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THEROPOD DINOSAUR TRACKS FROM THE UPPER CRETACEOUS (TURONIAN) MORENO HILL FORMATION OF NEW MEXICO

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Abstract—Field reconnaissance conducted for the Zuni Basin Paleontological Project in May 2005 encountered 13 three-toed dinosaur track impressions on a large block of Moreno Hill Formation sandstone located on U.S. Bureau of Land Management property in Catron County, New Mexico. Based on comparison with described fossil tracks, these were produced by mid- to large-sized theropod dinosaurs of at least three different sizes/ages as described below. The tracks are a rare, and possibly unique, example of Turonian-age theropod track impressions in the southwestern United States.

METHODS OF STUDY

The location of the track locality was noted using a hand-help GPS unit and also mapped on a USGS topographic base map. These locality data were provided to the U.S. BLM with a request for confidentiality due to the vulnerability and significance of the site. The sandstone block and individual tracks were photographed using film, digital and digital video formats. The track face was mapped by setting a level baseline between metal spikes at the base of the sandstone block, designating the lower western corner as the reference measurement origin. A graduated measurement rod and level were then used to collect reference landmark points on the block and at several points on each track according to an x-y coordinate grid system. Individual tracks were also sketched and additional internal measurements were collected for the tracks where this data was available. A schematic map of the track locations and orientations and idealized sketches of representative tracks were prepared by tracing enlarged transparencies of the track photos.

OCCURRENCE

The track impressions are less than a mile from, and slightly higher in the stratigraphic section than, the localities where several recently discovered dinosaurs, *Zuniceratops christopheri, Nothronychus mckinleyi*, a small theropod, and a small hadrosauromorph (this volume), have been recovered and described (Wolfe and Kirkland, 1998; Kirkland and Wolfe, 2001; Denton et al., 2004; McDonald et al., 2006). The paleogeographic and stratigraphic setting of the sites is described in those papers and in Molenaar et al. (2002, and references within). The sandstone bearing the tracks lies within the lower to middle portion of the lower Moreno Hill Formation and is therefore Turonian in age.

The track impressions are located on the north face of a sandstone block that measures approximately 30 feet wide by 9 feet high. The block is a piece of Moreno Hill Formation sandstone that has fallen to the base of slope beneath steep cliffs (Fig. 1). Based on stratigraphic relationships, the track-bearing surface of the sandstone block was originally the upper surface of the lower of two massive cross-bedded sandstones capping the top of the cliff. The track impressions appear to have been impressed into a laterally discontinuous fine mud/silt that overlay the firmer fine- to medium-grained, crossbedded sand beneath.

PRESERVATION ISSUES

The Moreno Hill Formation theropod tracks exhibit fine details that require further study. The fossils are at risk from environmental degradation and the finer material containing the track impressions will eventually peel away from the firmer underlying sandstone. The tracks are also at risk from vandalism. Efforts are currently underway to evaluate potential preservation options in a challenging wilderness setting. At a minimum the tracks will be cast following preparation and additional documentation.

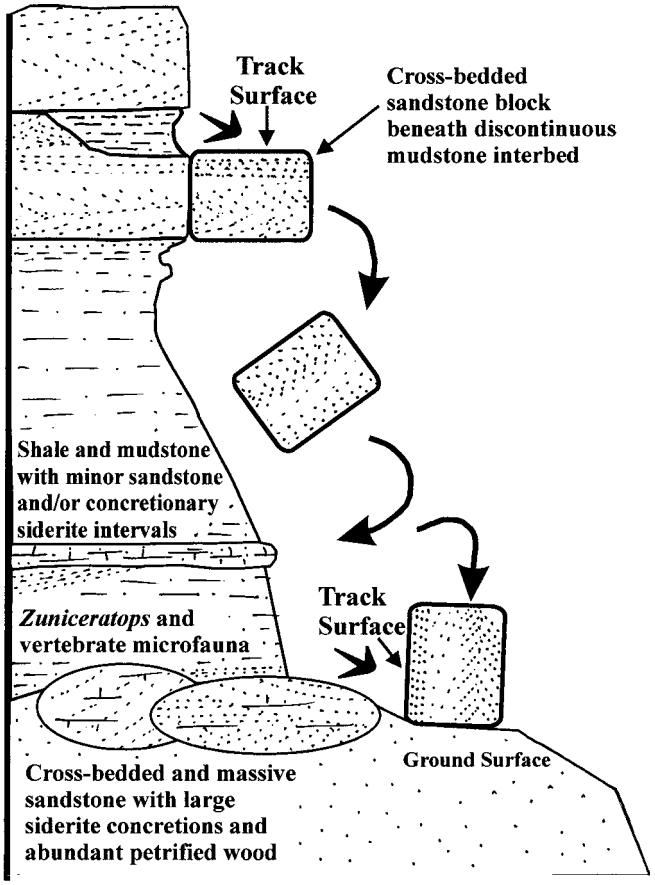

FIGURE 1. Schematic outcrop section of lower Moreno Hill Formation in the "Two Rocks Balanced" outcrop area showing fate of track-bearing sandstone block determined from stratigraphic relations. The track bearing surface was formerly beneath a laterally discontinuous shale lense between two massive sandstones capping the steep cliff. After falling, the sandstone block landed at the base of slope leaving the track-bearing surface vertical.

PRELIMINARY OBSERVATIONS

Preliminary observations have identified at least 13 well-preserved track impressions, apparently representing at least three size groupings (i.e., at least three individual dinosaurs). The largest specimen is approximately 33.5 cm across, the smallest approximately 20 cm across. The track impressions are relatively slender, asymmetrical, three-toed and several exhibit sharp terminal claw impressions indicating probable origin from theropod dinosaurs. Photographs of the best track examples are shown in

Figures 3, 4 and 5. Figure 2 attempts to highlight the relative position of track impressions identified here as small-, medium- and large-sized tracks based on measurement and field comparison. Arrows between tracks of similar size (Fig. 2) provide the suggestion that different track-size groupings follow a pattern, i. e., trending to the right, or perhaps returning along the same path from a nearby location. This observation is tenuous, however, and the arrows are not intended to reflect actual pace/stride for any individual track set except for the two tracks in Figure 4. The tracks in Figure 4 appear to represent a complement set (left and right) for the same individual approximately 80 cm apart (pace length), however, the upper track is still poorly exposed.

Gatesy (2003), Lockley (1998) and Milan (2006) have discussed the various mechanisms and factors that affect track imprint preservation, and the Moreno Hill tracks appear to present examples of several preservation styles. Several of the "small-sized" tracks noted on Figures 2 and 3 appear as underprints exposed after weathering removed the overlying finer mudstone to expose the underlying firmer sandstone. The underprints appear as relatively unsegmented fusiform shapes created by medial-to-distal digit impressions, suggesting a highly digitigrade posture of the track maker.

The better-preserved Moreno Hill tracks shown in Figures 4 and 5 show (but to a lesser degree) features described by Gatesy (2003) and Milan (2006), where relatively deep tracks were made in softer, fine-grained substrates. These include the displacement and subsequent in-filling of fluid-rich sediment as the pes was set down and later retracted upwards. The track impression shown here in Figure 5 shows some of the en-echelon sedimentary fabric within the impression typical of such "deep tracks" and may also preserve an impression of the digit II claw formed as sediment filled the track during/following retraction of the pes.

Because of the morphological variation inherent in tracks resulting from substrate, size and behavior of trackmakers and preservation differences, even within individual track courses, it is probably premature to assign a taxonomic designation to the Moreno Hill tracks. Distinguishing features include prominent asymmetry (indentation) between the inter-digit hypex, relatively wide inter-digit angles, and relative lack of segmentation or observable pads along the slender digits. Several of the tracks are notable for having deeper impressions along the outer digits (III and IV) so that these form a connected comma shape separate from digit II (Fig. 3). Also, the proximal ("heel") margin of the tracks appears indistinct on all the tracks, again suggesting that the digits bore most skeletal weight. However, Milan (2006) has shown how experimental track impressions produced by modern emus on various substrates may produce each of these conditions, including didactyl impressions, under specific conditions.

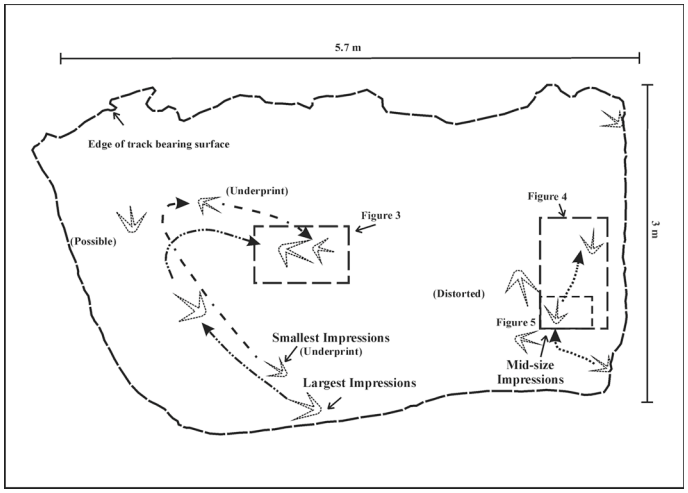

FIGURE 2. Relative size and orientation of mapped impressions from the Moreno Hill Formation (Turonian) Dinosaur Track Site (NMMNH Locality No. 6736), Catron County, NM. Dashed rectangles (location of 3, 4, and 5) refer to photographs figured elsewhere in this paper. Arrows indicate track impressions of similar sizes. Although the arrows are suggestive of a pattern (turn to the right) there are other possible explanations and the arrows are not intended to outline a specific track pathway except for the tracks figured in Figure 4 which appear as a complement set.

FIGURE 3. Largest and smallest track impressions as shown on Figure 2. The largest track is 33.5 cm wide (tip of digit II to tip of digit IV) and 25 cm from proximal to distal (heel to center toe tip) dimension. The smallest track is 20 cm wide by 17 cm heel to toe. Note deeper, comma-shaped impressions formed by digits III and IV relative to digit II and en-echelon sediment deformation structures.

DISCUSSION

Jones (2001) discussed the relative rarity of middle to early Late Cretaceous vertebrate track faunas (from the Turonian in particular) while noting a probable ornithopod trackway in the upper Turonian Ferron Sandstone Member of the Mancos Shale in eastern Utah. Lockley (1998) provided a generalized summary of the type and distribution of theropod dinosaur tracks for the Mesozoic of western North America. Theropod track impressions are noted in great abundance from the Albian-Cenomanian of New Mexico (Kappus and Cornell, 2003), southeast Colorado (Schumacker, 2003), and the Cenomanian Woodbine Formation of Texas (Lee, 1997) and at many Early Cretaceous localities (Farlow and Chapman, 1997). Harris et al., (1996, 1997), describe four-toed theropod footprints from the Maastrichtian of Wyoming, and small theropod tracks are noted (Wright and Lockley, 2001) from the Maastrichtian Laramie/Arapahoe formations of central Colorado. Of the most common recognized ichnogenera figured by Lockley (1998), the Moreno Hill track impressions resemble *Irenesauripus* (Sternberg, 1932), in size and in being relatively slender. However, further preparation and comparison may show the Moreno Hill specimens to be distinct in being relatively broad, with slender, relatively unsegmented digits.

Most importantly, the Moreno Hill Formation theropod track impressions are evidence of bird-like theropod predators in the Zuni Basin that were much larger than any of the theropod skeletal material (excluding the presumably 4-toed *Nothronychus*) encountered to date. The tracks are a rare, possibly unique, example of a medium to large theropod dinosaur along the western margin of the Western Interior Seaway during the Turonian and provide an important missing piece in the Zuni Basin paleontological puzzle.

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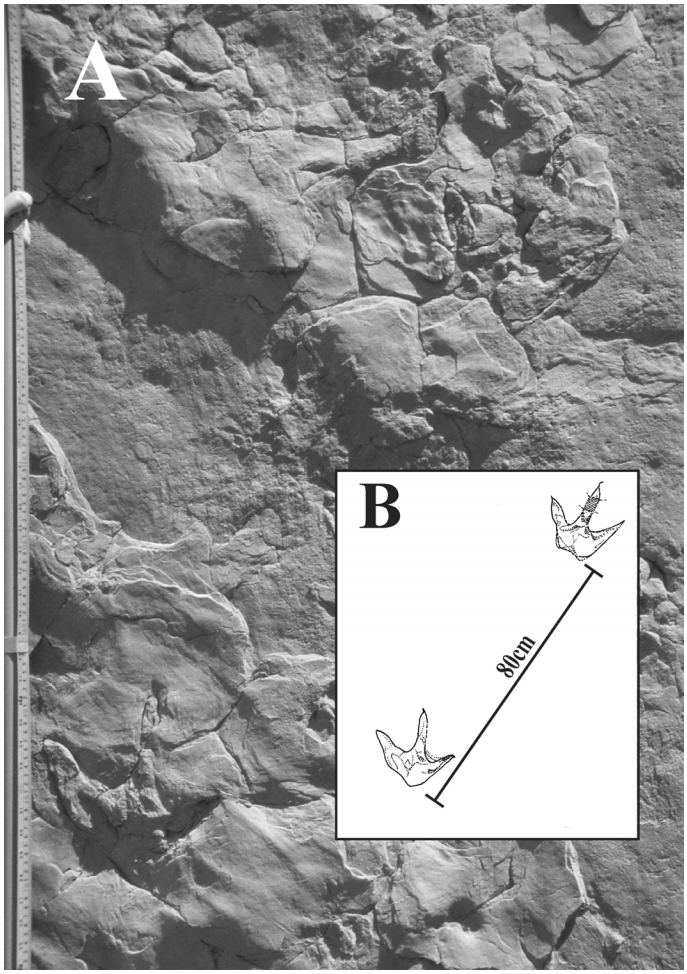

FIGURE 4. A. Medium-sized track impressions representing possible matched (left/right) pair. See Figure 2 for relative location and orientation. Upper track is largely covered and in-filled. B. Idealized sketch of track imprints shown in photograph drawn by tracing enlarged photo transparency. The tracks are measured at 80 cm heel to heel.

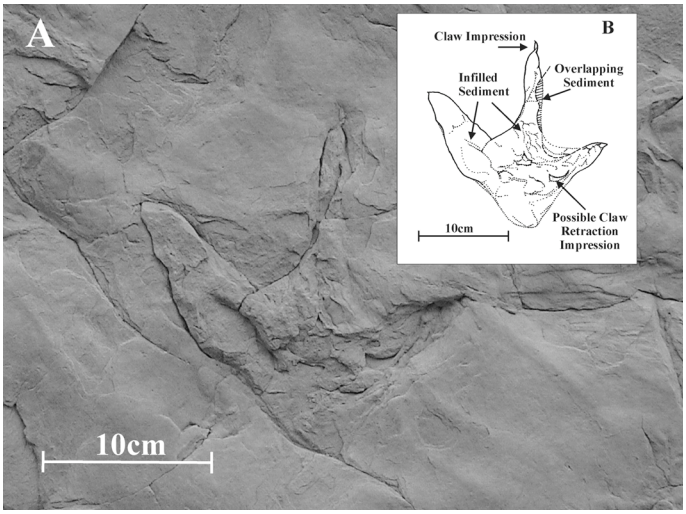

FIGURE 5. A. Well-preserved medium-sized "deep" track with claw impression and possible claw trace from pes retraction noted within digit II. See Figure 2 showing relative location and orientation of impressions. B. Idealized trace of medium-sized track drawn from enlarged photo transparency showing some en-echelon sediment deformation/infill features but ignoring features (including desiccation cracks) outside the direct impression.

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REFERENCES

Denton, R., Ranson, WV, Nesbitt, S., Wolfe, D.G., and Holtz, T., 2004, A new small theropod dinosaur from the Moreno Hill Formation (Turonian, Upper Cretaceous) of New Mexico [abs.]; Journal of Vertebrate Paleontology, v. 24, sup. no. 3, p 52A.

Farlow J., O. and Chapman, R. E., 1997, The scientific study of dinosaur footprints; *in* The Complete Dinosaur: Bloomington, Indiana University Press, p 519-553.

Gatesy, S., 2003, Direct and indirect track features: what sediment did a dinosaur touch?: Ichnos, v. 10, p. 91-98.

Jones, R, 2001, Dinosaur trackway from the Ferron Sandstone Member of the Mancos Shale Formation (Upper Cretaceous) of central UT, Proceedings of the Sixth Fossil Resource Conference, Geologic Resources Division Technical Report NPS/NRGRD/GRDTR-01/01, p.48-51.

Harris, J. D., Johnson, K. R., Hicks, J. and Tauxe, L., 1996, Four-toed theropod footprints and a paleomagnetic age from the Whetstone Falls Member of the Harebell Formation (Upper Cretaceous: Maastrichtian), northwestern Wyoming: Cretaceous Research, v. 17, p. 381-401.

Kappus, E., and Cornell, W.C., 2003, A new Cretaceous dinosaur tracksite in southern New Mexico: Paleontologica Electronica 6,6p.

Kirkland, J. I. and Wolfe, D.G., 2001, First definitive therizinosaurid (Dinosauria; Theropoda) from North America: Journal of Vertebrate Paleontology, v. 21, p. 410-414.

Lee, Y., 1997, Bird and dinosaur footprints in the Woodbine Formation (Cenomanian), Texas: Cretaceous Research, v. 18, p. 849-864.

Lockley, M., 1998, Philosophical perspectives on theropod track morphology: Blending qualities and quantities in the science of ichnology: GAIA, no. 15, p. 279-300.

Milan, J., 2006, Variations in the morphology of emu (*Dromaius novaehollandiae*) tracks reflecting differences in walking pattern and substrate consistency: Ichnotaxonomic implications: Paleontology, v. 49, p. 405-420.

Molenaar, C.M., Cobban, W.A., Merewether, E.A., Pilmore, C.L., Wolfe, D.G., and Holbrook, J. M., 2002, Regional stratigraphic cross section of Cretaceous rocks from east-central Arizona to the Oklahoma panhandle: U.S.Geological Survey, Miscellaneous Field Studies Map, MF-2382, sheets 1-3.

Schumacher, B.A., 2003, An addition to the dinosaur freeway megatracksite, Dakota Group (Upper Cretaceous), Bent County, Colorado: Ichnos, v. 10, p. 255-262.

Sternberg, C. M. (1932), Dinosaur tracks from Peace River British Colombia: Annual Report National Museum Canada, (for 1930), p. 59-85.

Wolfe, D. G. and Kirkland, J.I., 1998, *Zuniceratops christopheri* n. gen. & n. sp., a ceratopsian dinosaur from the Moreno Hill Formation (Cretaceous, Turonian) of west-central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 14 p. 303-317.

Wright, J. and Lockley, M., 2001, Dinosaur and turtle tracks from the Laramie/Arapahoe formations (Upper Cretaceous), near Denver, Colorado, USA: Cretaceous Research, v. 22, p. 365-376.