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DINOSAUR TRACKS IN THE DAKOTA FORMATION (APTIAN–ALBIAN) AT CLAYTON LAKE STATE PARK, UNION COUNTY, NEW MEXICO

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INTRODUCTION

Nearly 500 dinosaur footprints, pertaining to one ornithopod taxon and three theropod taxa, occur in exposures of the Dakota Formation in the spillway at Clayton Lake State Park in northeastern New Mexico. The tracks are in three horizons consisting of lacustrine or marine sediments, including massive, crossbedded sandstone, siltstone and shale.

LOCALITY

The tracks are known exclusively from horizontal exposures of sedimentary rocks in the Dakota Formation at the spillway of Clayton Lake State Park (Fig. 1), Union County, New Mexico (Fig. 2). Whether other exposures in the area contain footprints cannot be established, for exposures are rare and generally covered. The authors have spent several days searching for other sites in the vicinity without success.

The exposures at the spillway cover an area of approximately one-half hectare, over which the distribution of footprints is irregular. According to State Park officials, water has never passed over the spillway since the dam was built, and there has been little erosion at the site. Most tracks occur in hard rock and are not in danger of being lost to erosion or vandalism. Consequently, we have not collected tracks from the site, but instead have taken numerous documentary photographs and several rubber molds and plaster casts.

HISTORY OF STUDY

The tracks were apparently discovered by amateurs sometime before 1982. In 1982 their existence came to the attention of State Park officials Martin Franz and Bernard Fones, who discovered that several people were carrying positive in-fillings of dinosaur tracks away from the site. They confiscated the positives and alerted paleontologists at the New Mexico Museum of Natural History to the footprints. Donald Wolberg (New Mexico Bureau of Mines and Mineral Resources) and one of us (DAT) visited the site later in 1982 and confirmed the park officials' identification. In 1983 Wolberg and the authors revisited the spillway and recognized several problematical tracks and trackways, which are described below.

Later in 1983 the New Mexico Museum of Natural History organized a crew of volunteers who mapped the footprints. Subsequent short visits to the site have resulted in the discovery of additional footprints and other features pertinent to understanding the trackways. We found that tracks are most easily recognized under oblique lighting, in the early morning and late evening. Moreover, with the changing position of the sun through the year, tracks that are not easily distinguished in one season are more readily recognized later.

METHODS AND MATERIALS

Study of dinosaur footprints is relatively simple, but requires detailed observation and repeated visits to a site. After clearing rubble from track-bearing strata, the first step at this site was to make preliminary identifications of footprints and establish the extent of their occurrence. Subsequently, we took detailed measurements on individual tracks and trackways, accompanied by documentary photographs. For exceptional tracks we produced molds, on site, in latex rubber and RTV silicone rubber; latex is less expensive but requires repeated application, over a period of at least 7 or 8 days, while molding with RTV silicone rubber

FIGURE 1. Photograph to northeast overlooking lake from basalt rim at southern boundary of the park. The white area beneath the arrow indicates position of the spillway, cut into the Dakota Formation, where the trackway site is located.

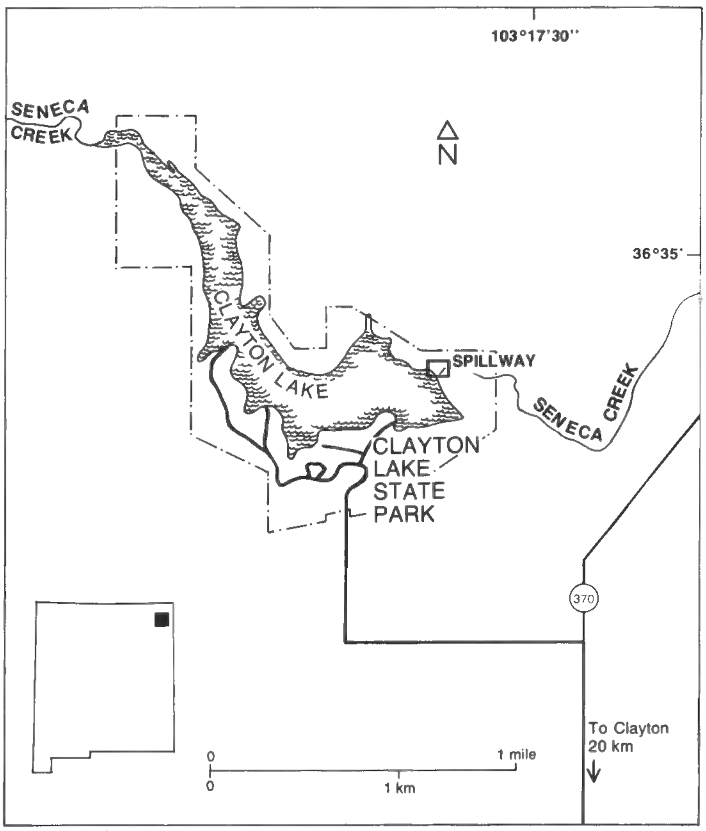

FIGURE 2. Index map showing location of Clayton Lake State Park. The rectangle at the spillway is the area mapped in Figure 3; the oblique line at the right side of the rectangle marks the abutment at the end of the riprap dam as a permanent landmark adjacent to the spillway.

FIGURE 3. Map of the trackway site. The oblique dark line at lower right represents the dam abutment. Numbers identify the three track-bearing units. The lower sandstone unit (1) is overlain by a thin unfossiliferous shale; the middle siltstone layer (Unit 2) contains the majority of footprints and the best details. The upper shale horizon (Unit 3) is continuous with the middle unit, although the composition and weathering features change. Footprints that appear to be part of a series are darkened. Note ripple marks and mudcracks in Unit 1. A few isolated tracks in the western side and southwestern corner of the map were too isolated to be recorded here.

can be completed in one day. In the laboratory we prepared casts from these molds for deposition in the collections at the New Mexico Museum of Natural History. Mapping by the team of volunteers was done on a 1-m grid, supplemented by tape and measure techniques. That map is presented below (Fig. 3). Photography and mapping are best undertaken early in the morning and late in the afternoon on sunny days, when shadows are oblique and enhance trackway definition.

OVERVIEW OF THE FOOTPRINTS

Tracks occur in three horizons in the spillway, as indicated on the trackway map (Fig. 3). Track density and diversity are greatest in the middle and upper horizons, which are also the most extensively exposed. The lower horizon, at the top of a massive sandstone, is separated from the middle level by a thin, unfossiliferous shale of uniform thickness, indicating an interval of time which separated the depositional events that produced the lower and middle footprint layers. It is possible that the middle and upper trackway levels were deposited without interruption, but the change in their composition (from siltstone to shale) and weathering characteristics indicates a change in depositional conditions. Thus, it is fair to deduce that the site reveals at least two episodes of trackway production and preservation.

Trackways are easily distinguished in several areas of the exposure, some extending for considerable distances and indicating changes in direction and velocity. There is no clearly recognizable preferred orientation, although it appears that in several places the direction of one individual's progression parallels that of another.

Track quality and depth seem to vary according to sediment conditions at the time of impression. Some tracks are deep and demonstrate fine details of foot anatomy, while others, occasionally in the same trackway, are shallow and reveal few details, or have been altered by soft-sediment deformation or subsequent erosion (Fig. 4). Especially where the substrate was soft, the sediment could not maintain the shape of the footprint, obscuring the tracks. In several instances the substrate influenced behavior, as shown by heel impressions and sliding feet on the slippery surface.

GEOLOGY

Baldwin and Muehlberger (1959) prepared a comprehensive review of the geology of Union County. Clayton Lake is formed by damming Seneca Creek, a tributary of Carrizo Creek, which in turn is a tributary of the Canadian River. Clayton Lake State Park is situated between the Sierra Grande arch to the west and the Dalhart basin to the east. Mesozoic sedimentary rocks and Tertiary sediments and volcanics dominate the surficial geology.

According to the convention adopted by Baldwin and Muehlberger (1959), the Upper Jurassic Morrison Formation in Union County is overlain by the Dakota Group, which consists of two formations, (ascending) the Purgatoire Formation and the Dakota Formation. They mapped the sedimentary rocks in the Clayton Lake vicinity as Dakota Formation, which in this region includes a massive, crossbedded sandstone variously overlain by shale, shaly sandstone and sandstone.

The lower set of tracks in Unit 1 (see Figures 3 and 5) is in the lower, massive, crossbedded sandstone of the Dakota Formation as recognized by Baldwin and Muehlberger. The middle and upper sets of tracks at the site (Units 2 and 3, respectively) occur in their upper shale and shaly sandstone strata. On the south side of the lake, the Dakota Formation is overlain by Tertiary–Quaternary basalt. Exposures of the Dakota Formation along the basalt rim are covered and not readily correlated with the exposures at the spillway.

A composite measured section of the Dakota Formation at the spillway is presented schematically in Figure 5. The base of the lower massive sandstone is covered; its thickness in the beds of Seneca Creek exceeds 5 m. This sandstone unit is red and buff, extensively crossbedded and contains abundant mudcracks and ripple marks on its upper surface, some of which are modified by dinosaur footprints. The crossbedding is prominent, ranging to a meter in height. Burrows and trails are abundant on the upper surface, which appears to be a thin, muddy layer that was responsible for preservation of the footprints; it is designated as Unit 1.

FIGURE 4. Photograph from dam abutment looking northwest. Nearly every depression is a footprint. Man at right is standing on Unit 2.

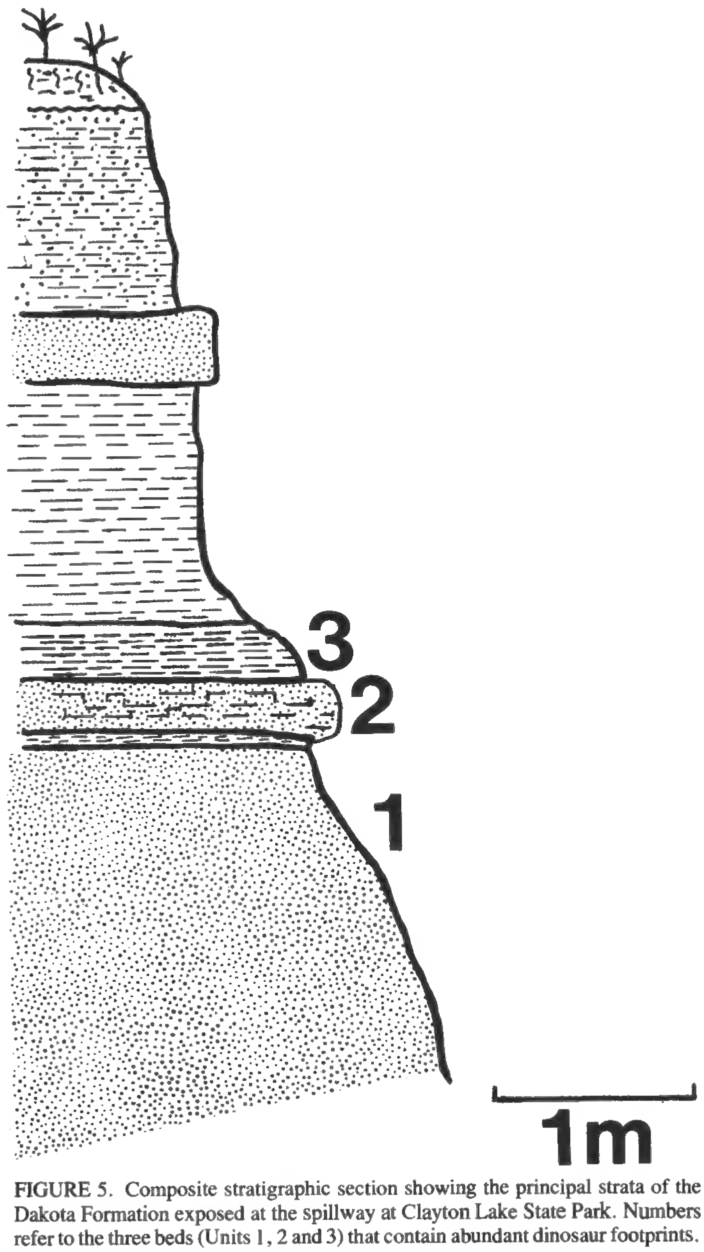

FIGURE 5. Composite stratigraphic section showing the principal strata of the Dakota Formation exposed at the spillway at Clayton Lake State Park. Numbers refer to the three beds (Units 1, 2 and 3) that contain abundant dinosaur footprints.

FIGURE 6. Close-up photograph that shows the upper surface of the lower massive, crossbedded sandstone (Unit 1) in the foreground. The middle, unfossiliferous shale layer is beneath the woman's hand, and the track-bearing siltstone (Unit 2) is the ledge behind the woman's hand. The rubble surface that constitutes Unit 3 is visible in the background.

Above the massive sandstone is a dark-gray shale (Fig. 6) that separates it from the track-bearing siltstone designated as Unit 2. The gray shale is generally 15 cm thick and has a hummocky upper surface where it is in sharp contact with the overlying siltstone. The hummocky structure might have been produced by soft-sediment deformation when dinosaurs walked in the overlying siltstone.

The siltstone layer (track-bearing Unit 2) averages 25 cm in thickness (Fig. 6). Like track-bearing Unit 1, it is crossbedded and contains ripple-marks. Iron stains are common on bedding planes, especially where grain size is relatively large. It is capped by an irregular layer of gray mud, possibly carbonate in content, in which most of the tracks in this layer were impressed. Some of the tracks in Unit 2 were filled in by coarser sand, which was cemented by iron and now forms positive infillings (see, for example, the infilling shown in Figure 8).

Above the siltstone layer is a gray shale (Unit 3) in gradational contact with Unit 2. Its composition and structure are variable, and the unit does not exceed 15 cm in thickness. This shale weathers to chunky, irregular blocks, causing erosional damage to tracks. Rubble at the site has come primarily from weathering of this horizon.

Above Unit 3 is a gray shale, generally 45 cm thick, a fine-grained sandstone that is a ledge-forming unit with a uniform thickness of 35 cm and a cap of shale and siltstone at the surface. All strata were sampled for microfossils, without success.

Lockley (1985) reported several dinosaur trackway sites in the Dakota Group in Colorado, some of which he attributed to hadrosaurians. Whether those sites can be correlated with each other and with the Clayton site has not been determined, but at least at Clayton the lower massive sandstone unit is a distinctive marker bed that distinguishes the Dakota Formation. The age of the Dakota Formation is difficult to determine. The most recently published age assignment for the Dakota was by Lockley (1985), who followed recent workers in regarding this formation as roughly Aptian–Albian, 100–110 m.y.B.P.

FOOTPRINTS

Track descriptions

Tracks of theropod dinosaurs are only slightly less abundant than those made by ornithopods. At least three theropod taxa can be recognized at the site, distinguishable by size and morphology.

Coelurosaur footprints

The smaller theropods, probably belonging to the general category of small carnivorous dinosaurs often referred to as "coelurosaurs," left several excellent trackways, such as the set of bird-like prints shown

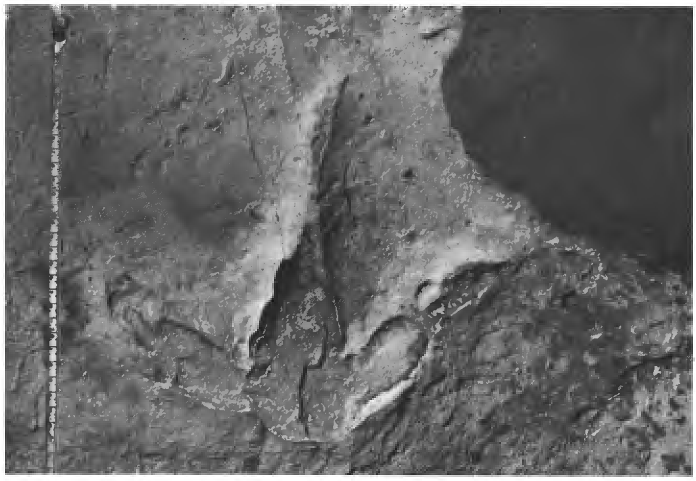

FIGURE 7. Footprint of the smaller variety of theropod dinosaur, here called a "coelurosaur." This track is part of the trackway mentioned in the text and on the left side of the map in Unit 2.

in the left third of the trackway map (Fig. 3) in the north–south peninsular exposure of Unit 2. The coelurosaur footprints (Fig. 7) reveal slender toes and prominent claws. The lateral toes are widely spread (the angle of divarication), and heel-pad impressions demonstrate that locomotion included walking on heavily muscled metatarsal elements. Coelurosaur footprints at the site are up to 28 cm long (tip of middle toe to heel).

Carnosaur footprints

Larger theropod tracks were made by a heavier-bodied animal that, for convenience, we have identified as a carnosaur (Fig. 8) to distinguish it from the more lightly built coelurosaurs. The carnosaur tracks were made by feet with clawed, robust toes that had a smaller angle of divarication than the coelurosaur footprints. The carnosaurs walked on their toes and did not use the metatarsal bones for support, hence the lack of "heel" impression in their footprints. Only two large theropod footprints have been recognized with confidence at the site, both probably from the same individual. They are approximately 30 cm wide and 35 cm long (tip of middle toe to indistinct heel impression).

Ornithopod footprints

The majority of footprints at the site were made by heavy-bodied bipedal dinosaurs, possibly related to the Hadrosauridae. These orni-

FIGURE 8. Footprint of the larger theropod at the site, here regarded as a carnosaur, demonstrating heavier foot anatomy and lack of heel impression. The tear-drop shape in the right toe is a positive infilling of the toe impression consisting of iron-cemented sand. Note the abundance of trace fossils in this layer (Unit 2).

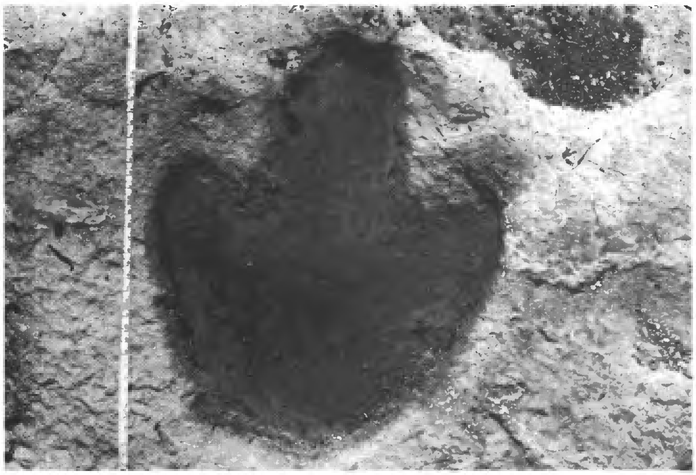

FIGURE 9. Water-filled footprint of an ornithopod dinosaur, demonstrating the blunt, rounded anatomy of the foot and the exceptionally long middle toe. This print is 35 cm long; others reach approximately 50 cm in length.

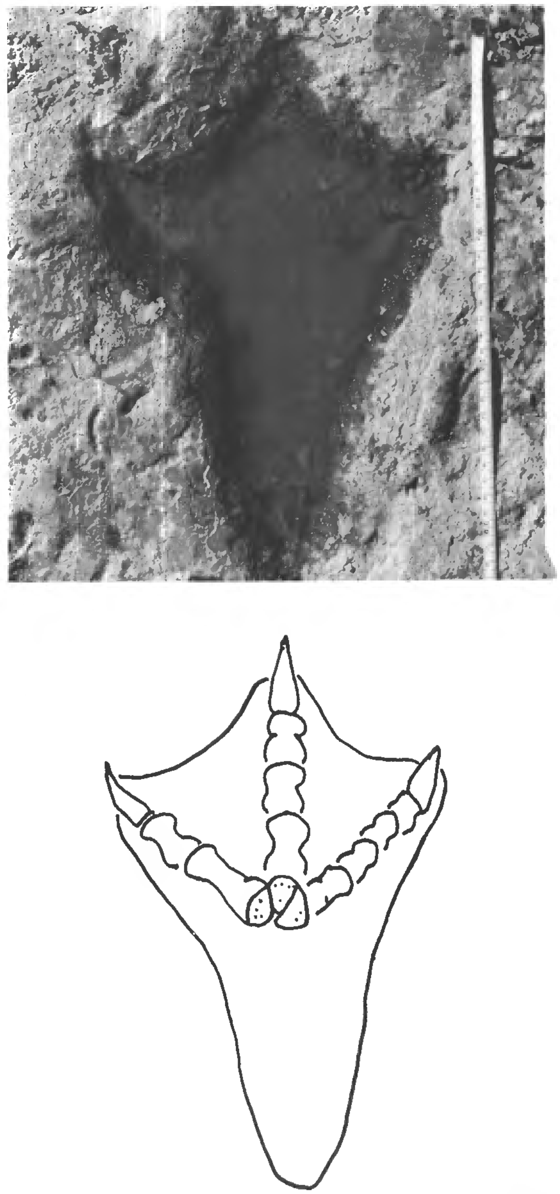

FIGURE 10. Water-filled footprint of a "web-footed theropod" dinosaur demonstrating the typical diamond shape. Forward is to the top of the photograph; this print is relatively large, with a total length of 35 cm. It is the fourth in the sequence presented in Figure 11. The line drawing is our interpretation of the position of the foot bones when the print was made; the heel print, made by the metatarsal pad (not shown), is less deeply impressed.

thopods are represented by a wide variety of sizes, ranging from juvenile to adult. A typical adult-ornithopod footprint is shown in Figure 9. The toe prints are rounded and blunt, without any claw impression. The heel is also rounded and, in some footprints, is more deeply impressed into the substrate, indicating a substantial pad buttressing the metatarsal elements of the foot. The middle toe is approximately twice the length of the side toes. In some trackways the middle toe seems to have been dragged through slippery mud, leaving a groove where it dug into the substrate. The largest of these tracks is approximately 50 cm long and 42 cm wide, somewhat larger than the one shown in Figure 9. In overall configuration, these footprints are similar to the supposed hadrosaurian ichnogenus *Amblydactylus* from the Aptian–Albian of British Columbia (Currie, 1981; Currie and Sargeant, 1979), and the single ornithopod footprint that was possibly associated with hadrosaurian bones in Alberta (Langston, 1960).

Cf. web-footed theropod

The most problematical footprints at the site are diamond-shaped and range in length from 15 to more than 35 cm. In these tracks the blunt end of the diamond is the leading edge of the footprint (Figs. 10–12). Toe positions are the lateral points in the diamond-shaped impressions, and the central point is the middle-toe impression. These prints possess claw impressions and what appear to be rather distinct impressions of a fleshy connection that united the digits to the position of the terminal phalanges. This web feature is consistently developed through the entire course of several trackways, without change in configuration, leading us to propose that these web impressions were made by webbed feet and not by sediment deformation. These are among the footprints that we earlier identified as pertaining to hadrosaurian ornithopods (Gillette and Thomas, 1983; Thomas and Gillette, 1985).

In these footprints the elongate and padded metatarsal elements came into full contact with the substrate, leaving heel impressions that mark the pointed rear end of the diamond-shaped tracks. Although less deeply impressed into the sediment than the toe impressions, the heel prints are uniformly associated with prints that contain web impressions, without change in configuration. The animals that made these prints routinely walked with metatarsal support.

Footprints that demonstrate similar anatomy, but lacking indication of web impressions, were described by Zhen et al. (1983) from Upper Jurassic rocks in Sichuan Province, China. Their footprints, like the ones at the Clayton site, are diamond-shaped, with distinctive metatarsal impressions. According to their analysis, the Chinese footprints are attributable to the ichnofamily Anomoepedidae Lull, 1904, erected for footprints in North America. Because the Clayton footprints differ somewhat in shape and in their possession of the web impressions, we have decided not to assign the tracks formally to a particular taxon. According to our interpretation, these tracks were made by web-footed theropods that walked with the metatarsal pads in contact with the substrate.

Trackways

Tracks associated in linear fashion, produced by a single individual moving from one point to another, are easily recognized at this site (for example, see the set presented in Figure 11). These trackways record a wealth of information that extends far beyond identification of the animal: direction and changes in locomotion, velocity, weight, hip height and subtle aspects of behavior.

At the Clayton site, the trackways that can be clearly recognized show no preferred orientation, indicating that the animals were not simply passing between points, but instead were milling about, perhaps feeding or engaging in social interaction with others of their kind.

An aspect of one individual's behavior that is preserved in these rocks records a tantalizing episode in dinosaur locomotion. The track-

FIGURE 11. Photograph of an associated set of water-filled tracks pertaining to the "web-footed theropod" form. Arrows indicate the four footprints in this trackway, starting with a left footprint in the foreground. The fourth footprint (at the top of the photo) is the one shown in Figure 10.

way in question was produced by a large ornithopod, apparently sliding in the slippery mud on an unstable surface Unit 2 (Fig. 13). A set of footprints demonstrate a feature that we interpret as the trail of the animal's tail, being used as a brace for stability in the mud. This feature is a sinuous groove that passes through the heel of at least six footprints and is clearly associated with the trackway.

This "tail-trail" records the active use of the tail in one aspect of locomotion, a clear departure from the drooping, passively dragged tail of early reconstructions. The fact that the mud was unstable, indicated

FIGURE 12. Footprint of the largest "web-footed theropod" at the site; forward is to the upper left. The toes are in the upper right, upper left and lower left positions, and the heel impression is at lower right. Not evident in this photograph are distinct claw impressions, to which is attached the web impression that connects the toes. This footprint is approximately 40 cm long and 40 cm wide.

FIGURE 13. Photograph of two of the footprints in the ornithopod trackway with the "tail-trail." Direction of the trackway is upper left to lower right. The groove that passes from the center of the track on the left (actually the heel position) in an arc toward the geologist's pick and into the heel of the track on the right marks the impression of the animal's tail as it was being used to brace the body on an unsteady surface. The tracks are elongated because of slippage in the mud.

by the depth and asymmetry of the traces, further supports the postulated tail-bracing function indicated by this trackway. Although most paleontologists today agree that dinosaur tails were carried well off the ground in locomotion, there are few tangible records that actually document the use of the tail. If this feature represented a "tail-drag" instead, then other iguanodont tracks at the site should have tail-drag features as well.

ACKNOWLEDGMENTS

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