. Paleogeographic reconstruction of North American 115 million years ago (Early Cretaceous) by Prof. R. Blakely, Northern Arizona University. The map shows development of a broad coastal plain extending from central Texas across Arkansas, Mississippi, Alabama and northward along the Atlantic coast. Arkansas trackway site indicated by black dot on map. (Image from http://www2.nau.edu/rcb7/namK115.jpg).

Methods

During summer 2011, 32 dinosaur tracks (29 theropod and 3 tetradactyl tracks) were cast using plaster, burlap, and wire mesh. The casts were made by greasing dinosaur track impressions in the trackway limestone and carefully coating the track interior with plaster, then filling the track with plaster-coated burlap. Plaster casts were strengthened by adding a layer of wire mesh to the middle of the track cast, then covering the wire mesh with additional layers of plaster-coated burlap. Using strips of plaster-coated burlap conserved plaster, lightened the weight of each track cast, and made casts less brittle, helping to keep them intact during transport. Each plaster cast was labeled according to its trackway, and to its sequence within the trackway. For example, a designation of T3#1, means the first track in trackway 3. All plaster casts were also marked with an arrow indicting track orientation relative to north.

Plaster casts of individual tracks from a single trackway were measured using the parameters length, width and length/width ratio of each track impression, length, width, and length/width ratio of each digit impression for all three digits, and the angle between digit impressions (Hasiotis et al. 2007).

Each measurement was made by hand using a large protractor, and a 1-m measuring tape. All length and width data were measured in centimeters and converted to meters. Angular measures were in degrees.

Scatter plots of various parameters were plotted to characterize the morphometrics of all measured tracks and to compare the Arkansas tracks to those documented from the Glen Rose Formation, Texas (Farlow 2001) and tracks from similar age rocks in Australia (Romilio and Salisbury 2011). For this study, the most useful measures comparing tracks were plots of track length versus width and length-width ratio of tracks. Figure 4 is a plot of track width versus track length for all tridactyl (n=29) and tetradactyl (n=3) plaster casts acquired from the study site. Figure 5 plots track width versus length-width ratio.

Obviously, casts of tracks obtained from individual trackways represent left and right footprints of a single organism. Organizing track morphometrics according to individual trackways permitted an examination of the variation in track size and shape for several individual dinosaurs (Fig. 4).

Tracks associated with a single individual should cluster closely on the plots and provide some indication of closeness of association to other tracks; tracks of the same species should display similar morphometric relations regardless of stage of development (e.g. juvenile versus adult) whereas tracks from different species of theropod would be expected to display rather different morphometric characteristics.

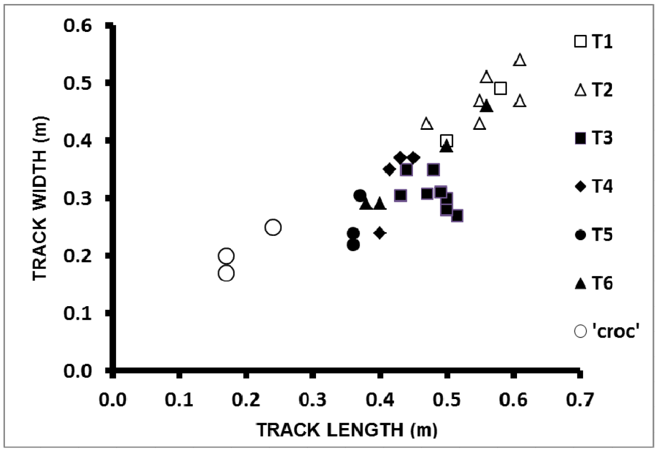

Figure 4. Plot of track width (meters) versus track length (meters) from plaster casts of tetradactyl tracks (open circles = ‘croc’) and tridactyl tracks of 6 theropod trackways (numbered T1 through T6) acquired from the Howard County dinosaur trackway site. Note that tracks within an individual trackway are more similar to each other than tracks between trackways, indicating that each trackway was produced by a different individual.

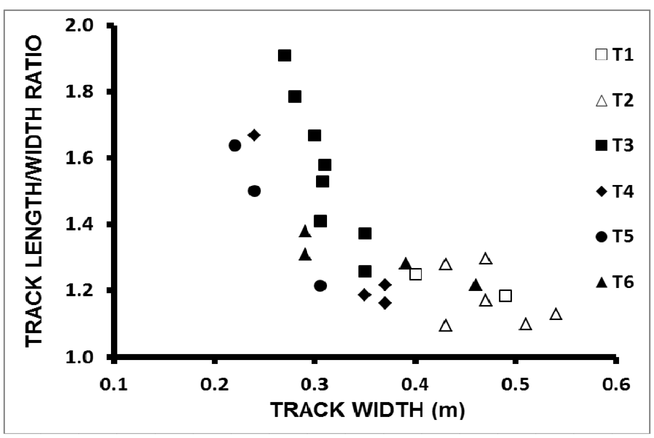

Figure 5. Plot of track length/width ratio versus track width (meters) for plaster casts of theropod tracks from 6 trackways at the Howard County trackway site. Note that as track width increases (corresponding to larger individuals in Fig. 4 above), the length/width ratio approaches 1.

Published lengths and widths of *Eubrontes glenrosensis* tracks from Cretaceous strata of Texas from Pittman (1989) and Farlow et al. (2006) were also plotted with the Arkansas data to determine similarity or differences among tracks from these geographically separated locations. Cretaceous tridactyl tracks from Australia (Romilio and Salisbury 2011) served as an additional group for comparison (Fig. 6).

Clustering of the Arkansas track data within the Texas data would be suggestive of close affinity to the presumed *Eubrontes glenrosensis* trackmaker and suggest the Arkansas tracks were also made by this large predatory dinosaur, whereas significant differences between Arkansas and Texas tracks would be suggestive of different theropod species. *Acrocanthosaurus atokensis* was the largest theropod known to occupy this region (Farlow 2001) and the presumed trackmaker of the ichnospecies, *Eubrontes glenrosensis* Shuler 1935.

Only three tetradactyl prints were recovered from the track site. Because of their small size, shallow depth, poor preservation, and few examples, these prints were compared visually to known tracks of the Cretaceous in North America in an effort to provide a preliminary assignment of these tracks to known ichnotaxa or organisms.

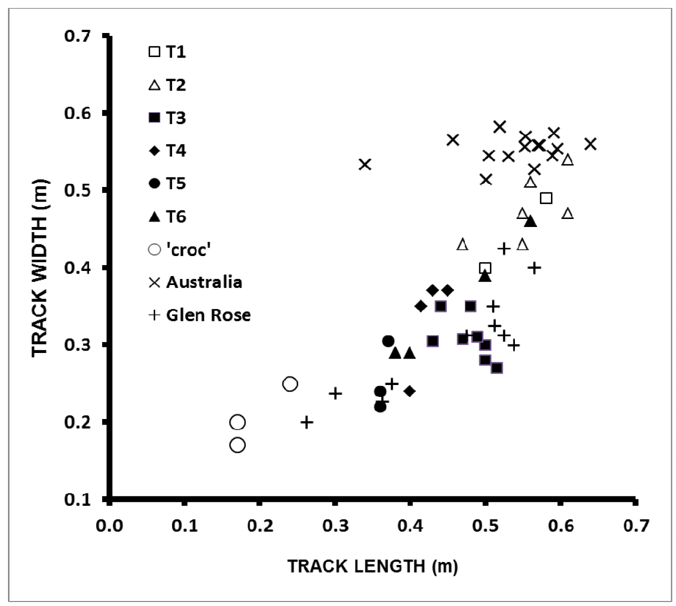

Figure 6. Track width (meters) versus track length (meters) for 29 theropod tracks from 6 Arkansas trackways (T1 through T6) and 3 tetradactyl tracks (‘croc’) from the Howard County, Arkansas dinosaur trackway site plotted with theropod tracks from equivalent strata in Texas (Glen Rose Formation; Farlow 2006 and Pittman 1989) and ornithopod tracks from Australia (Romilio and Salisbury 2011 and 2013). Overlap of the Texas and Arkansas theropod tracks indicates very close affinity of these tracks, though there is some linear variation in track sizes as represented by length versus width. Note that Australian ornithopod tracks and Arkansas tetradactyl tracks do not overlap theropod tracks, indicating the length versus width measures can discriminate among different dinosaur species.

Results

Overview of Tracks and Trackways

The total extent of the Howard County dinosaur trackway site exposed in 2011 was approximately 6,000 m^2, with approximately 4,200 m^2 displaying concentrated areas of dinosaur tracks from sauropods and 8 distinctive theropod trackways up to 40 m long (http://trackways.cast.uark.edu). Sauropod trackways preserved excellent impressions of both manus (front foot) and pes (rear foot) tracks as well as innumerable poorly preserved sauropod tracks with several generations of tracks superimposed in some areas of the exposed trackway site. The resulting rock surface appeared thoroughly trampled.

Individual theropod tracks displayed impressions of scimitar-shaped claws and often preserved impressions of fleshy foot and toe pads (Fig. 7). Only three tetradactyl tracks were found, but these were poorly preserved, shallow impressions so determination of their organismal affinity is problematic.

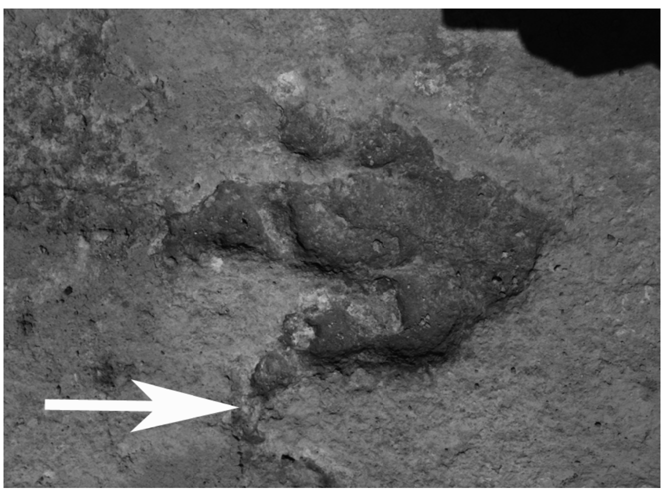

Figure 7. Relatively small theropod track from the Howard County, Arkansas dinosaur trackway site displaying a scimitar-shaped claw impression (arrow) and well-preserved impressions of foot and toe pads. Heel-to-toe length approximately 40 centimeters.

Sauropod tracks

Hundreds of sauropod tracks were observed at this site. This is consistent with observations made elsewhere in Howard County (Pittman and Gillette 1989). Both manus and pes prints were observed and several recognizable trackways could be discerned among the many tracks and trampled areas. Individual sauropod pes tracks were roughly circular and up to 0.65 m in diameter (Fig. 8). Langston (1974) assigned tracks of this type and age to the genus *Pleurocoelus*, and this genus has since been reclassified as *Astrodon* (Carpenter and Tidwell 2005). These tracks tended to exist in parallel rows representing multiple individual trackways that covered much of the new site.

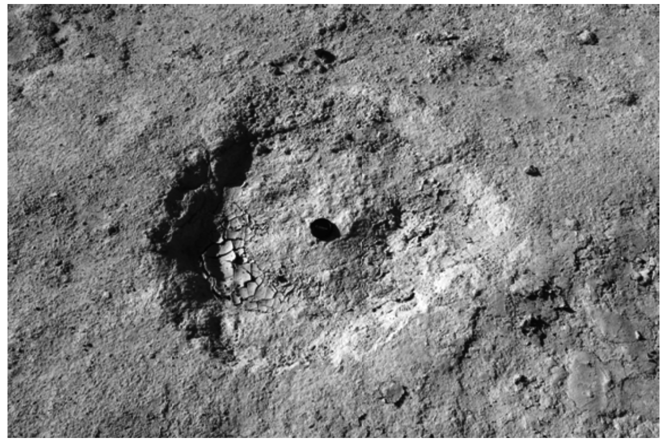

Figure 8. Relatively well-preserved sauropod pes track (hind foot) showing grossly circular impression and evidence of toe claws (left side, in shadowed relief). The camera lens cap in the center is approximately 6 cm.

Theropod Tracks

Tridactyl theropod tracks were observed in a variety of sizes throughout the site and included 8 relatively long trackways representing at least seven individuals. Two trackways composed of the largest theropod tracks and among the longest at the site (>30 m length each) were situated adjacent to each other, but indicated walking in opposite directions. One trackway represent an individual walking northwest to southeast and the other, several meters away, an individual walking from southeast to northwest.

The largest tridactyl trackways differed from the other prints not just in size, depth, location, and direction. Compared to the smaller theropod tracks, the large tracks displayed inward rotation of each footprint giving the appearance of being 'pigeon-toed' (i.e. with toes rotated inwards instead of more typical parallel to the direction of motion; Fig. 9).

Tetradactyl Tracks

Three poorly preserved tetradactyl tracks were observed and cast in plaster from the trackway site. Each track was approximately 0.20 m long and approximately 0.2 m wide, or approximately twice the size of a human hand (Fig. 10).

Using simple visual comparison to other track types from the same time period, the tetradactyl tracks appeared most similar to the tracks of known crocodilians of the Early Cretaceous (Kukihara and Lockley 2012).

Figure 9. Photo mosaic (left) and schematic diagram (right) of a portion of trackway T1 of a large theropod dinosaur from the study site. The image length is approximately 10 meters. Individual theropod tracks are up to 0.65 m long and approximately 0.65 m wide. Note the inward rotation of the tracks and their apparent alignment with a very narrow stance; tracks indicate the theropod was stepping almost foot-over-foot.

Pittman et al. (2002) and Pittman (1989) reported fragments of crocodilian fossils (scutes, partial teeth, or bone fragments) from the De Queen Limestone, so it is possible these poorly preserved tracks represent shallow impressions made by a crocodilian. However, the poor preservation of these tracks makes definitive interpretation impossible.

Figure 11. Image of poorly preserved tetradactyl track (upper) with schematic diagram (lower). Impressions of all four digits are visible in the image oriented approximately as the hand in the foreground. Hand for scale.

Morphometric Analysis of Theropod Tracks

Morphometric measurements of 32 casts of theropod tracks obtained from 6 theropod trackways were recorded and tabulated as T1, T2, T3, T4 T5, T6 (Table 1). Morphometric measurements of three tetradactyl tracks cast in plaster were tabulated as, "croc" owing to the affinity of these poorly preserved

Table 1. Number of plaster casts from each trackway, number of right vs. left foot tracks cast, mean length of left and right foot casts, mean width of left and right foot casts.

TRACKWAY	# casts	Left tracks vs. right tracks	Mean length of left tracks vs. mean length of right tracks (cm)	Mean width of left tracks vs. mean width of right tracks (cm)
“croc”	3	1/2	17/21	20/21
T1	2	2/0	54/na	44/na
T2	6	3/3	56/55	48/47
T3	8	2/6	45/48	32/33
T4	4	1/3	45/41	37/32
T5	3	3/0	36/na	28/na
T6	4	2/2	39/51	29/32

tracks to Cretaceous crocodilian tracks observed from other locations.

Of the 18 morphometric parameters recorded for this study, only track length, track width, and length/width ratio appeared to be meaningful with respect to characterizing these tracks and comparing them to limited morphometric data from other studies (e.g., Pitmann 1989, Farlow 2001, Farlow et al. 2006, Romilio and Salisbury 2011). Table 1 catalogues the tracks cast from each trackway.

The first pair of measurements chosen when testing relatedness was length versus width (Fig. 4; Table 2). When the length/width scatter-plot was constructed the tetradactyl data clustered in the bottom-left of the graph, while the tridactyl data clustered in the top right; well away from the tetradactyl data. This initial separation of points suggested that simple length to width comparison was sufficient to discriminate relatedness (or lack thereof) between tetradactyl and tridactyl tracks at this site.

Each trackway clustered in its own region of Fig. 4 with relatively little overlap with other trackways. This indicated that morphometric variation of tracks within a single trackway (i.e. tracks from an individual theropod) showed less variation than morphometrics between trackways suggesting the possibility that each trackway was produced by a different theropod individual.

Similarly, measured track width versus length/width ratio appeared to reasonably discriminate individual trackways, though there was more overlap owing to greater variation in length/width ratio within individual trackways (Fig. 5). Interestingly, as track

Table 2. Ranges of measured track lengths and track widths obtained from plaster casts of theropod and tetradactyl tracks.

TRACKWAY	TRACK LENGTH (Range in cm)	TRACK WIDTH (Range in cm)	LENGTH/ WIDTH (Range)
“croc”	17 – 24	17 – 25	9 – 1.0
T1	50 – 58	40 – 49	1.2 – 1.3
T2	47 – 61	43 – 54	1.1 – 1.3
T3	43 – 52	27 – 35	1.4 – 1.9
T4	40 – 45	24 – 37	1.2 – 1.7
T5	36 – 37	22 – 31	1.2 – 1.6

length became larger, so did track width (Fig. 4). Consequently, the length/width ratio for larger individuals approached 1 whereas the smallest individuals it was nearly 2 (Fig. 5)

Figure 6 compares length versus width of Arkansas dinosaur tracks to tracks considered to *Eubrontes glenrosensis* from Texas (Farlow 2001) using data from Farlow et al. (2006) and Pittman (1989). Additionally, we have included lengths and widths of tracks from a Cretaceous trackway in Australia (Romilio and Salisbury 2011) to demonstrate that length versus width data are useful in discriminating different dinosaur species.

The Australian data showed little overlap with the far upper boundary of the Arkansas theropod tracks. Generally, the Australian tracks showed broad variability in length, but were almost always wider than Arkansas and Texas theropod tracks. Romilio and Salisbury (2011) originally attributed these tracks to be theropods, but recently reinterpreted them as tracks attributable to the ornithopod, *Amblydactylus* cf. *A. gethingi* (Romilio and Salisbury 2013). It is not surprising then that these tracks show little overlap with Arkansas and Texas tracks on the scatter plot (Lockley 2009). In contrast, the Texas theropod tracks overlapped the Arkansas data almost entirely, with only two points falling outside of the overlap with the Arkansas data.

Overlap between Arkansas and Texas data suggested a relationship between all of the Arkansas theropod trackways and the creator of the Texas tracks. Trackways T1 and T2 are the largest theropod tracks observed at the Arkansas site and are larger than any of the tracks measured from Texas. However, T1 and T2 tracks plot at the upper end of the linear distribution for tracks attributed to *Eubrontes glenrosensis* Shuler 1935. Figures 4 and 6 illustrate a strongly linear relationship (r = 0.81) between track width and track length. This relationship indicated a consistent pattern of scaling of track width (and therefore foot width) with track length (and therefore foot length).

Discussion

There were three track morphologies identified at the study site: sauropod tracks similar to those previously described from a nearby location (Pittman and Gillette 1989, Pittman 1989, Pittman et al. 2002), tridactyl theropod tracks representing the first known documentation of a large carnosaur in Arkansas, and several poorly preserved tracks of an unidentified tetradactyl organism. Sauropod tracks at the site are very similar to those attributed to *Astrodon sp.* (Langston 1974, Carpenter and Tidwell, 2005).

Scatter plots of theropod track length and width indicated a linear relationship with scaling along an allometric trajectory indicating several individual theropods in different growth stages were responsible for the observed trackways (Figs. 5-6). Morphometric parameters of *Eubrontes glenrosensis* Shuler 1935 (attributed to *Acrocanthosaurus atokensis*) from Texas (Farlow, 2001; Farlow et al. 2006) overprint the Arkansas tracks indicating close affinity and suggesting the Arkansas tracks might also be attributed to *Acrocanthosaurus*. The observed overlap in most of the Arkansas and Texas data thus seems to confirm the initial hypothesis that at least some of the Arkansas track makers are also Texas track makers. The largest theropod tracks observed at the study site (trackways T1 and T2) appear on our scatter plots (Figs. 4-6) at the extreme high end of an allometric gradient and may represent a near-maximum size individual of mature age. Additional, detailed morphometric data from known trackway sites representing *Eubrontes glenrosensis* Shuler 1935 would benefit this present analysis.

The enigmatic tetradactyl tracks remain unidentified due to their relatively poor preservation and small number of observed specimens (n=3), though they appear morphologically similar to crocodilian tracks preserved in Cretaceous strata of the Dakota Group (Kukihara and Lockley 2012). If these tracks are indeed crocodilians, possible candidates for the maker of these tracks are *Pachycheilosuchus trinquei*, a species from the Glen Rose formation, or an unclassified Glen Rose crocodile dubbed the Glen Rose Form (Rogers 2003). Importantly, the observed tetradactyl tracks here suggest a larger organism than known fossil specimens of these crocodilians.

Dinosaur tracks at this site were impressed into calcareous and gypsiferous mud along a broad, very low relief coastal sabkha formed along the southern margin of North America during the early Cretaceous (Pittman 1984 and 1989, Hawthorne 1990). The water content of this mud as well as its trafficability influenced the overall shape and preservation of tracks and contributed to some of the observed scatter in morphometric parameters. Tracks impressed into wet but stiff mud were the best preserved and most accurately reflect the shape of the theropod foot. Mud with very high water content is subject to slumping or lacks sufficient cohesiveness to accurately preserve the true outline of footprints and accounts for at least some of the observed variation (or scatter) in the morphometric measures. Nonetheless, the tracks appear to preserve sufficient detail to indicate their affinity to known dinosaur track ichnospecies of the lower Cretaceous Gulf Coastal Plain.

This dinosaur trackway in Howard County, Arkansas is the second known occurrence of a very extensively tracked limestone surface exposed by quarrying activity during the past few decades (Pittman and Gillette 1989, Pittman et al. 2002). Given the occurrence of two areally extensive dinosaur trackways from the same horizon of the De Queen Limestone separated by many kilometers, it is reasonable to speculate that additional large exposures of dinosaur trackways are possible across southwest Arkansas in the area underlain by early Cretaceous strata. Additional exposures may be exhumed by quarrying activity, and it is hoped that new discoveries will be brought to the attention of the scientific community as they occur. The authors are indebted to the private citizens who took it upon themselves to report this remarkable trackway site. It enhances understanding of the distribution of sauropod and theropod tracks in the south-central United States and provides a tantalizing glimpse into the diversity of dinosaur species that inhabited southwestern Arkansas during the Early Cretaceous Period.

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