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A PRELIMINARY REPORT ON A NEW DINOSAUR TRACKSITE IN THE CEDAR MOUNTAIN FORMATION (CRETACEOUS) OF EASTERN UTAH

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Abstract—The Mill Canyon Dinosaur Tracksite (MCDT) is the eighth hitherto reported from the Lower Cretaceous Cedar Mountain Formation of eastern Utah, occurring in the Ruby Ranch Member. It is also the largest, and yields the most diverse ichnofauna. Most tracks are exceptionally-well preserved and indicate a dinosaur-dominated ichnofauna representing at least three theropod, one sauropod and two ornithischian trackmakers. Additional traces are tentatively attributable to crocodilians. Thus, a high ichnodiversity is indicated. Many footprints occur in recognizable trackways including two distinctive tridactyl theropod morphotypes (*Irenesauripus*, and an ichnotaxon indicating a short metatarsal IV). A distinctive didactyl dromaeosaurid trackway (cf. *Dromaeopodus*) is the first reported from North America. Sauropod trackways occur in normal configuration with manus-pes sets, but also as manus-only trackways, some of which show a conspicuous postero-lateral trace of digit V. Ornithopod trackways indicate an iguanodon-size trackmaker. Enigmatic traces tentatively attributed to swimming vertebrates, probably crocodilians, include presumed manus, pes and body or tail traces. Most trackways indicate walking progression on an emergent, but wet (or very shallow, subaqueous) substrate. However, probable crocodile traces and a high incidence of enigmatic "slide" marks indicate vertebrate activity in shallow water, or saturated substrates near a body of water. This preliminary report summarizes previously unpublished information submitted to the Bureau of Land Management (Utah) since 2009, and highlights the fact that the site presents interesting research opportunities and management challenges. The opportunities arise from the large size of the site and the potential to study a much larger area covered only by shallow overburden. In 2013, further excavation of the MCDT was undertaken, leading to new results described in a companion paper in this volume. Management challenges arise from the potential impacts related to studying this large area, natural erosion through runoff and freeze-thaw actions in the dry wash exposing the track-bearing surface and the potential for intentional or unintentional vandalism of exposed tracks due to the proximity of the site to trails heavily used by tourists and motorized vehicles. In addition, this site (as many in the Moab area) has public education and outreach potential.

INTRODUCTION

Although well known for its vertebrate fauna, the Lower Cretaceous Cedar Mountain Formation has yielded relatively few dinosaur tracksites. The first detailed report summarized "five different geographic sites" (Lockley et al., 1999, p. 253) that have yielded only a few isolated tracks. Collectively, these sites provided evidence of theropod, ornithopod, sauropod and possible ankylosaur trackmakers. However, none of these footprints occurred in continuous trackways.

A later discovery from the basal part of the Ruby Ranch Member of the Cedar Mountain Formation within the boundaries of Arches National Park represented the sixth documented site. This site revealed two different track-bearing layers (Lockley et al., 2004). The lower layer yielded several dozen theropod tracks, forming short trackway segments, and the lower layer revealed short segments of sauropod trackways, tridactyl tracks of theropod and possible ornithopod affinity, and tetradactyl and didactyl tracks of possible ankylosaurid and dromaeosaurid affinity, respectively. However, the latter identifications were tentative, and based on isolated tracks with sub-optimal preservation. A seventh Cedar Mountain tracksite dominated by bird tracks was reported by Wright et al. (2006) and is currently under investigation (Foster et al., in prep).

We herein report an eighth site of considerable importance found just south of the Moab airport (Figs. 1-2). The site, designated as the Mill Canyon Dinosaur Tracksite, (CU locality L-00675), was discovered by John Cowan and reported on briefly by Cowan et al. (2010), who noted the presence of three theropod track morphotypes (*Irenesauripus*, and an unnamed tridactyl ichnotaxon similar to *Carmelopodus* and a didactyl dromaeosaurid trackway, cf. *Dromaeopodus*), well-preserved sauropod trackways, iguanodontian trackways, and probable crocodilian traces. These details were presented with appropriate illustrations in a report submitted to the Bureau of Land Management (Utah) in 2009.

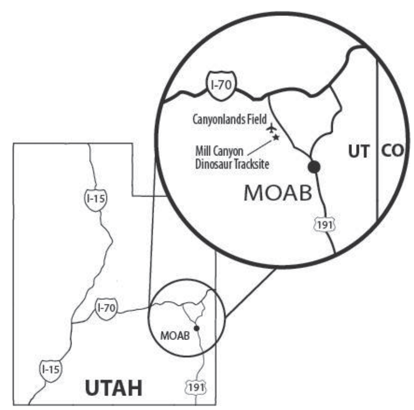

FIGURE 1. Locality map for the Mill Canyon Dinosaur Tracksite.

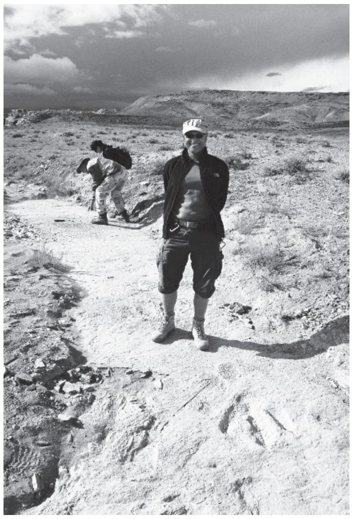

FIGURE 2. Photograph of part of the main exposure of the Mill Canyon Dinosaur Tracksite in the Cedar Mountain Formation. Exposure is as it appeared in 2009 as the result of natural erosion: i.e., before excavation began in 2013.

Due to the unique paleontological resources preserved at this site and the potential for extensive study, as well as its vulnerability to erosion and vandalism, a number of steps were taken to obtain preliminary documentation and preserve the site for further detailed study. These steps, which comply with BLM permit requirements and guidelines, are outlined in the following section. Because the site is considered of great importance, a team was assembled to continue the present study and undertake further investigation, beginning with a small excavation in 2013. The 2013 team is somewhat different in composition from the pre-2013 team that coauthors this paper. For this reason it was deemed necessary to present our results as two separate but complementary papers, appearing sequentially in this volume. The second paper on the MCDT site (Lockley et al., 2014) follows this one

METHODS, MATERIALS AND PREVIOUS WORK

At the time that the site was reported to the senior authors and Bureau of Land Management (BLM) survey permit holders, (MGL and GDG), in early 2009, the discoverer, John Cowen, had evidently already obtained silicon rubber molds of selected tracks. This was done before the present authors had any knowledge of the site. As permit holders, two of us (MGL and GDG) made a preliminary documentation of the site, in 2009, using traditional compass and tape mapping methods, and tracings of representative tracks using clear acetate film. We also prevailed on Mr. Cowen to give the silicon molds to the University of Colorado Denver, Dinosaur Tracks Museum, where they were cataloged as specimens CU 199.69 through CU 199.75 (now re-cataloged in the University of Colorado Museum of Natural History as UCM 199.69-75). Also, in our preliminary 2009 study, we made two additional molds of the didactyl tracks (now UCM 199.67 and 199.68). These molds were later used to make hard copies in plaster of Paris and fiberglass. We reported our preliminary survey activity, including the preliminary map of the main exposure (Fig. 3), to the BLM in 2009, stressing the importance of the site, and its vulnerability to inadvertent damage by cattle and persons using off road vehicles. A preliminary abstract on the site was then published (Cowen et al., 2010).

As interest in the site grew and management concerns heightened, the site was visited by two of us (BHB and NAM) to obtain photogrammetric images of part of the main exposure and selected individual tracks. These procedures are necessary once tracks are uncovered, either naturally or through human interaction, because such valuable paleontological resources begin to degrade (e.g., erosion, vandalism, inadvertent

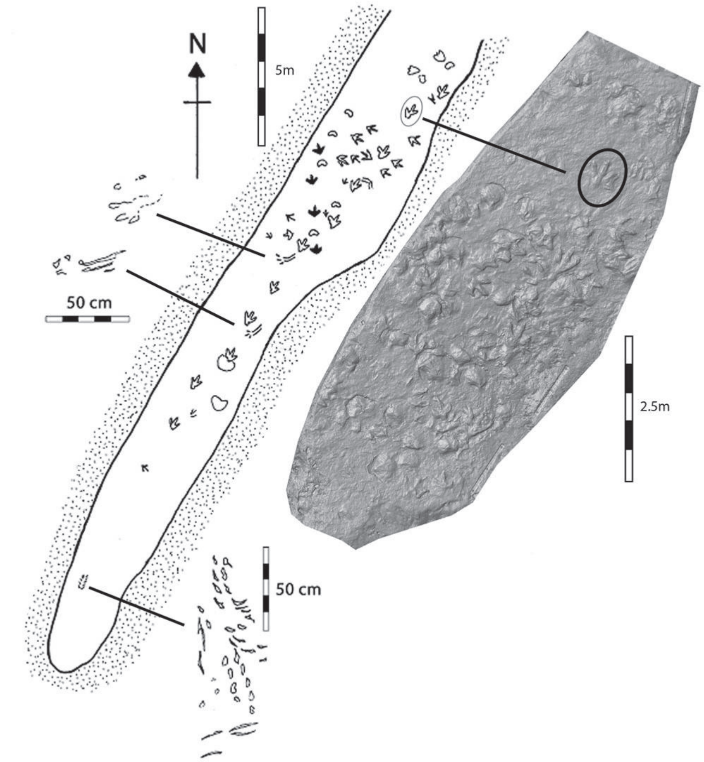

FIGURE 3. Partial map of main exposure of the Mill Canyon Dinosaur Tracksite showing about 45 identifiable tracks. Digital surface model produced photogrammetrically depicted as gray scale with artificial shadowing to enhance the visibility of surface features. Photogrammetric image is at twice the scale of the hand drawn map. Compare with maps in Lockley et al. (2014).

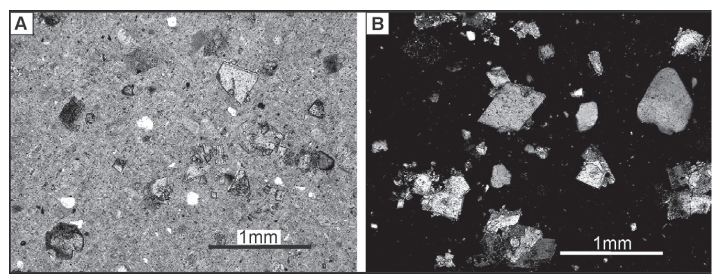

FIGURE 4. Thin section of track-bearing bed in transmitted light (A) and plane-polarized light (B).

trampling), Thus, tracks should be digitally documented as soon as possible after they are exposed. Currently, photogrammetry is the easiest and most cost effective method of digitally documenting a tracksite (Matthews, 2008). This technique is being successfully used at tracksites around the world (Breithaupt, et al., 2004; Matthews, et al., 2006; Matthews and Breithaupt, 2009; Falkingham, 2012).

A hand specimen of the track-bearing substrate was also used to make a thin section for petrographic analysis (by ZD). In 2011, a fence was put around the site to keep out cattle and off-road vehicles.

PRELIMINARY DESCRIPTION OF THE SITE

The Mill Canyon Dinosaur Tracksite is located on Bureau of Land Management (BLM) –administered lands in Grand County, Utah south of the Moab Airport Canyonlands Field (Fig. 1). As show in Figure 2, an important part of the main track- bearing surface is found in a narrow but shallow gully about 25 m long and less than 3-4 m wide. This site is referred to as the "main exposure" to distinguish it from a number of other nearby outcrops, within a radius of 0-50 meters, that also reveal interesting traces. A total of at least 45 discrete tracks and traces have been mapped at the main site (Fig. 3), which consist of a northeast-southwest trending strip of track-bearing surface. Photogrammetric images obtained for most of this main exposure, are combined with the map to show two methods of illustration (Fig. 3).

The track-bearing layer consists of a strongly lithified light-green microcrystalline lithology with a conchoidal fracture. It has proved difficult to define the lithology unambiguously as noted in the following paper (Lockley et al., 2014), which defines the track-bed as a silica rich impure chert. Microfacies analysis indicates that the lithology is terrigenous clastic containing more than 60 % fine- grained matrix (almost opaque in plane-polarized light) and small angular quartz grains and calcareous lithoclasts (Fig. 4). Further details are given in Lockley et al. (2014).

DESCRIPTION OF THE TRACKWAYS

Dinosaur trackways (Figs. 5-7), including a distinctive large theropod trackway (Figs. 5-6), a medium-sized theropod trackway (Fig. 7) and a didactyl theropod trackway (Figs 5-6), a manus-only sauropod trackway (Fig. 8A) and an ornithopod trackway (Fig. 8B) are present. As noted above, nine representative tracks from these trackways were molded with silicon and/or latex and reposited in the CU collections under the numbers UCM 199.67-199.75. Photogrammetric images of important tracks have been collected, including the images presented here (Fig. 6).

Theropod Trackways

The morphology of large theropod tracks (Figs. 5A, 6A) quite strongly resembles that of large Comanchean theropod footprints from the Lower Cretaceous of Texas. This distinctive morphotype was labeled as *Irenesauripus glenrosensis* by Langston (1974) and more recently has been discussed, and inferred to be of *Acrocanthosaurus* origin (Farlow, 2001; Adams, et al., 2010). When Sternberg (1932) originally defined *Irenesauripus* from the Lower Cretaceous of Canada, he inferred that it lacked digital pad impressions. However, the type specimen, preserved in the Royal Ontario Museum, has been examined by the senior author and clearly has digital pad impressions similar to these found in the tracks from the MCDT.

The medium-sized theropod tracks occur just southeast of the main exposure and are very well-preserved, showing fine detail of the pads (Fig. 7). These tracks are similar in two features to those reported from the Ruby Ranch Member of the Cedar Mountain Formation in Arches National Monument (Lockley et al., 2004, figs. 3-4). They have a sub-symmetric posterior margin due to digit IV being short: this is evidently due to the lack of a trace of the proximal metatarsal phalangeal pad. This feature, seen in the much smaller track *Carmelopodus* (Lockley et al., 1998), was interpreted as evidence of a short metatarsal IV, which could elevate the proximal end of the metatarsal-phalangeal joint above the substrate. However, as noted below this does not mean that we can label these tracks as *Carmelopodus*.

This track type also appears to consistently have a very narrow distal phalangeal pad on digit III. These tracks may represent a new theropod ichnotaxon, close to *Carmelopodus* in heel morphology. However, although similar to *Carmelopodus*, which is currently known only from Middle Jurassic strata in the Northern Hemisphere, the Mill Canyon and Arches morphotypes are considerably larger, and also display some other differences, including digit divarication angles. Further study is required before an ichnotaxonomic label can be confidently assigned. For instance, there are also Early Cretaceous forms similar to *Carmelopodus* recognized in China, such as *Wupus* and/or *Xiangxipus* (Zeng, 1982; Xing et al., 2007; Lockley et al., 2013), which need future reassessment in comparison with the Mill Canyon material.

A shallowly-impressed but diagnostic didactyl trackway of a relatively large dromaeosaurid dinosaur (Figs. 5B and 6) is found near the main site on the main surface. This is the first unequivocal trackway of a dromaeosaurid dinosaur from North America. According to Cowan et al. (2010), the tracks are similar to the Chinese ichnogenus *Dromaeopodus* (Li et al., 2007), although significantly smaller, being only 75% as long (21 cm compared with 28 cm for the Chinese ichnite). Lockley et al. (2014) report other dromaeosaur tracks from the Mill Canyon site and argue that the morophology of these ichnites is closer to *Dromaeosauripus*, which is known from the Early Cretaceous of Asia (Kim et al., 2008, 2012; Xing et al., in press)

All other purported dromaeosaur tracks previously reported from North America (e.g., Lockley et al., 2004) are ambiguous and represent poorly preserved material. As shown in Fig. 5B, the trackway configuration is clear. Five tracks were identified in the first-found trackway, of which numbers 2-4 in the sequence are illustrated. They are consistently 21 cm long and 11-12 cm wide with a step that varies between 1.38 and 1.42 m (stride 2.77-2.82 m).

Sauropod Trackways

The first sauropod trackway identified at the site (Fig. 8A) shows only manus traces. Similar isolated manus-only tracks are found elsewhere on this surface. The evidence suggests that the trackmakers were walking on a layer above the layer where the tracks were registered. This is not considered evidence of swimming behavior: see Lockley and Rice (1990) and Lockley et al. (1994, 2014) for discussion. Isolated manus tracks, and trackways with manus-pes sets, have been noted elsewhere in the area and are in need of further study (Lockley et al., 2014).

Ornithischian Trackway

One clear trackway of an ornithopod dinosaur is seen in the main exposure. (Fig 8B). The animal appears to have been progressing bipedally. The tracks are about as long (~30 cm) as wide ~30 cm) with slight inward rotation of the footprint as measured along the axis of the trace of digit III. The step is 110-115 cm.

Other Traces

The main exposure also reveals a number of enigmatic

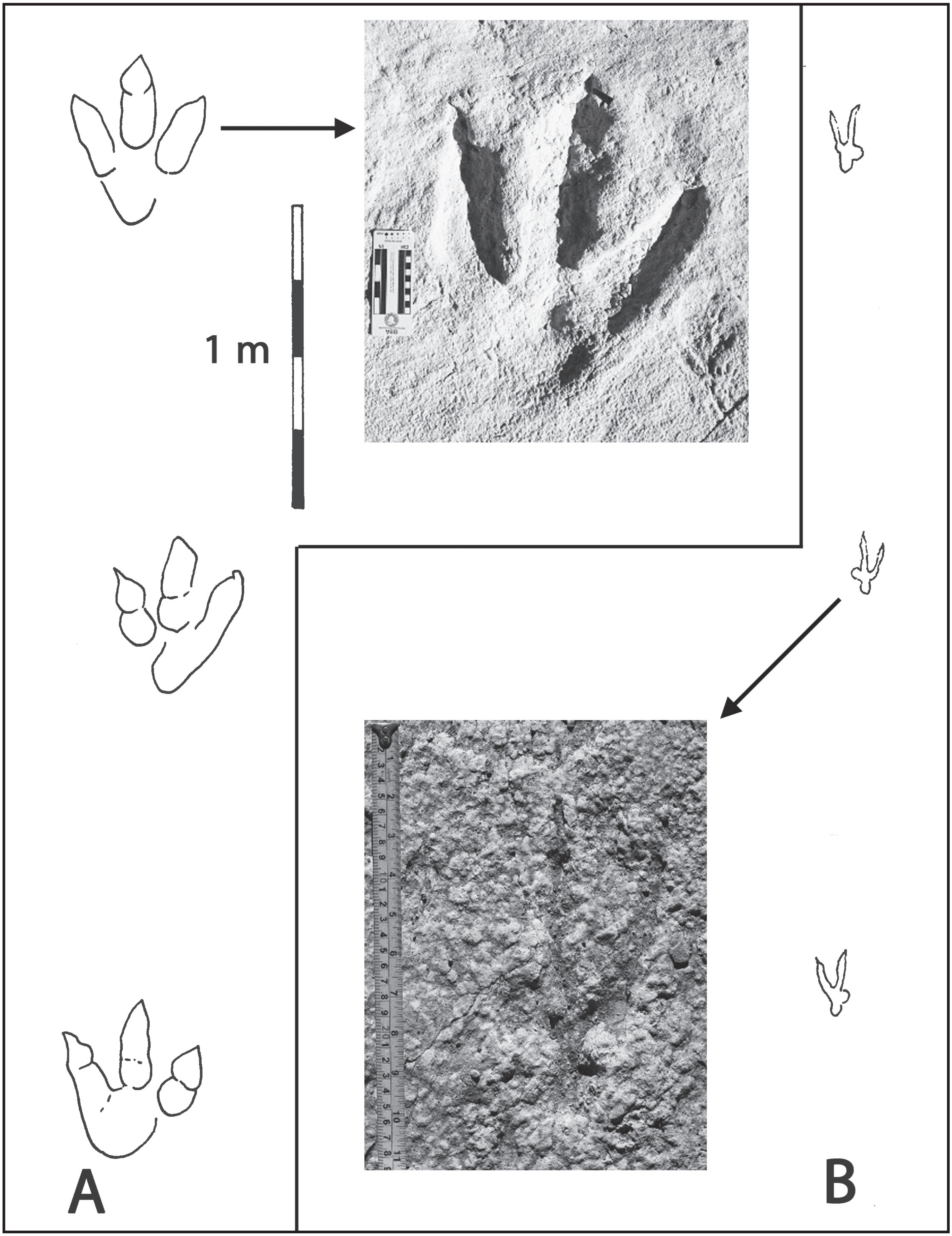

FIGURE 5. A, *Irenesauripus* trackway and detail of track. B, cf. *Dromaeosauripus* trackway and detail of tracks. Tracings shown at same scale. Compare with photogrammetrically-generated images in Fig. 6.

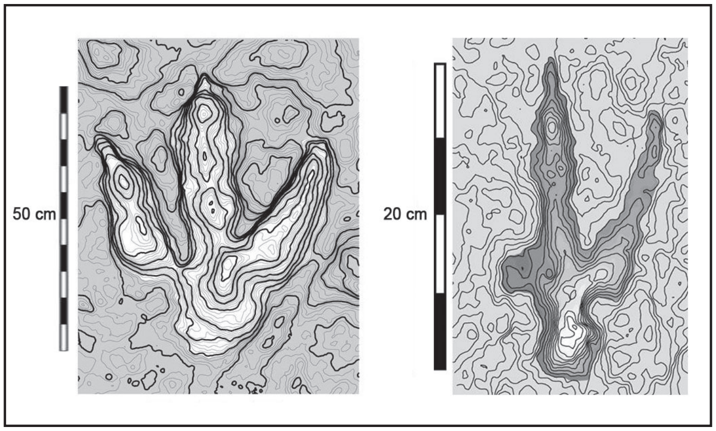

FIGURE 6. Contour maps of large tridactyl *Irenesauripus* track (left) and smaller didactyl *Dromaeopodus* (right) tracks based on photogrammetric images, Compare with Fig 5. Both digital surface models produced photogrammetrically depicted as gray scale with artificial shadowing to enhance the visibility of surface features. Note 1 mm topographic contours interpreted from photogrammetrically produced digital surface model. Underlying colorization derived from digital surface model to illustrate changes in depth correlated to footprint morphology, but do not follow a consistent contour.

traces of uncertain affinity. Among these, the most striking consists of two separate traces, both consisting of a double row of paired indentations that are essentially symmetrical about a median axis between the two rows. Both these sets of symmetric traces are close together with similar orientations. The two rows contain 5-6 pairs of traces (Fig. 9). The rows of traces are about 10 cm apart. In the deeper set (right in Fig. 9), each trace is oval to bluntly fusiform and about 5 cm long and 2 cm wide. In the second set (left in Fig. 9), the individual traces are not as deep and are slightly more elongate. The long axis of these individual traces is sub-parallel to very slightly oblique to the rows in which they occur, thus creating a subtle chevron pattern.

Despite the distinctive and regular pattern exhibited in these traces, we know of no similar examples hitherto described in the literature. These are not the only enigmatic traces in the area. Just east of the main exposure are some large elongate traces, up to 1 meter long, that occur in a paired configuration on a surface with distinctly undulating topography (Fig. 10). We assume that they were made by large vertebrates, possibly crocodilians, but this inference is tentative and needs to be tested by further detailed study of the morphology of these traces.

IMPORTANCE AND VULNERABILITY OF THE SITE

This site is of considerable scientific importance as it is the largest tracksite currently known from the Cedar Mountain Formation (one of the best known dinosaur-bearing units in Western North America), and arguably the most important in the Early Cretaceous. It is also the first site in North America to yield an unambiguous dromaeosaurid trackway. The site has considerable potential for extensive study of a larger area. Future studies will provide a better understanding of the number, and diversity of the tracks and the interrelationship of the various trackways. These studies should also help us understand the enigmatic traces (Figs. 9-10).

Several of the present authors have already begun the second phase of study at the site (Lockley et al., 2014) and we anticipate continuing this work so as to more fully understand and document the site. Due to its location in a naturally incised arroyo, the site is very vulnerable to erosion, by runoff and freeze-thaw action, as well as by human activity. The site periodically floods. Also of concern is the fact that it is located near a major dirt road and camp sites, both heavily used by back country visitors with off road vehicles. Prior to the installation of the fence, there was no obstacle to livestock, in search of ponded water, walking over the site. Likewise, persons unaware of the important dinosaur footprints preserved there may have inadvertently damaged these paleontological resources by walking or riding over them with wheeled vehicles. Of equal concern is the danger of deliberate vandalism or overuse by visitation. That is why further survey and documentation is ongoing and necessary at the site, and will continue as an ongoing, short term priority by the authors and their colleagues: see Lockley et al. (2014)

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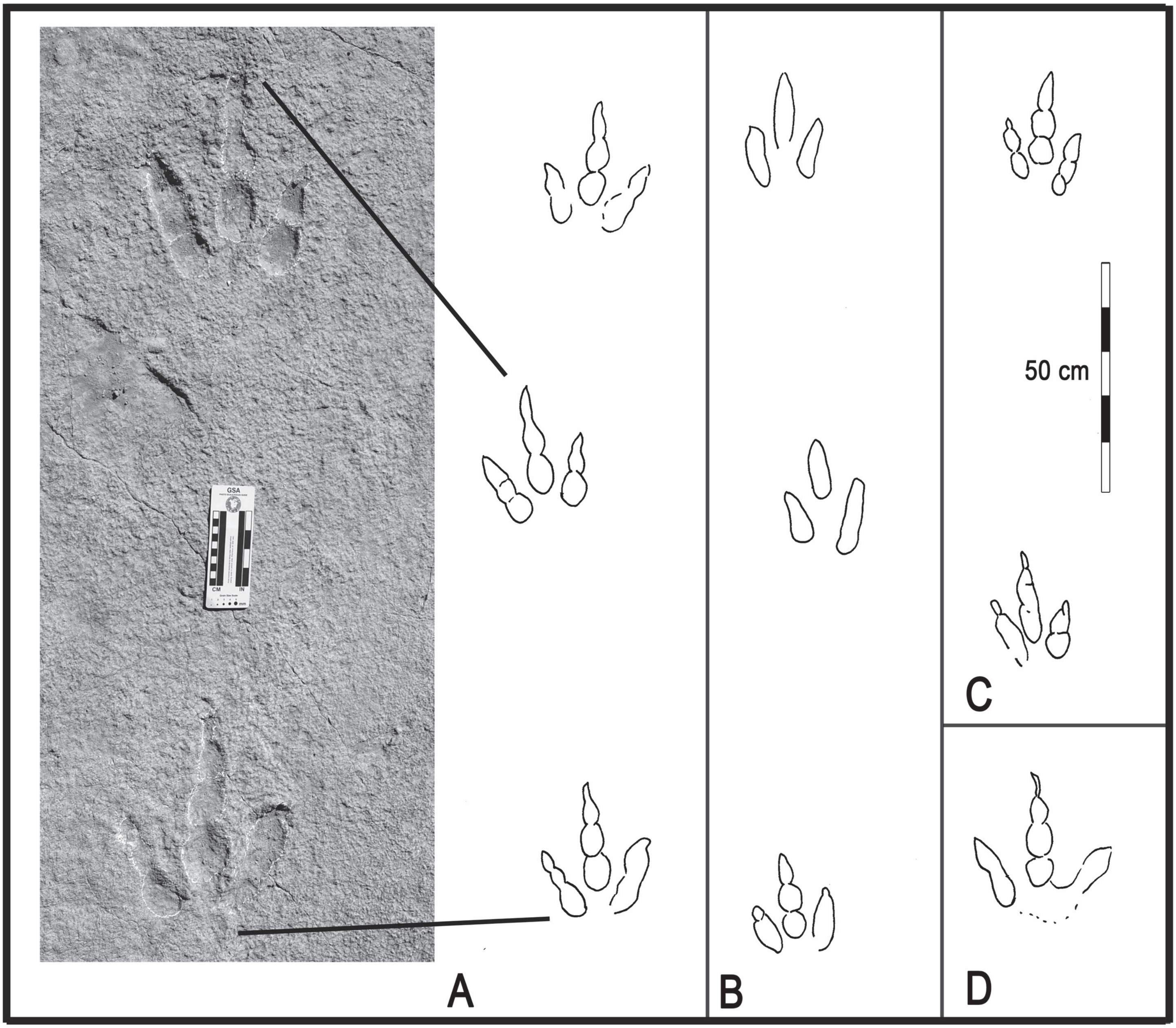

FIGURE 7. Trackways of medium-sized theropod tracks from the Cedar Mountain Formation. A, Photo and tracing of consecutive tracks from the Mill Canyon Dinosaur Tracksite. B and C, Tracings of tracks from the Arches National Monument site (after Lockley et al., 2004). D, A track from an additional small site NW of the main exposure of the Mill Canyon Dinosaur Tracksite site. Tracings shown at same scale.

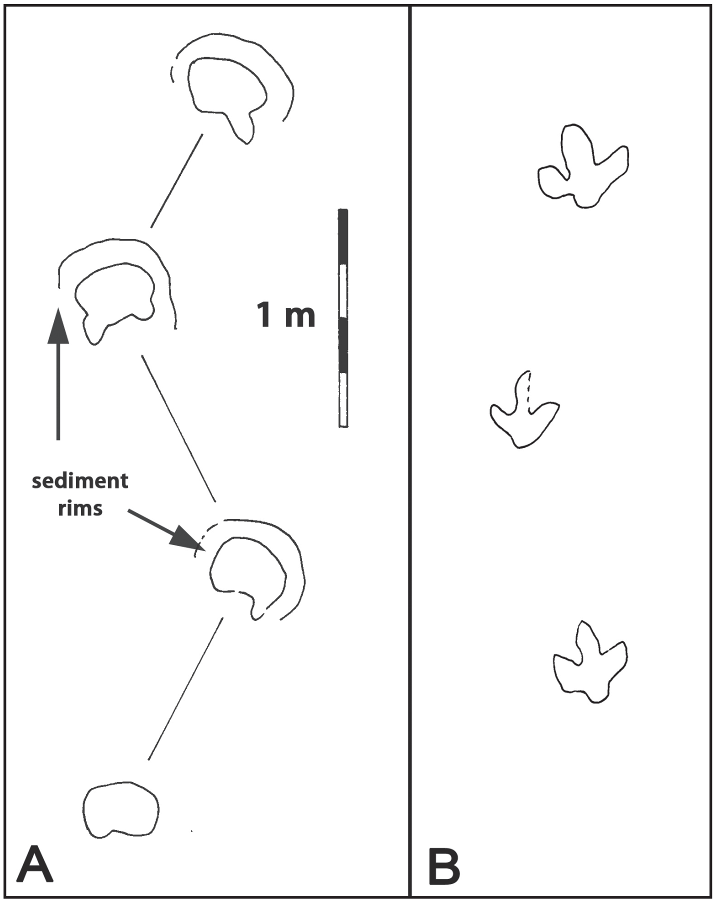

FIGURE 8. A, Detail of manus-only sauropod trackway based on full-sized tracing in the CU Denver archive. B, Ornithopod trackway based on full-sized tracing in the CU Denver archive. Both trackways shown at same scale

FIGURE 9. Detail of enigmatic trace from the Mill Canyon Dinosaur Track-

FIGURE 10. Elongate traces of inferred vertebrate origin.

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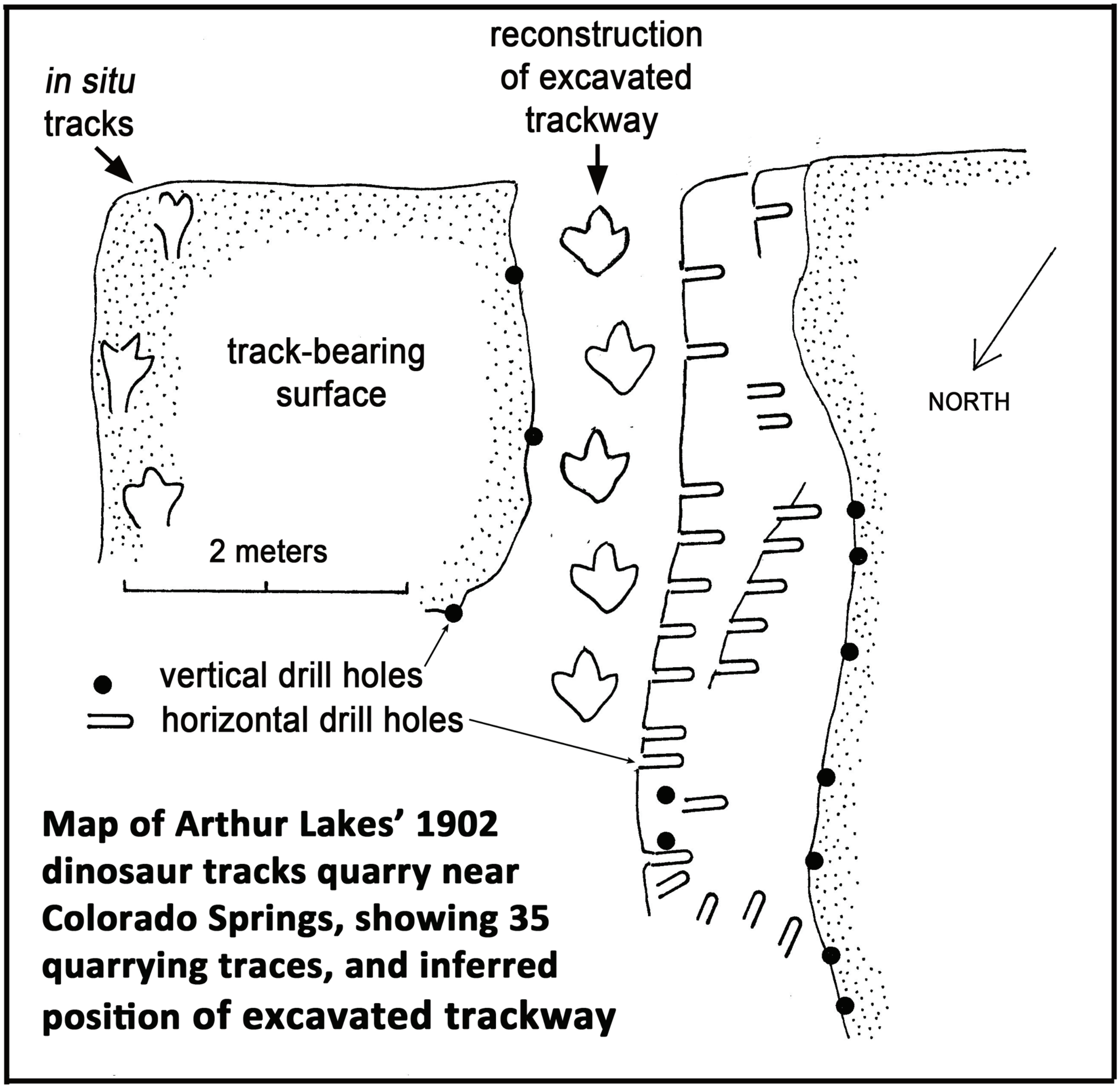

Map of Arthur Lakes' 1902 dinosaur tracks quarry near Colorado Springs, showing 35 quarrying traces, and inferred position of excavated trackway