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NEW EXCAVATIONS AT THE MILL CANYON DINOSAUR TRACK SITE (CEDAR MOUNTAIN FORMATION, LOWER CRETACEOUS) OF EASTERN UTAH

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Abstract—The discovery of the Mill Canyon Dinosaur Tracksite (MCDT) in the Cedar Mountain Formation (Ruby Ranch Member), near Moab in eastern Utah, has generated considerable interest. Following the completion of a preliminary study of natural exposures, reported elsewhere in this volume, an international team was assembled to excavate the site in 2013. Complementary to the preliminary report published elsewhere in this volume, we here outline the initial cartographic results of the 2013 excavation in order to show the extent of the exposed track-bearing surface, the diversity of track types and the excellent potential for further development of the site. Results of the excavation indicate a diverse vertebrate ichnofauna with a minimum diversity of at least 10 named ichnotaxa, including three distinct theropod tracks morphotypes identified as *Irenesauriopus*, a *Dromaeosaurpus*-like form and an un-named ichnite. Poorly preserved bird tracks have also been identified. Sauropod tracks include *Brontopodus* and another morphotype of probable titanosaurid affinity. Ornithopod tracks resemble *Caririchnium*. Footprint density and preservation quality varies across the site and is evidently controlled by variations in the original topography of the site as well as by variation in the substrate and the direction of progression of the trackmakers. Novel sedimentological evidence demonstrates that some manus-only sauropod trackways are undertracks, thereby providing new lines of evidence to weaken the once-popular swimming sauropod scenario. The tracks occur in the upper part of the Ruby Ranch Member, which consists mostly of gray, calcareous mudstone with micritic limestone beds and nodules. However, the track bed is a light gray, impure chert. It is interpreted as a lacustrine or palustrine deposit that was originally limestone, and was later silicified. A large coprolite was found on the track bed; it is composed of plant fragments cemented by calcite and silica, so was probably produced by a large, herbivorous animal, presumably a dinosaur.

INTRODUCTION

Despite being well known for its vertebrate fauna, the Lower Cretaceous Cedar Mountain Formation has until recently yielded relatively few dinosaur tracksites (Lockley et al., 1999) among which the sixth site (in Arches National Park) and the seventh, a bird tracksite, are particularly noteworthy (Lockley et al., 2004, 2013; Foster et al., in prep). However, together with the important report of the bird tracksite, the eighth discovery, that of the Mill Canyon Dinosaur Tracksite (MCDT) in 2009, has added a significant new chapter to vertebrate tracks research in the Cedar Mountain Formation. The site is located in the Ruby Ranch Member, which is the same member in which the Arches National Park site occurs.

Here we demonstrate that the MCDT (Figs. 1-2) is by far the largest and most diverse hitherto known from the Cedar Mountain Formation. To date ~170 tracks have been mapped in an area of ~500 m², while it can be shown unequivocally that there is potential to expose at least 5,000 m² (~100 x 50 m) of track-bearing surface, which would make the site one of the world's largest known from the Lower Cretaceous.

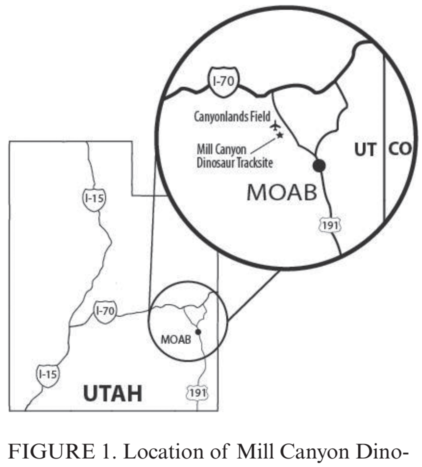

FIGURE 1. Location of Mill Canyon Dinosaur Tracksite, after Lockley et al. (2013)

METHODS, MATERIALS AND PREVIOUS WORK

As reported by Lockley et al. (2014, this volume) the senior authors and Bureau of Land Management (BLM) survey permit holders (MGL and GDG) used traditional compass and tape mapping methods, and tracings of representative tracks on clear acetate film to document the largest natural exposure at the site. We also obtained and cataloged 9 specimens for the University of Colorado Denver, Dinosaur Tracks Museum (now re-cataloged in the University of Colorado Museum of Natural History as UCM 199.67-75). Preliminary survey activity was reported to the BLM in 2009, stressing the importance and vulnerability of the site (cf. Cowen et al., 2010). As a result, in 2011 a fence was put around the site to keep out cattle and off-road vehicles.

Subsequently the site was visited by two BLM researchers (Brent Breithaupt and Neffra Matthews) in order to obtain photogrammetric images of part

FIGURE 2. Photograph of main exposure of the Mill Canyon Dinosaur Tracksite showing dinosaur tracks preserved on a bed in the Ruby Ranch Member of the Cedar Mountain Formation. View is towards the southeast.

of the main exposure and selected individual tracks. Photogrammetry is strongly encouraged by the BLM as an easy and cost effective method of digitally documenting tracksites (Breithaupt et al., 2004, Matthews et al., 2006, Matthews, 2008; Matthews and Breithaupt, 2009; Falkingham, 2012). Images suitable for photogrammetry have been obtained for representative tracks (Lockley et al., 2014), but as yet not enough of the site has been exposed to be able to obtain a continuous large 3D image for the whole site: see Fig. 3 for simplified map of exposed and covered areas.

As the result of collaboration between the University of Colorado Denver and Korean researchers from the National Research Institute of Cultural Heritage (NRICH) and National University of Education, Chinju, a permit was obtained to excavate the site in 2013. This work was conducted by hand using the efforts of most of the authors and several dozen volunteers from the Utah Friends of Paleontology (Moab chapter). An average of about 10-12 persons dug, cleaned and otherwise worked the site for 6-8 hours a day for 7 days, leading to a conservative estimate of at least 500 "man hours" and a maximum estimate closer to 650-700 hours. As a result it was possible to remove many tons of alluvial overburden and expose large areas of track-bearing surface. These areas were mapped, as before, using compass and tape. In addition, eight additional latex molds were obtained (CU 199.82-199.89). We also obtained additional acetate tracings and photographs for photogrammetric analysis, as well as track and trackway measurements (Table 1).

Two sections were measured with a Jacob's staff and a Brunton compass (Fig. 4). The Corral Canyon section was measured approximately 2.2 miles (3.5 km) southeast of the Mill Canyon tracksite, and includes the entire Ruby Ranch Member. The Mill Canyon section includes the upper part of the Ruby Ranch Member from the top surface of the track layer to the base of the Dakota Formation, and was measured in a southwesterly direction from the tracksite. The UTM coordinates (Zone 12S, NAD 27) of the base and top of each section are as follows: Corral Canyon base – 612485E, 4283793N; Corral Canyon top – 612277E, 4283661N; Mill Canyon base – 610144E, 4286571N; Mill Canyon top – 609967E, 4286383N.

GEOLOGY

At the Mill Canyon tracksite locality, only the uppermost approximately 60 feet of the Ruby Ranch Member are partially exposed. However, a complete and better-exposed section of the entire Ruby Ranch Member can be seen near Corral Canyon, about 2.25 miles south-southeast of the Mill Canyon Site (Fig. 4).

The Ruby Ranch section at Corral Canyon consists mostly of gray, calcareous mudstone to claystone with micritic limestone nodules and beds. These lithologies are interpreted as

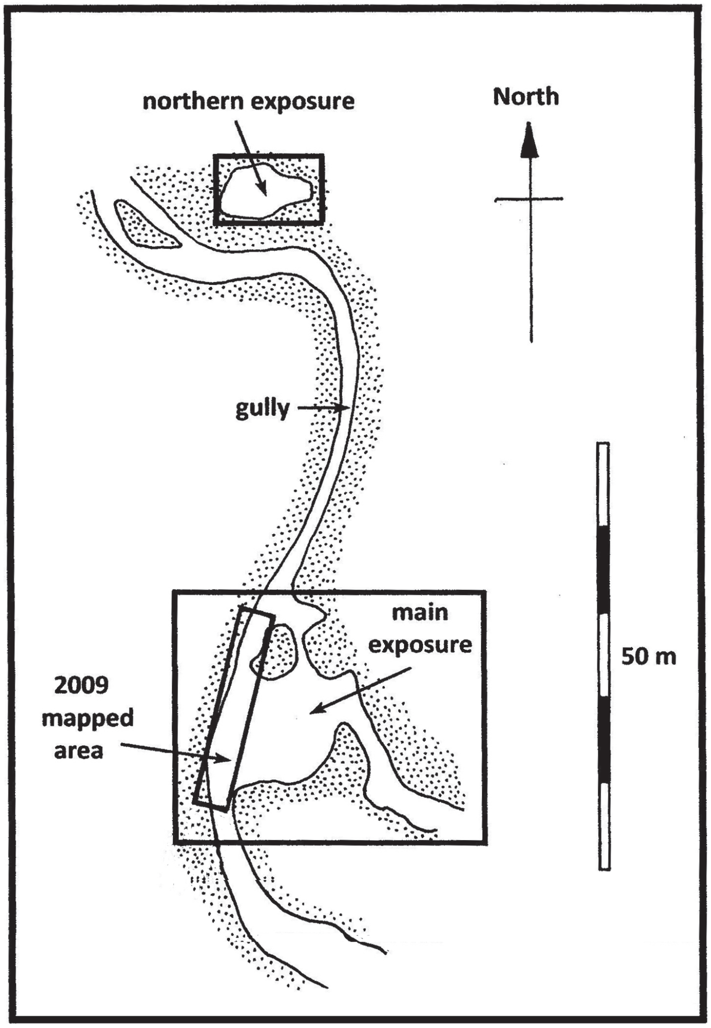

FIGURE 3. Simplified map of the Mill Canyon Dinosaur Tracksite contrasting areas where the track bearing surface is exposed with areas covered with overburden. A shallow naturally formed gully connects the main exposure to the south and the smaller northern exposure.

lacustrine and palustrine deposits, some of which have undergone pedogenic and/or diagenetic modification (Sorensen et al., 2002; Ludvigson et al., 2003). The other common lithology in the Corral Canyon section is beds of gray to tan, fine- to medium-grained sandstone to pebbly sandstone. These have trough cross-bedding, lag deposits, planar cross-bedding and asymmetrical ripple marks. The sandstone beds are interpreted as fluvial channel deposits (Harris, 1980; Kirkland et al., 1997, 1999). One sandstone bed with symmetrical ripples may be a lacustrine deposit. Most of the sandstone beds in the Ruby Ranch Member at Corral Canyon are quartz-rich, grain-supported, and cemented with calcite. However, the highest set of sandstone beds (about 30 feet below the top of the Ruby Ranch Member) is tightly cemented with silica. These beds are matrix-rich, and include a distinctive, granular to pebbly, very coarse sandstone with black chert pebbles.

The contact of the Ruby Ranch Member with the overlying Dakota Formation is thought to be disconformable. However, different workers have used different methods for placing the contact (see, for example, Doelling and Morgan, 2000; Kirkland and Madsen, 2007). We followed Kirkland and Madsen, placing the contact at the point of the highest carbonate nodules and calcareous shale. The contact has significant relief in the Moab area (Young, 1960).

At the Mill Canyon tracksite locality, the uppermost 60 feet of the Ruby Ranch Member are similar to the corresponding deposits at Corral Canyon, consisting mostly of gray, calcareous mudstone with micritic limestone beds and nodules. These, too, are interpreted as lacustrine and palustrine deposits, possibly with some pedogenic and/or diagenetic modification. The track layer is overlain by a fining-upward sequence consisting of the distinctive matrix-rich conglomeratic sandstone seen in the upper part of the Corral Canyon section--fine sandstone, siltstone, and mudstone (Fig. 4). This may be a fluvial deposit. The conglomeratic sandstone provides interesting information about the preservation of manus-only sauropod tracks. Pebbles and granules from the overlying conglomeratic sandstone were pressed into the sediment in the manus-only tracks, but not into the sediment around the tracks. This relationship implies that the manus-only tracks were made by animals walking on a surface above the conglomeratic sandstone, rather than below it. The relationship has a bearing on the argument that manus-only sauropod tracks in the Glen Rose Formation of Texas (and elsewhere) might be undertracks, transmitted downwards by animals walking on overlying layers of sediment (Lockley and Rice, 1990; Lockley 1991; Lockley and Hunt, 1995). The observations at Mill Canyon independently support the hypothesis that the manus-only tracks are indeed undertracks.

The track-bearing layer at Mill Canyon is microcrystalline with porcelain-like luster and easily scratches window glass (Mohs hardness = 5.5). It is light gray (N7) when fresh, and weathers to a light greenish gray (5G8/1). It contains sparse grains of detrital sand; most are quartz, but a few are feldspar. It also contains numerous sand-sized vugs (some of which have rhombohedral outlines) lined with brown calcite crystals. Its hardness precludes common sedimentary rock types, such as mudstone, claystone, limestone, or dolostone. XRD analysis shows large quartz peaks with smaller calcite peaks. Thus, the lithology of the track layer is impure chert. Thin sections reveal a complex diagenetic history. The oldest mineral phase is calcite. It was partially replaced by rhombohedral dolomite. At a later time, the calcite was extensively replaced by chert, but the dolomite rhombs were left untouched. Finally, the dolomite in the rhombs was replaced by calcite, resulting in calcite pseudomorphs after dolomite. Given that the oldest mineral phase is calcite, it is likely that the track layer was originally deposited as calcareous sediment in a lacustrine or palustrine setting, and later silicified. The track layer appears to be at about the same stratigraphic horizon as the silicified interval in the Corral Canyon section.

The hardness of the track-bearing layer is likely to have contributed to its preservation. Most of the Ruby Ranch Member is made of layers of soft mudstone and claystone. Though animals may have walked on these layers, the layers weather in the outcrop in such a way that any tracks are unlikely to survive the weathering process and be discovered. The track-bearing layer is so resistant to weathering that its surface has remained intact after the softer overlying layers were removed by natural erosion, leaving the track-bearing surface well-preserved and therefore easy to discover. The additional parts of the track surface that were uncovered recently through excavation are also likely to be resistant to natural weathering and to damage by tourists. This is a useful feature for a tracksite that is being

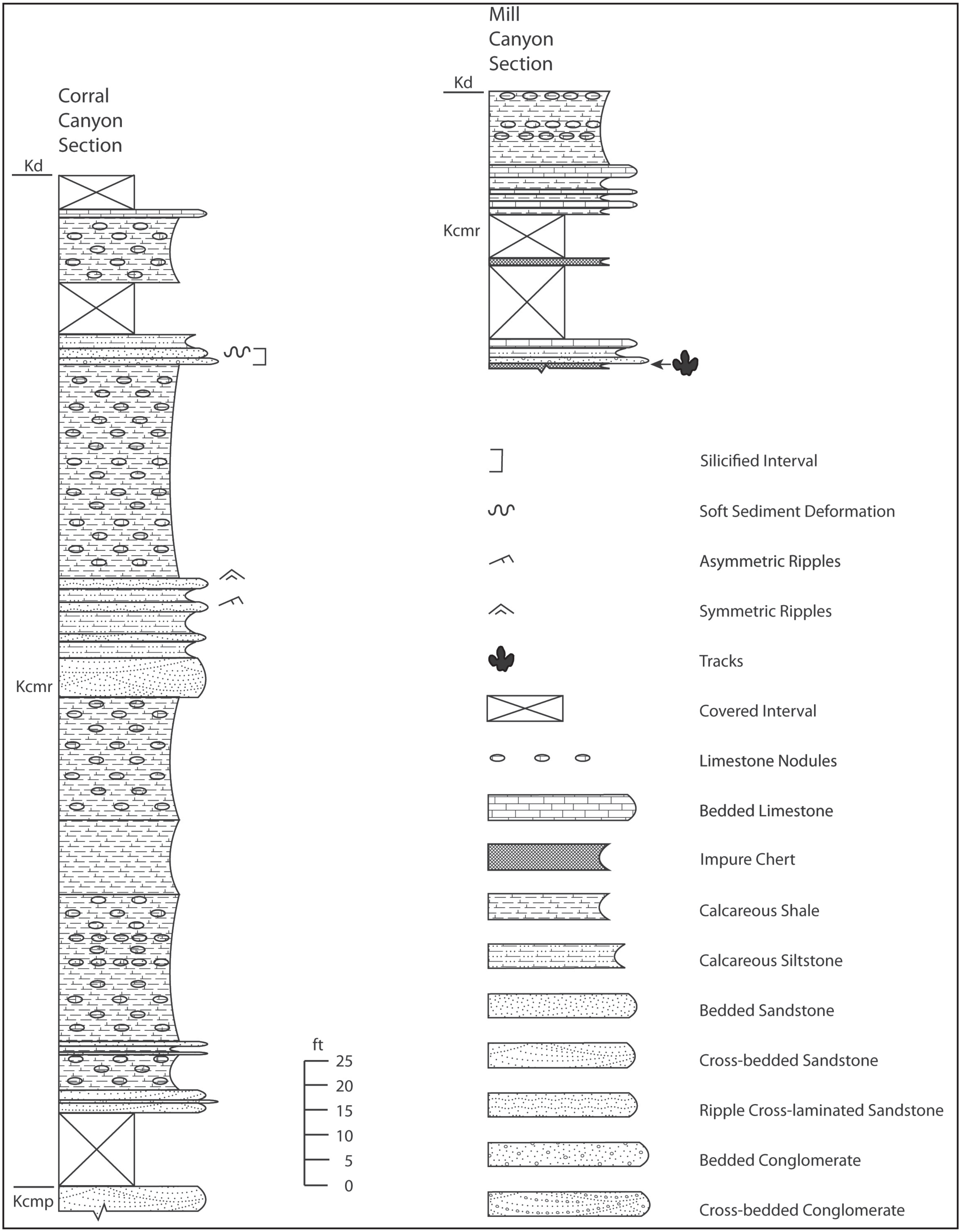

FIGURE 4. Stratigraphic sections of the Ruby Ranch Member of the Cedar Mountain Formation near Corral Canyon and at the Mill Canyon tracksite. Kd = Dakota Formation; Kcmr = Ruby Ranch Member, Cedar Mountain Formation; Kcmp = Poison Strip Member, Cedar Mountain Formation.

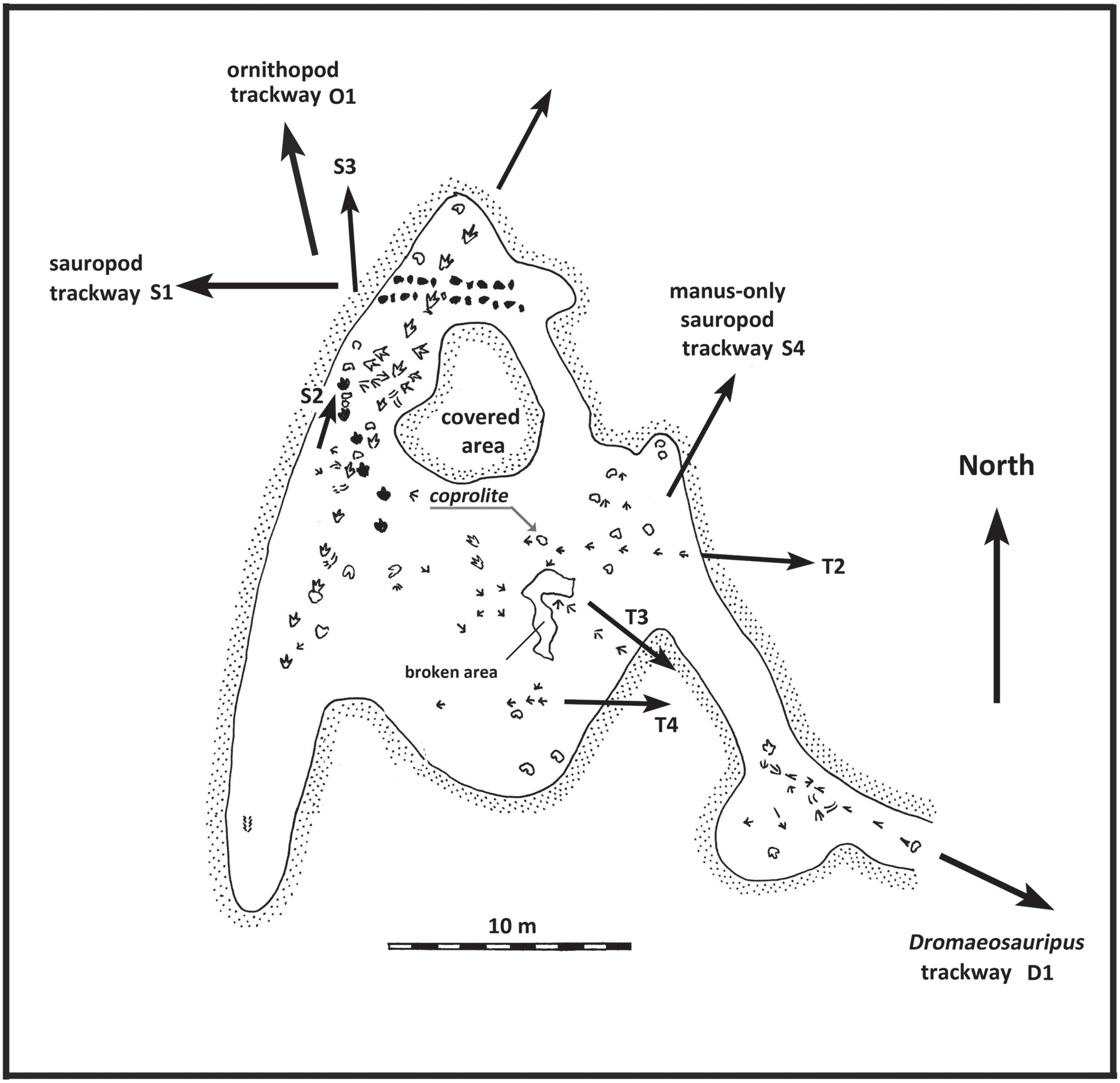

FIGURE 5. Map of the main exposure of the Mill Canyon Dinosaur Tracksite. Note that the western sector of the map represents most of the area exposed before 2012 (see Lockley et al., 2014). Well defined theropod (T1-T4), dromaeosaur(D1) sauropod (S1-S4) and ornithood (O1) trackways are indicated by arrows: compare with Table 1.

considered for public interpretation and visitation. Nevertheless, the track layer is brittle and broken by fractures in some places. This is inferred to be due to the proximity of the Moab fault and/or other tectonic factors, not the inherent resistance of the track bed lithology.

The preservation of tracks in chert is unusual, and helps account for the abundance of well-preserved tracks, which are the main focus of the following sections. Also of unusual interest is the occurrence of a large coprolite found sitting on the track layer (location shown on map, Fig. 5). As discussed below, such track-coprolite co-occurrences are quite unusual, and may require caution in making interpretations that are not unduly speculative.

TRACK MAPPING PROCEEDURES

Traditionally vertebrate tracksites are either mapped in their entirety by hand, or represented in descriptive reports only by photographs and line drawings of representative tracks, in which case complete tracksite maps are not published. However, we mapped all exposed track-bearing surfaces by hand using compass and tape methods. At some sites large areas have been scanned or subjected to photogrammetric analysis in order to produce 3D images suitable for analysis. In theory these latter methods should produce very accurate maps that also provide information on track depth: i.e., not only the 2D outlines. We hope to subject the MCDT to such scanning analysis in the near further when more of the surface is exposed. However, track mapping ("ichnocartography") is undergoing something of a transformation at present, and many new methods are being employed, some still in the testing phase. Although 3D scanning methods are not necessarily more accurate than the human eye's ability to discriminate, or recognize morphological detail, they generally produce accurate cartographic frameworks in which individual tracks and other features of topography, including non-biogenic irregularities in the track surface, are represented. In cases where both methods have been applied, such as at the Jurassic, Red Gulch site in Wyoming, ichnologists can potentially evaluate the relative merits of the two methods in producing maps that are useful for analysis and interpretation. Breithaupt and Matthews (2004) have shown that 3D maps are useful for extracting step and stride measurements, but these can also be obtained directly from the outcrop, as done in traditional studies.

These considerations leave open the question of whether, and how, site maps can be improved by various traditional or new digital methods, and which of the various recently-introduced methods will prove most effective and widely applicable. In the meantime the traditional "compass and tape" maps presented here are a useful preliminary guide to the geography of the site, allowing clear black and white representations of the distribution and location of well-preserved, distinctive or otherwise important tracks and trackways. These maps help highlight preferred trackway trends, but generally cannot be used to extract reliable track and trackway measurements. However, such measurements are recorded independently and can also be obtained from tracings, molds, replicas and 3D images.

OVERVIEW OF THE 2013 MILL CANYON DINOSAUR TRACKSITE EXPOSURE

The MCDT was partially exhumed by natural erosion that has created a small, shallow, sinuous gully on BLM land just north of the Mill Canyon Road, west of highway 191 and south of the Moab Airport Canyonlands Field (Figs. 2-3). In comparison with the narrow, 2-3 meter wide, gully exposure shown in the preliminary site report (Lockley et al., 2014, fig. 2), referred to as the "main exposure," the 2013 excavation opened an area up to 20 meters wide and long: i.e., ~20 meters from east to west and north to south (Figs. 2-3). This continues to represent the "main exposure," which was connected by excavation to the southeast with another previously exposed area.

Forty meters to the north a smaller area, situated in the same gully complex as the "main exposure," was excavated. This area, the "northern exposure," measures ~5 x ~10 meters, respectively, in maximum N-S and E-W directions. Altogether the 2013 excavation has increased the exposed area of track-bearing surface from less than 100 m^2 to about 500 m^2.

DESCRIPTION OF THE MAIN EXPOSURE

The 2013 excavation helped expose an area in an around the main exposure that is on the order of 300 m^2 (Fig. 5), including areas previously exposed by natural erosion and the area mapped during the initial study period (2009-2012: see Lockley et al., 2014, this volume). Within the continuously exposed area a small island of overburden remains with an aerial extent of about 25 m^2. As show in Figure 3, the distribution of tracks in the exposed area is somewhat variable and includes high and low density areas and areas that appear trampled or dominated by surface texture features that make identification of unequivocal tracks and trackways difficult. However, in the central area where track density is low, several clear trackways are visible.

The previously mapped western sector reveals a high density of well-preserved tracks, including unbroken trackway segments of a large theropod and an ornithopod (Lockley et al., 2014, this volume). The central and eastern areas reveal a lower density of tracks, including a few continuous and discontinuous theropod trackway segments, isolated sauropod manus undertracks, a short manus-only trackway segment and a few other tracks of uncertain affinity. An east-west band of dinoturbation or trampling appears to characterize the middle of the area. The main exposure is connected to a smaller southeastern sector with a dromaeosaur trackway by an area where no tracks have been identified.

DESCRIPTION OF THE NORTHERN EXPOSURE

The "northern exposure" consists of area of ~40 m^2 which reveals at least 40 relatively well preserved tracks (Figs. 6-7) including several theropod trackway segments, one of which is attributable to a dromaeosaurid. Parts of the western sector appear heavily trampled. An ornithopod trackway segment was also recognized in the eastern sector. Two poorly preserved bird tracks have also been identified.

DESCRIPTION OF THE TRACKS AND TRACKWAYS

Preliminary descriptions of representative tracks and trackways presented elsewhere in this volume (Lockley et al., 2014) were based on limited track-bearing exposures investigated between 2009 and 2012. The present phase of study 2013 has increased the available track sample from about 45 tracks to more than 170. As indicated above (Figs. 5 and 7) a number of individual trackways are visible that were not previously exposed, and others that had been noted are now represented by longer segments. To avoid repetition of information presented in the preceding paper in this volume we here focus attention on new and supplemental information.

Theropod Tracks

Theropod tracks and trackways are provisionally assigned three ichnotaxonomic labels: *Dromaeosauripus, Irenisauripus* and a *Carmelopodus*-like morphotype of uncertain ichnotaxonomic status.

Dromaeosauripus

Two trackways (D1 and D2: Table 1) attributed to the ichnogenus *Dromaeosauripus* (Kim et al., 2008) have been identified. These include the five-track (four step) trackway in the southeastern sector reported by Cowen et al. (2010) as ichnogenus *Dromaeopodus*, illustrated by Lockley et al. (2013, fig.5), and represented by specimens UCM 199.67 and UCM 199.68. During the 2013 excavations another *Dromaeosauripus* trackway with three tracks (2 steps) was uncovered at the northern exposure (Figs. 6-8). The first track in the sequence (UCM 199.82) is well preserved (Fig. 8A), showing clear pad and claw traces, and is 22 cm long, compared with the 21 cm-long tracks from the southeastern sector of the main exposure. All *Dromaeosauripus* tracks from the MCDT site show slender (gracile) digit III and IV traces, and very faint impressions of the proximal portion of digit II. These seem to be characteristic features of type *Dromaeosauripus* from Korea (Kim et al., 2008) as well as for other *Dromaeosauripus* occurrences. Thus, these gracile features help distinguish the ichnogenus from the more robust *Dromaeopodus*, with wider digit impressions and a robust pad representing the proximal trace of digit II. Thus, *contra* Cowen et al. (2010), we infer that *Dromaeopodus* is so far known only from well-preserved Lower Cretaceous material from the type locality in Shandong Province, China (Li et al., 2007). In contrast, *Dromaeosauripus* appears to be known from two sites in Korea (Kim et al., 2008, 2012), a site in China (Xing et al., 2013) and the MCDT.

Irenesauripus

A distinctive large theropod trackway, revealing at least 13 consecutive tracks (12 steps) is a prominent feature of the western sector of the main exposure: see Fig. 5 and Lockley et al. (2014, fig. 5). The trackway reveals individual footprints more than 50 cm long and 40 cm wide, with steps of ~155 cm. As noted by these authors, the morphology of these large theropod tracks strongly resembles that of large Comanchean theropod footprints from the Lower Cretaceous of Texas, labeled as *Irenesauripus glenrosensis* by Langston (1974). According to Farlow (2001) and Adams et al. (2010), the track maker may have been *Acrocanthosaurus*. As noted elsewhere in this volume (Lockley et al., 2014), where the MCDT tracks are also illustrated, *Irenesauripus* is in need of revision. Sternberg (1932) mistakenly suggested that the track lacked pad impressions, but we have examined the type specimen and found that it has pad impressions similar to those seen in tracks at the MCDT.

The northern exposure reveals a similar trackway (Fig. 8B) with track length and width of ~40 and ~30 cm respectively, and a step of 138 cm. This trackway indicates an animal with a foot length only about 80% the length of the larger track-making individual. Other examples of tracks attributable to *Irenesauripus* have been observed in the main exposure area, but few show continuous trackway segments.

Other Tridactyl Theropod Tracks

A medium-sized theropod track morphotype, referred to as *Carmelopodus*-like by Lockley et al. (2014, fig. 7A) occurs abundantly at the site (Fig. 8C-D) The reason for the comparison with *Carmelopodus* is simply that the tracks consistently lack any heel trace representing the metatarsal phalangeal pad of digit IV (Fig. 8): i.e., they have a sub-symmetric posterior margin due to the trace of digit IV being too short to make contact with the substrate proximally (Lockley et al., 1998). As noted by Lockley et al. (2014) the tracks are similar to those reported from the Ruby Ranch Member in Arches National Park (Lockley et al., 2004, figs. 3-4), which is the nearest Cedar Mountain Formation tracksite to MCDT. While the lack of a heel trace might be considered a preservational phenomenon if seen in only a small sample, this is not the case in the material illustrated here (Fig. 8C) and by Lockley et al. (2014, fig 7A). To date, all examples of this track type from both the main and the northern exposures show this characteristic lack of a heel trace.

There are a number of small tracks that are not easily assigned to any of the three aforementioned categories. Few of these are particularly well preserved. They include small tridactyl tracks on the order of 15-18 cm in length, all of which appear to be represented by single tracks rather than continuous trackway sequences: see Fig 8E for an example of a track apparently showing unusually short traces of digits II and IV. This and other small tridactyl tracks likely represent either small individuals of larger species, or distinctive small species. However, based on the small sample size no further inferences can be drawn.

Bird Tracks

Two probable bird (avian theropod) tracks (Fig. 9) were observed at the northern exposure site. There are not well preserved but they are moderately deep and measure about 4.5 cm long and wide. These dimensions are typical of Cretaceous bird tracks (Lockley and Harris, 2010). The clearest track appears to show a pronounced posterior configuration to one hypex, (presumably between digits II and III), as compared to the more anterior orientation of the other hypex (presumably between digits III-IV). This is also a typical of many avian tracks.

Sauropod Trackways

Sauropod tracks and trackways from the MCDT are variable in morphology and mode of preservation (Fig. 10). Two modes of preservation have been observed: Trackways of animals progressing quadrupedally while creating true manus and pes tracks (Fig. 10C), and manus-only trackways that are inferred to represent undertracks (Lockley et al., 2014, fig. 8A). In addition, track morphology is variable, suggesting the possibility that different sauropod track makers may have been active at the site.

Lockley et al. (2014, fig. 8A) identified a single manus-only sauropod trackway in the western sector of the main exposure where track density is high. They noted that the trace of manus digit V was very prominent, and that the manus tracks were deep with marginal sediment rims. Subsequent investigation reveals that there is at least one shallow pes track (Fig. 10C) associated with this trackway, making it a manus-dominated rather than a manus-only trackway. This proves that the manus-only configuration cannot be explained as swimming behavior.

A similar manus-only trackway was identified in 2013, in the center of the main exposure after excavation of an area with a low density of trackways. Manus tracks in this trackway show a concentration of chert pebbles on the floor of the track, but not outside. Because chert pebbles occur at the base of the fine sandstones overlying the track-bearing surface, and not in the track-bearing beds, it can be inferred that the pebbles were pushed down by animals walking in the thin sandy layers above the track-bearing surface: i.e., they were pushed into the track bed, and no longer sit on, but above the track bed surface. This evidence of the undertrack origin of the sauropod manus-only and manus dominated trackways is independent of other lines of evidence presented by Lockley and Rice (1990) and Lockley et al. (1994), which demonstrate that manus-only trackway configurations indicate normal walking progression, and cannot be used as evidence of swimming behavior.

The manus pes set (Fig. 9C) from the western sector of the main exposure shows diagnostic lateral curvature of the pes claw traces (digits I-II). In this example, the pes track is very shallow, again suggesting that registration of the pes on the main track-bearing surface may have been prevented if the animals were walking on thin layers of sand deposited above the main track-bearing surface. This manus-pes set can be assigned to the ichnogenus *Brontopodus*.

The most complete sauropod trackway from the northern sector of the main exposure (Fig. 9A-B) represents quite a small animal (pes length ~35 cm) that registered a very wide gauge trackway: outer trackway width ~1.00 m and inner trackway width ~35 cm. Although the pes tracks show outward rotation, the pes digit traces are less strongly rotated than in typical *Brontopodus* (Fig. 9C), giving the appearance of titanosaur sauropod tracks from the Fumanya tracksite in Spain (Vila et al., 2013). The trackway is also similar to *Sauropdichnus* named

FIGURE 6. Photograph of the northern exposure looking east, compare with Figure 7

by Castenera et al. (2011). The manus trace shows a well developed digit I (pollex) trace in some cases.

Ornithopod Trackways

One clear four track (three step) trackway of an ornithopod dinosaur was reported from the main exposure (Lockley et al., 2014, fig. 8B). The trackmaker was progressing bipedally, to the north northeast (Fig. 5) with a step of 110-115 cm, making tracks about 30 cm long and wide. The 2013 excavation has uncovered two more tracks in the sequence. The trackway configuration shows slight inward rotation of the footprint relative to the long axis of the trace of digit III. A similar trackway, with an easterly orientation, was uncovered at the northern exposure (Fig. 6).

Other Traces

As reported by Lockley et al. (2014), a number of enigmatic traces of uncertain affinity have been observed on the main exposure and at other nearby outcrops. Two striking examples were illustrated by these authors (op cit., figs. 9 and 10) and need not be discussed in detail here. Some of these traces can be described as slide marks, and indicate that the track makers were negotiating slippery substrates. It is possible that a few of the traces could be interpreted as swim tracks. However, this inference is tentative.

As discussed above, the 2013 excavation has revealed some heavily trampled areas that contrast with other areas were clear tracks stand out against wide areas with undisturbed substrate. It appears therefore that there are recognizable trampled zones. The density of dinoturbation (*sensu* Lockley, 1991) may be related to variations in the original surface topography.

One of the most unexpected results of the 2013 excavation was the discovery of a relatively large and distinctive coprolite that was found right in the middle of the tracksite. This result was unexpected because coprolites are rarely reported as conspicuous features on track-bearing surfaces. The coprolite is well-preserved, sub circular to slightly oval in plan view (Fig. 11) and measures ~ 16 cm long and ~ 15 cm wide, and is

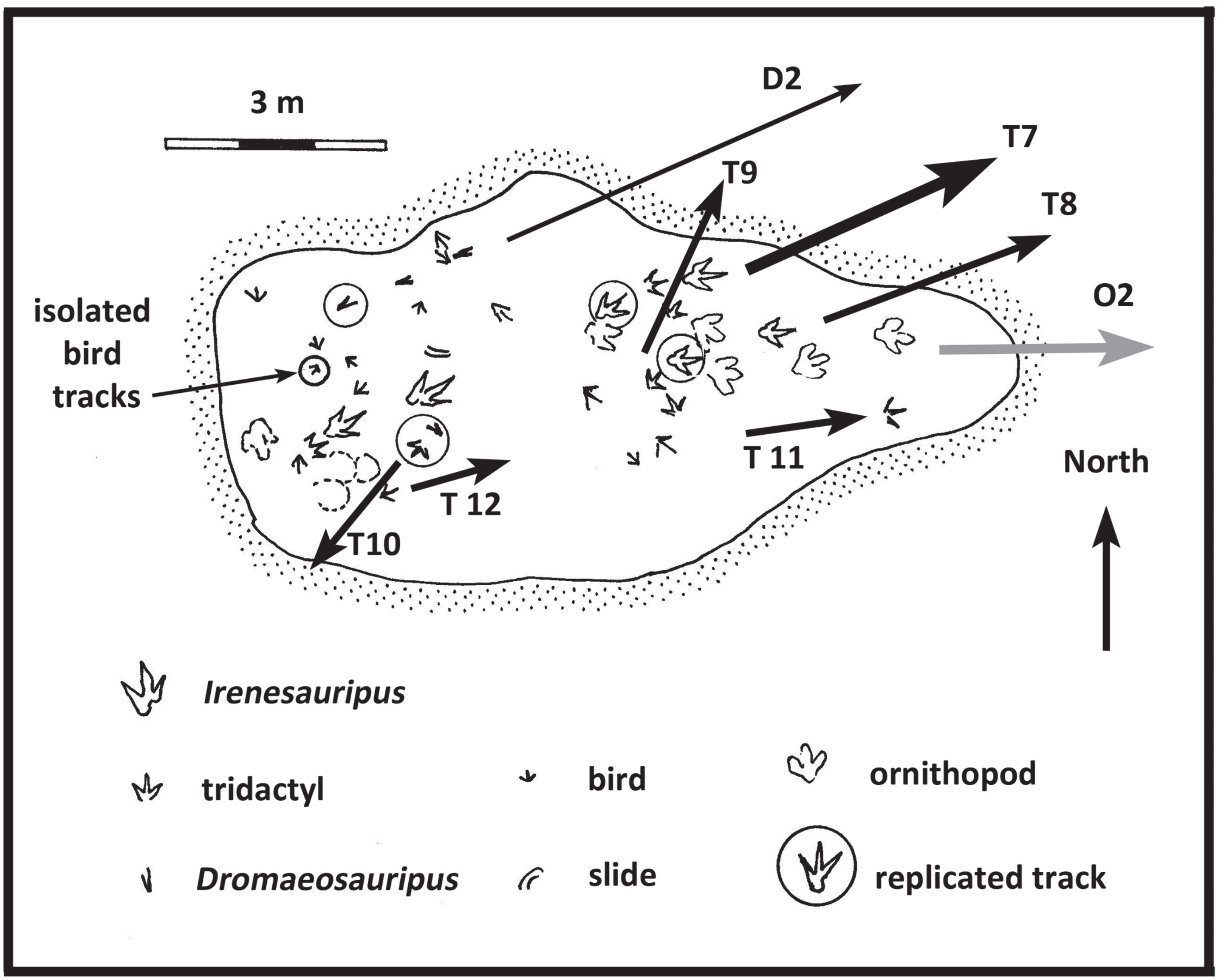

FIGURE 7. Map of the northern exposure: compare with Figure 6. Note northeast-trending *Dromaeosauripus* (D2) trackway, theropod trackways (T7-T12) and ornithopod trackway (O2: gray arrow).

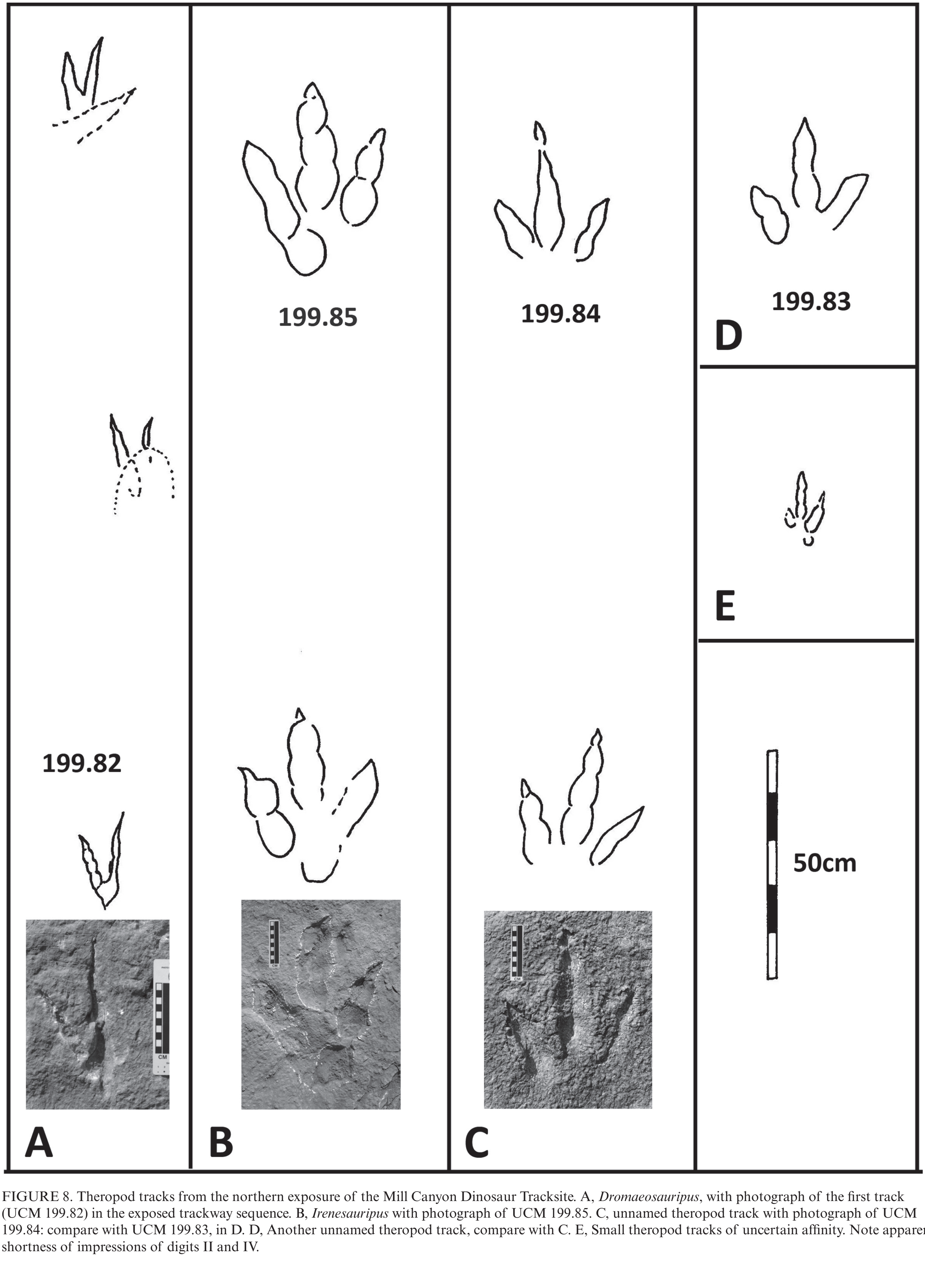

FIGURE 8. Theropod tracks from the northern exposure of the Mill Canyon Dinosaur Tracksite. A, *Dromaeosauripus*, with photograph of the first track (UCM 199.82) in the exposed trackway sequence. B, *Irenesauripus* with photograph of UCM 199.85. C, unnamed theropod track with photograph of UCM 199.84: compare with UCM 199.83, in D. D, Another unnamed theropod track, compare with C. E, Small theropod tracks of uncertain affinity. Note apparent shortness of impressions of digits II and IV.

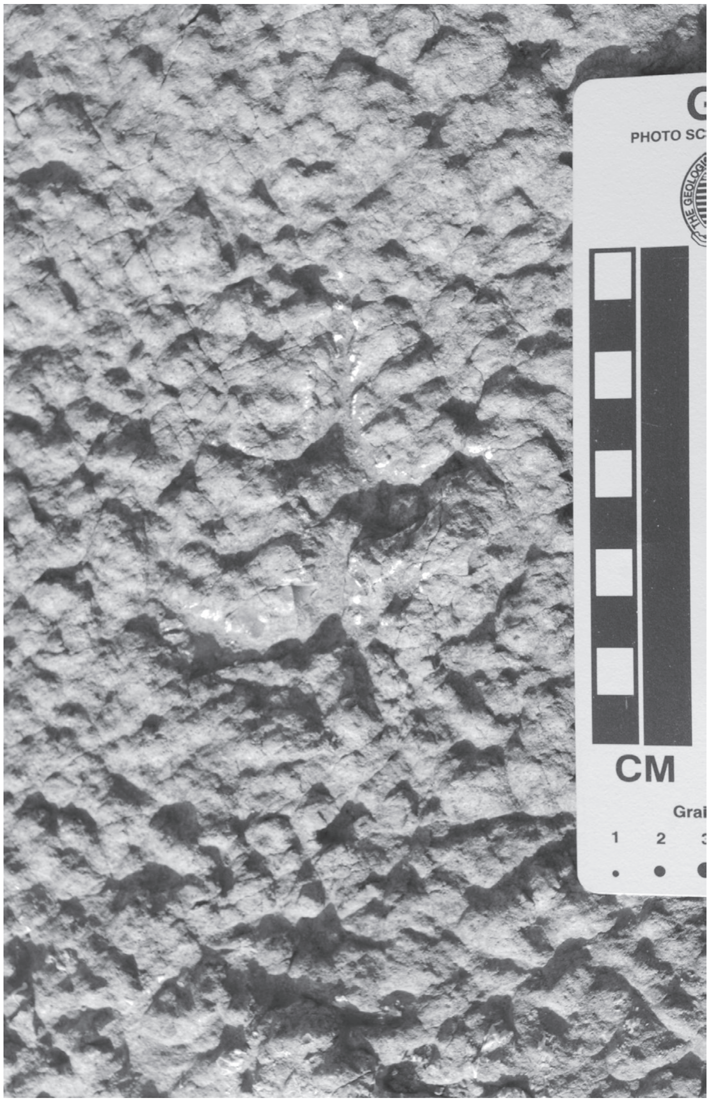

FIGURE 9. Bird (avian) theropod tracks.

about ~6.0 cm in maximum thickness. It has coarsely nodular to irregularly-ridged upper and lower surfaces. A thin section reveals that it consists of a large number of finely-macerated plant fragments cemented by poikilotopic calcite, chert, and chalcedony. Some of these fragments still show recognizable cellular morphology and clearly indicate that the coprolite was produced by a large herbivore.

While we refrain from further detailed interpretation, it is important to note that there is no evidence to connect the coprolite with any of the individual trackways recorded at the site, especially as there are no clear trackways of herbivorous dinosaurs near where the coprolite was found. This does not preclude the possibility that the coprolite was produced by a dinosaur that belonged to an individual representing one of the herbivorous dinosaur groups that registered tracks at the site: i.e., an ornithopod or a sauropod. Such animals presumably traversed the area at some point in time, during, or not too far removed from the period of time when the tracks were made. The duration of this time period cannot be determined with confidence. Thus, we cannot identify the coprolite-producer's trackway from the tracks recorded on our map, or precisely date the "deposition" of the coprolite in relation to the registration of most of the trackways, on the main surface. However, given that we have already identified some of the tracks on the main surface as transmitted undertracks, we infer that the coprolite was deposited before this later phase of trackmaking. Pending further study we refrain from any further inferences about the sequence of track registration and coprolite deposition.

DISCUSSION

This site is of considerable scientific as the largest tracksite currently known from the Ruby Ranch Member of the Cedar Mountain Formation, from the formation as a whole and from this interval in the Lower Cretaceous of the western USA. Several ichnotaxa, including *Dromaeosauripus* and *Irenisauripus,* have not previously been identified in the Cedar Mountain Formation. Likewise, the *Carmelopodus*-like form appears to be a new ichnotype.

Despite revealing at least 170 tracks a significant number occur as isolated specimens, and in some places trackways end abruptly as the results of sudden changes in substrate consistency or the irregular distribution of areas of intense trampling. Unequivocally-identified trackway segments, consisting of two or more consecutive footprints, include the following:

2 *Dromaeosauripus* trackways
2 *Irenesauripus trackways*
4 *Carmelopdus* like trackways
4 sauropod trackways
2 ornithopod trackways

This distribution suggests a saurischuian-dominated ichnofauna in which birds (avian theropods) are also represented. Although theropods collectively dominated the ichnofauna, the variety of theropod types indicates a significant theropod diversity. Presumed crocodilian traces also occur and are in need of further analysis.

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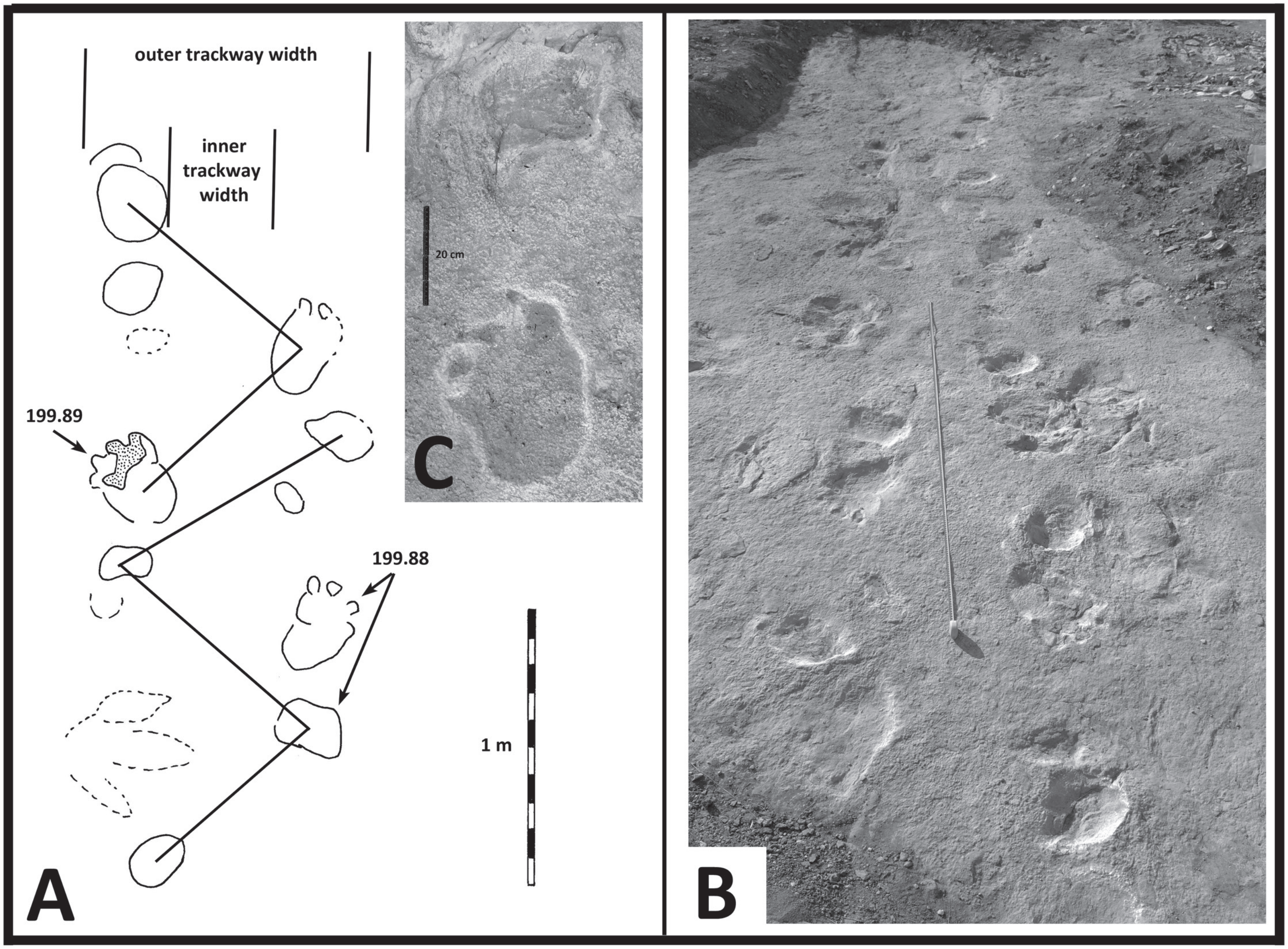

FIGURE 10. Sauropod trackways. A-B, Line drawing and photograph of the most continuous wide gauge trackway. Note pace angulations less that 90º in A. Tape measure in Fig. B is 2 meters long. C, Manus-pes set from western sector of main exposure. See text for details

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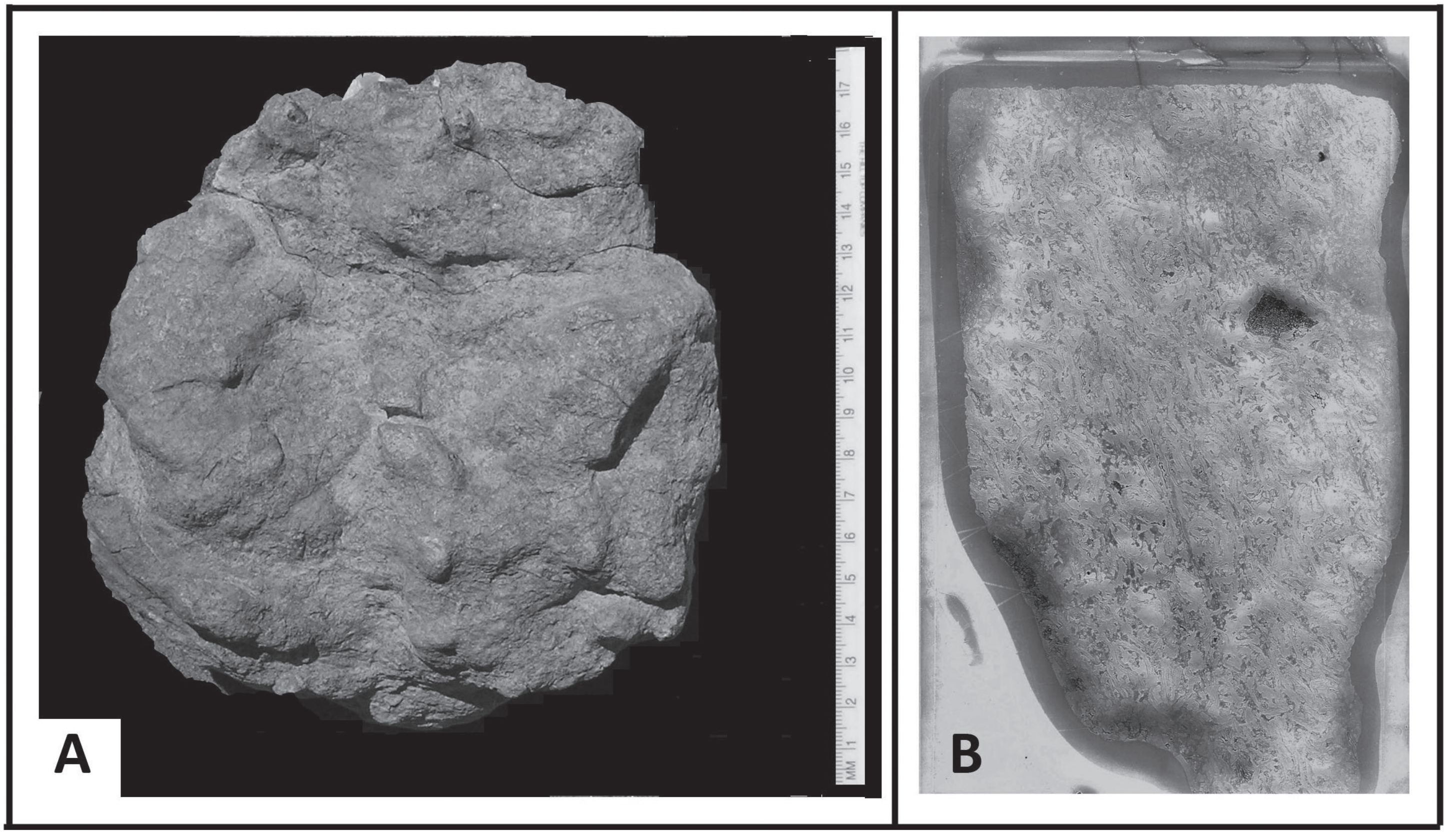

FIGURE 11. A, Coprolite of a large herbivore, presumably a dinosaur. B, Photomicrograph (non-polarized light) of thin section of the coprolite matrix showing abundant, finely macerated plant debris. Longest dimension of thin section is ~3.5 cm.

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Trackway	morphotype	length	width	step	stride	specimen
T1	*Irenesauripus*	55	45	155	312	199.74
T2	new	29	27		262	
T3	new	35	35	137		
T4	new	28	24	88		
T5	?	24	20			
T6	*Irenesauripus*	50	45			
T7	*Irenesauripus*	44	34	135		199.85
T8	new	31	27	138		199.84
T9	new	18	21	95		199.83
T10	new	28	26			
T11	new	28	28			
T12	new	25	23			
D 1	*Dromaeosauripus*	21	12	140		199.67-68
D2	*Dromaeosauripus*	22	9	83-87	169	199.82
S1 pes	sauropod	35	23	70-70	`101	199.88-89
S1 manus	sauropod	24	17			
S2 pes	*Brontopodus*	48	31			
S2 manus	sauropod	22	25			
S3 manus	sauropod	20	32	103		199.75
S4 manus	sauropod	20	30	140		
O1	*Caririchnium*	39	40	115	226	199.69 + 73
O2	*Caririchnium*	42	43	128-145	264	

TABLE 1. Measurements for representative trackways from the Mill Canyon Dinosaur Tracksite