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A HIGH-ALTITUDE SAUROPOD TRACKWAY SITE IN THE JURASSIC OF COLORADO: THE LONGEST KNOWN CONSECUTIVE FOOTPRINT SEQUENCE REVEALS EVIDENCE OF SHARP TURNING BEHAVIOR

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Abstract—An extensive sauropod tracksite, here named the West Gold Hill Dinosaur Tracksite (WGHDT), occurs at a high altitude (~9300 ft/ ~2835 m) locality near Ouray, Colorado. Although known to local citizens and hikers for many decades, the site has not previously been scientifically documented. The tracks, now better exposed than previously, are associated with the upper surface of the locally named "Lower Quartzite," which has been correlated with the Junction Creek Sandstone, and placed by some workers in the Morrison Formation, but correlated by other workers with the Bluff Sandstone. Regional stratigraphic relationships and age data indicate that the tracks are Late Jurassic (probably Oxfordian) in age, and there is an isolated report of a few, very localized tracks at the same stratigraphic level only ~1.8 km away.

The tracks are deeply registered, and the trackway pattern is visually spectacular and easily recognizable, allowing for measurement of step, stride, pace angulation and trackway width parameters typical of sauropods. However, all appear to be pes tracks that are inferred to have overstepped the manus tracks, because the latter are consistently impossible to recognize, as often occurs in sauropod trackways. A few pes tracks have diagnostic, but poorly defined digit traces, but, otherwise, morphological detail reflective of foot anatomy is not well-preserved. Nevertheless, the sedimentary quartzite is extremely durable, and the track-bearing surface, including several sets of ripple marks, has survived glacial scouring, which reveals evidence of the northward movement of ice during the Pleistocene along the axis of the present Uncompahgre Valley. The site is only accessible on foot after a steep climb, and is thus protected from adverse effects by its relatively remote location and extremely resistant lithology.

Although the site only reveals a single trackway, it is of special interest as it demonstrates that the trackmaker registered a meandering trail ~96.3m long (comprising 134 consecutive steps, = 67 strides) that includes a straight northward progression for a minimum of ~45m, followed by a 180^o turn to the south, for ~15 m and then a further arcuate turn to the left (east) for ~36-37m. Trackways attributable to turning dinosaurs are relatively rare, with only six sauropodan examples known from five sites: three in China and two in the USA. Only one of these reveals the same complete "sharp" turn of >180^o to cross its own trackway, as seen at the WGHDT. This site is the second largest sauropod tracksite in the Jurassic of the USA, with an exposed surface of ~3,000m^2, and preserves the longest continuous sequence of sauropod pes prints known globally.

INTRODUCTION

Colorado is well-known for many significant dinosaur tracksites ranging in age from Late Triassic sites in the Chinle Group, and Early to Middle Jurassic sites in the Glen Canyon and San Rafael Groups, as well as the Late Jurassic Morrison Formation, to abundant sites in the "mid" Cretaceous Dakota Group, and the Late Cretaceous Mesaverde Group (Lockley and Hunt, 1995). Despite the abundance of tracksites and the valuable information they contain, there are relatively few very large tracksites representing track-bearing surfaces of more than 100-200 m^2 in extent, and even fewer that encompass areas of ~500-1000 m^2. For example, the "mid" Cretaceous Dinosaur Ridge tracksite, recently ranked number 1 in the USA (Alcala et al., 2016), and thus, by default, Colorado's No. 1 site, has an areal extent of barely 500m^2. As discussed elsewhere in this volume (Lockley and Schumacher, 2020), rankings are based on multiple criteria, such as size of site and number of tracks and trackways, scientific papers, quality of preservation, visitation numbers, site accessibility, associated geological and historical attributes, aesthetic setting, etc.

While measures of site "size" are easily calculated, the "importance" of a site is more difficult to compute objectively, as it is based on multiple criteria beyond size, as noted above: see Alcala et al. (2016). As noted below, all these factors can be used to assess the importance of the hitherto undocumented Ouray or West Gold Hill Dinosaur Tracksite (WGHDT), which, among its other interesting attributes, is quite extensive, occupying a track-bearing surface of ~60 x 50 (=3,000m^2) in a visually spectacular natural geological setting.

Colorado's largest dinosaur tracksite remains, the Purgatoire Valley site in the Late Jurassic Morrison Formation of southeastern Colorado, displayed an areal extent of 5,600m^2 and ~1,300 individual tracks when originally described, in 1986, as "North America's largest dinosaur tracksite" (Lockley et al. 1986). Based on the multiple criteria outlined by Alcala et al. (2016), the Purgatoire site was, in 2016, ranked 5th in the USA, and, based strictly on the size of track-bearing exposure, it ranked 15th on the global list presented by these authors. As of 2020, due to having been enlarged by further excavation the exposed dinosaur track-bearing surface is ~10,000m^2 with some 2,100 tracks recorded, ranking it yet higher based upon the evaluation system employed: see Schumacher and Lockley, (2014) for a report on the first stage of excavation, and Lockley and Schumacher (2020) for update on further excavation and adjusted ranking.

The purpose of this paper is to describe the West Gold Hill Dinosaur Tracksite (WHGDT), near Ouray (Fig. 1) and assess its stratigraphic context, age and ichnological significance. It is, as intimated above, a significant site in terms of its size, and, moreover, it is rare regional example of a high altitude site, situated at an elevation of about 9300 feet (2835 m), in an area best known for its historic prominence as a gold and silver mining district. The rare combination of dinosaur tracks on a glacially scoured surface is also an unusual convergence of biogenic and non-biogenic traces.

PREVIOUS OBSERVATIONS

Until now nothing has been formally published on the West Gold Hill Dinosaur Tracksite. However, the tracksite has long been known to local residents, including one of the present authors (RT), who discovered it as a youngster in the late 1950's when the track-bearing surface was mostly covered. The site is situated on a patented mining claim (see acknowledgments) whose owners have given the present team permission to document the site. However, the site is surrounded by US Forest Service land (Uncompahgre National Forest) crisscrossed by multiple "named" trails used by high country hikers. Over the years, through a combination of natural weathering of the thin mossy vegetation that covers parts of the site, and sporadic cleaning of the track-bearing surface by locals and other hikers, portions of the site have been exposed: i.e., those areas with recognizable tracks. This, in turn, has allowed photographers

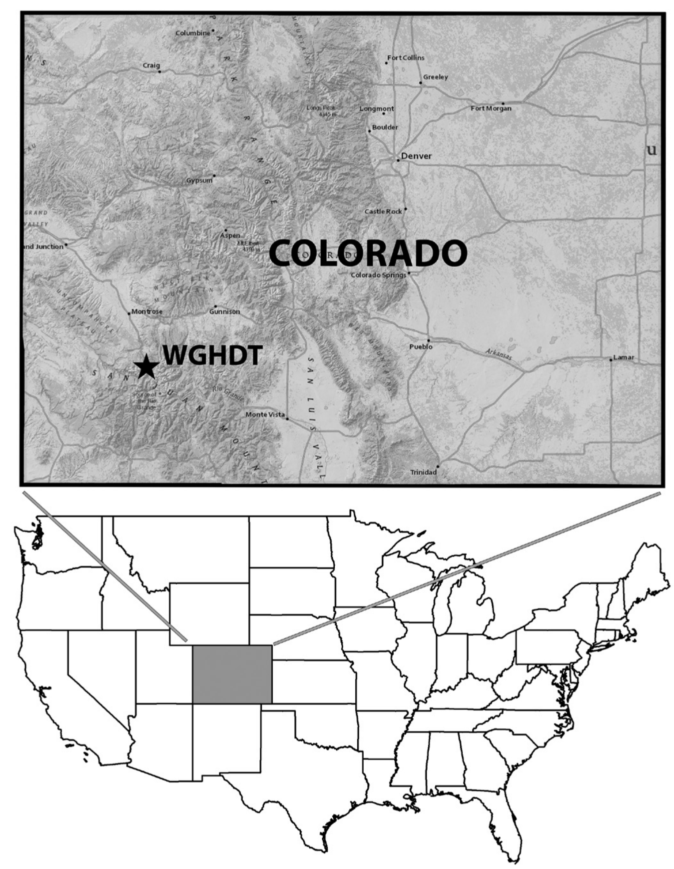

FIGURE 1. Location of West Gold Hill Dinosaur Tracksite (WGHDT) in the Ouray Mining District of southwestern Colorado; see Fig. 5 for stratigraphy.

to take pictures of the tracks, some of which have appeared on websites. To the best of our knowledge, however, photographers who have posted pictures of the site, have apparently deliberately not divulged the precise location beyond such generalizations as "above Ouray." But, the location is likely to become known as the bedding plane surface, and even individual tracks are large enough to be visible on Google Earth images!

These factors notwithstanding, the present authors, while further clearing the site, to show all the tracks (Figs. 2-4), have maintained the stewardship ethic, generally standard practice among researchers, of not divulging precise locality data. This ethic, generally required by state and federal legislation, notably the Paleontological Resources Preservation Act of 2009, is also upheld by public land managers, especially for sensitive sites not developed as known destinations. In the same "respect for resources and property" traditions most private landowners, and the researchers they admit, avoid divulging the location of important or sensitive sites. Because the tracks at the present study site are in a unit known as the "Lower Quartzite," which is well indurated and extremely resistant, and situated "off the beaten trail," we assess the potential for damage to individual tracks and the track-bearing surface as a whole to be extremely low.

GEOLOGICAL SETTING

Description of the Site

The track-bearing surface is situated on a near-horizontal, glacially-polished silicified sandstone that represents the uppermost surface of the "Lower Quartzite." Drone photographs (Figs. 2-3) reveal that the trackway has a visually spectacular loop configuration (Fig. 4). Evidence of Pleistocene glacial scouring, testimony to glacial activity at an altitude of ~ 9300 ft, is registered as striations and polishing on this resistant surface. In places the glacial scour has eroded the tracks preferentially on their northern rims, though only slightly, to show that the ice moved parallel to the axis of what is now the Uncompahgre Valley, from south to north. However, the hardness of the quartzite has rendered the tracks largely resistant even to the erosive force of glacial scouring. Nevertheless, the individual tracks, attributable to sauropods, were not well preserved in terms of detail at the time of registration/preservation prior to burial and lithification and appear as a series of quite deep, oval impressions attributable to the hind feet (pes) with no unequivocal evidence of front foot (manus) impressions. But, even in the absence of manus tracks, which were likely overprinted by the pes tracks, it is possible to determine the direction of travel of the trackmaker by the outward rotation of the pes tracks and the faint traces of claw impressions in a few tracks.

Stratigraphy

The WGHDT is at the top of a ~16' (~ 5 m) thick sandstone unit locally referred to as the "Lower Quartzite", and was labelled "bed A" by O'Sullivan (1992) and assigned to the basal section of the Tidwell Member of the Morrison Formation (Burbank and Luedke, 2008) (Fig. 5). These beds are durable, fluvial quartz sandstone (O'Sullivan, 1992) with fine to medium, subangular to well-rounded grains cemented with either carbonate or silica (Burbank and Luedke, 1962, 2008). Different stratigraphic nomenclature has been applied to this unit in the literature, and it has been placed within the Tidwell Member of the Morrison Formation (O'Sullivan, 1992; Burbank and Luedke, 2008), the Junction Creek Member of the Morrison Formation (Kelley, 1957), or the Junction Creek Member of the Bluff Formation (Lucas and Heckert, 2005; Lucas, 2017).

Here, we prefer this last usage, and place the WGHDT at the top of the Junction Creek Member of the Bluff Sandstone/ Formation (Fig. 5). In southwestern Colorado, the Bluff Sandstone is up to 152 m thick and consists of two members, a

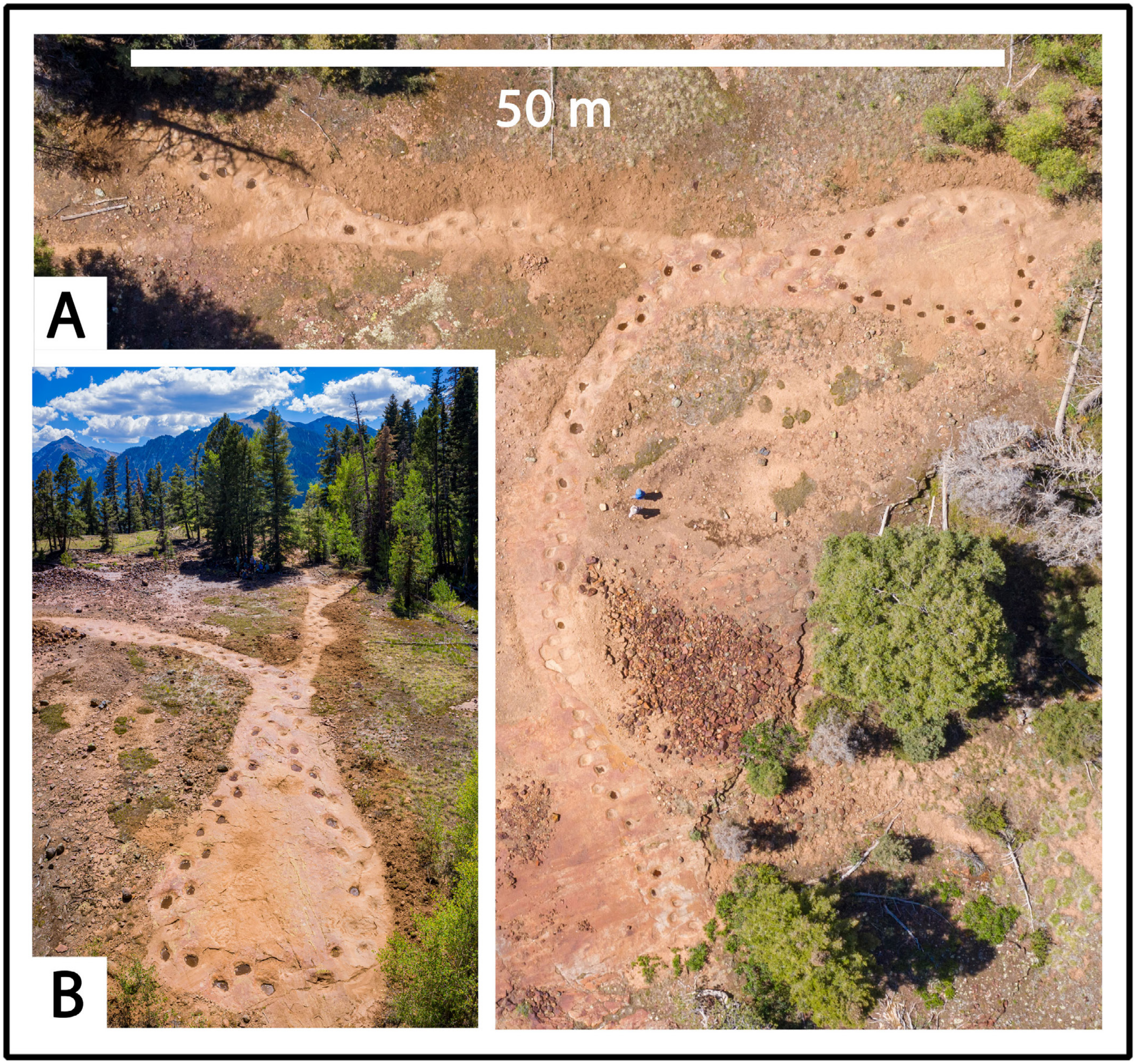

FIGURE 2. **A,** Aerial drone photographs of the WGHDT, showing complete trackway in plan view (note 50 m scale). **B,** Aerial drone view of turn around loop viewed from the north, looking south. Compare with Figures 3 and 4. Photographs courtesy of Mike Boruta. Published with the permission of the Jack Charles Real Estate Trust

lower Junction Creek Member and an upper Recapture Member (e. g., Lucas and Anderson, 1997, Lucas, 2014, 2017) (Fig. 1). The lower member is primarily eolian sandstone that was the Junction Creek Sandstone of Goldman and Spencer (1941). In the area of Ouray however, the Junction Creek beds thin to only 5 m, and lack evidence of eolian deposition. In the most recent contribution to the regional stratigraphy, Kirkland et al., (2020, p. 137) note that "researchers have disagreed about nomenclature and correlation of…Upper Jurassic stratigraphy … [in southeastern Utah] … the type area for the Bluff Sandstone, Recapture, Westwater Canyon, and Brushy Basin Members of the Morrison Formation." Although these authors place the Bluff and its equivalents in the Morrison Formation in southeastern Utah, it is outside the scope of this paper to extend the stratigraphic discussion to the Ouray district, and the stratigraphic position of the track-bearing unit.

Locally and historically, the track bearing unit at WGHDT was called the "lower quartzite of miners" due to local hydrothermal alteration of quartzite within the central part of the Uncompahgre Mining District (Kelley, 1954; Burbank and Luedke, 2008). Regionally, the Bluff Sandstone is bracketed by Late Jurassic units that indicate is early Late Jurassic (probably Oxfordian) in age (Trujillo and Kowallis, 2015; Lucas, 2017).

It is of historical interest to note that "a fossilized footprint was found in the Lower Quartzite near the boarding house of the American Nettie Mine" (Burbank and Luedke, 1962, 2008). The track-bearing surface at this location, 1.8 km from the large WGHDT location, has been observed by two of the present authors (ML and RT) and is a very small area, but also occurs on the upper surface of the quartzite. The surface reveals 2-3

FIGURE 3. Views of the West Gold Hill Dinosaur Tracksite (WGHDT) trackway (September 2020). **A,** Proximal (beginning) portion of trackway oriented and looking north (with cleaning in progress). **B,** Turnaround point on northern perimeter of site, looking south, with trackway segment on left representing progression towards the camera (compare with Fig. 2B); **C,** Distal (ending) portion of trackway heading east towards the camera (note high glacial polish on this portion of site). In all cases, water in the tracks was the natural result of rainfall. Compare images with map (Fig. 4). Photographs A and C by M. Lockley. Photograph B by B. Schumacher. Published with the permission of the Jack Charles Real Estate Trust.

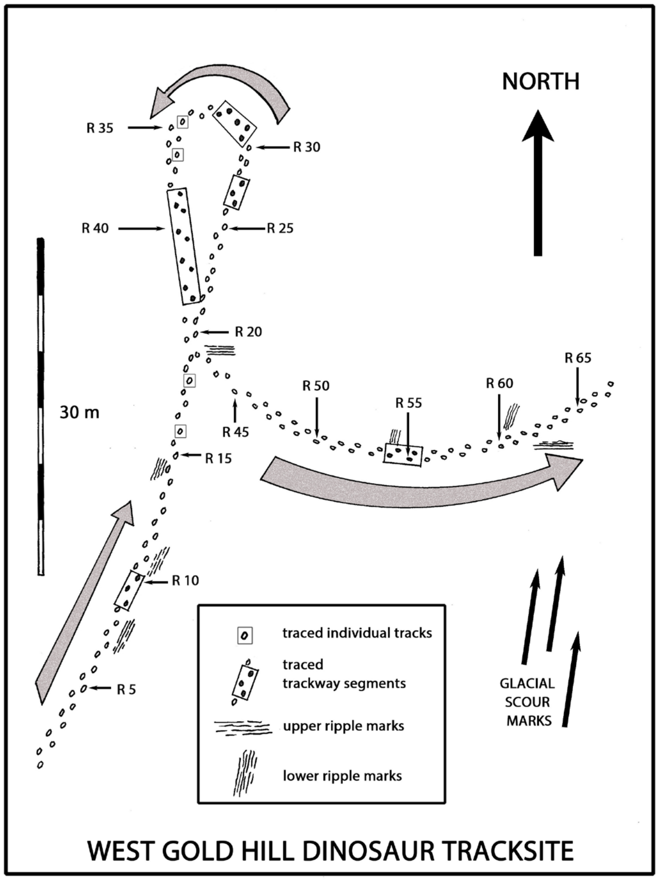

FIGURE 4. Preliminary map of WGHDT showing trackway consisting of 134 tracks. Note 180+° turn around at north end of site. Tracks (all pes) are numbered as R1- L 67 (with every 5th right track numbered). Individually traced and measured tracks, trackway segments and ripple mark orientations outlined. Compare with Figures 2 and 3.

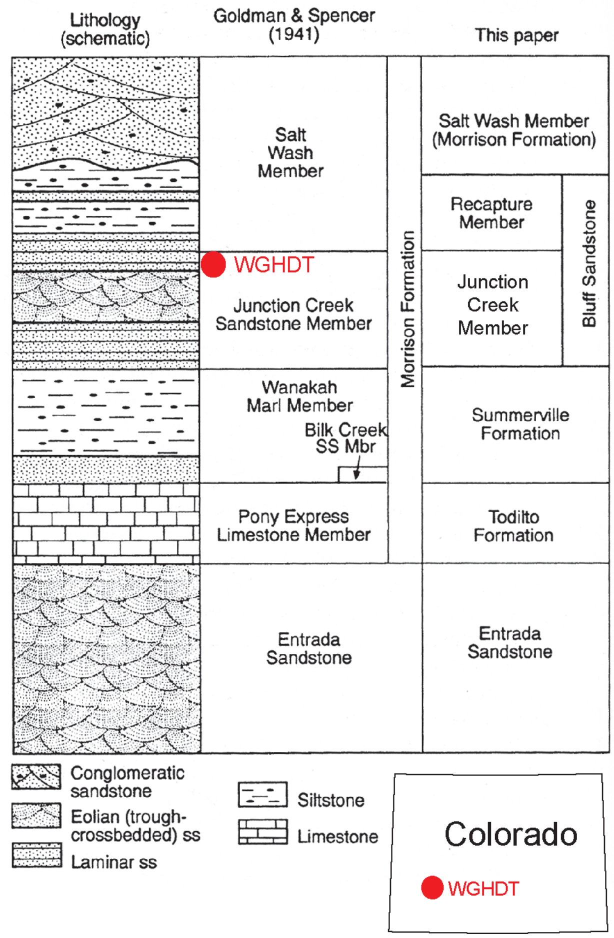

FIGURE 5. Stratigraphy of the Upper Jurassic sequence in the Ouray district showing the Junction Creek Sandstone, also known as the "Lower Quartzite" considered a member of the Morrison Formation according to Goldman and Spencer (1941), but here considered a member of the Bluff Sandstone following Lucas (2017, fig. 5). Note that the Junction Creek Member at WGHDT is a 4-5 m thick unit with laminar bedding, immediately under- and overlain by less resistant beds of Summerville Formation and Recapture Member, Bluff Sandstone, respectively.

oval impressions similar to those found at the main site.

Since 1962, when the American Nettie mine tracks were first reported (Burbank and Luedke, 1962, 2008), more than 70 dinosaur tracksites have been reported from the Morrison Formation, revealing them to be primarily dominated by saurischian (theropod and sauropod) tracks (Foster and Lockley 2006; Hunt and Lucas, 2006; Lockley et al., 2018). However, units underlying the Morrison, notably the uppermost surface of the Curtis Formation (formerly Moab Tongue Member of the Entrada Formation) and the thin, overlying Upper Summerville Formation tongue, equivalent to the "Wanakah Formation" (Gilluly and Reeside, 1928), have also yielded theropod and sauropod tracks in eastern Utah, as well as pterosaur tracks in the Summerville interval (Lockley and Hunt, 1995; Lockley et al. 2007).

Two sets of symmetric ripple marks occur near the top of the sandstone. The lower set occurs only ~3 cm below the top surface and has ripple crests oriented NNE-SSW with another set on the uppermost surface oriented E-W. Both sets have similar wavelengths (~6-7 cm). This evidence suggests that following the deposition of the sandstone variable winds generated wave ripples in shallow water. The sauropod subsequently walked on these upper surfaces, leaving deep tracks that indicate a saturated substrate.

METHOD AND MATERIALS

The portions of the WGHDT track-bearing surface on which tracks had been registered were cleared of debris using hand tools (shovels, small hand tools, whisk brooms) following a path dictated by the meandering trackway. Parts of the bedding plane had already been naturally cleaned by glacial scouring and subsequent erosion and were devoid of tracks. Mapping of the site was accomplished using two methods. First, outlines were chalked and photographed using an aerial drone and an iPhone camera (by ZG). Photos were then over-sketched and analyzed in Adobe Illustrator to determine spatial relationships and develop a trackway map. Second, using Google Earth images, a second version of the map was drawn, and tracks were inspected and numbered on the ground. Once it was determined that only a single trackway was registered at the site, the tracks were numbered from right pes 1 (RP1) and left pes 1 (LP1) sequentially as far as RP67 and LP67 to create a tracksite map (Fig. 4). Isolated tracks and representative trackway segments consisting of three or more tracks were again traced (Fig. 6), following outlines chalked by two of us (BS and ML). These outlines were then transferred onto transparent acetate sheets, which have been reposited as tracings in the University of Colorado Museum of Natural History (UCM) archive as tracings in the series T1961-T1964. The full-sized tracings allowed us to measure pes-track length, width, track mid-point and outward pes rotation as well as step, stride, pace angulation and inner and outer trackway width (Table 1). Only one trackmaker is represented: its average speed was also calculated as between 2.21 and 2.58 km/hour using the methods of Alexander (1976) and Thulborn (1990) and the data presented in Table 1.

Given that only one trackway is represented at the site (with 67 registrations of each of the trackmaker's hind feet: i.e., pes), only one or two well preserved tracks are necessary to correctly represent foot morphology. Our observation is that the smallest tracks most closely represent pes morphology (see Figs. 6A, 7B and Results) and that many tracks are poorly preserved extramorphological expressions of the trackmaker's foot morphology, including distortions of actual footprint size due in part to the aforementioned lack of recognizable manus tracks attibutable to overprinting. Thus, track outlines were not measured from the outermost edge, where the tracks curved downward from the flat rock surface, but rather from the point where the track walls are steepest (see Lallensack, 2019, and Figure 7 herein). The latter method generally avoids over-estimation of track size, and is useful where tracks lack a steep, well-defined marginal wall. Thus, in Table 1 the measurements of the smaller tracks more accurately reflect trackmaker foot size than larger tracks, and like the mean values reflect a component of extramorphological distortion.

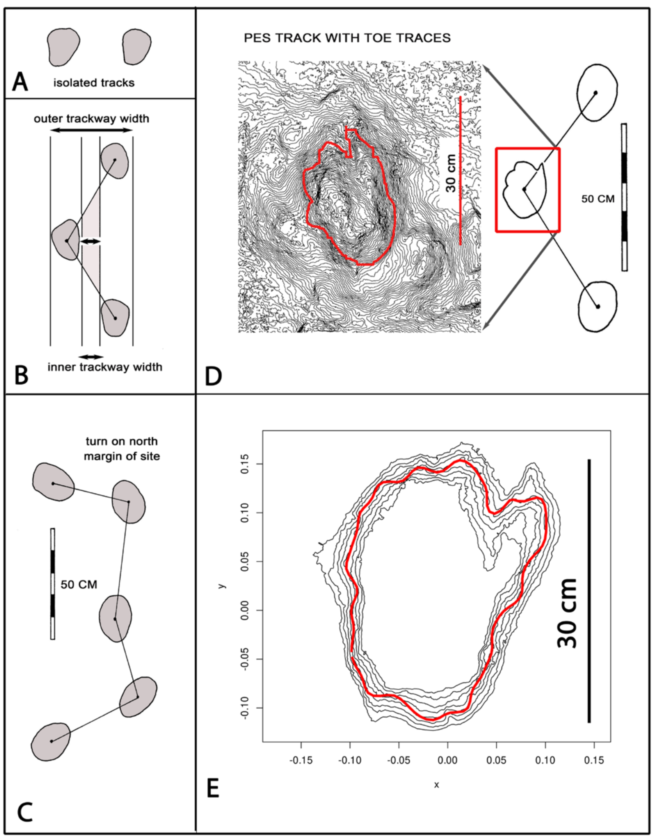

FIGURE 6. Representations of tracks and trackways from the WGHDT. **A,** Tracings of individual tracks (L 34 and L 33). **B,** Tracing of three-track, trackway segment (R 26, L 26, R 27) to show two steps (stride) pace angulation and inner and outer trackway width. **C,** Tracing of five-track, trackway segment, at turnaround point, to show four steps (2 strides: L 30 - L 32) and variable pace angulation. **D,** Virtual 3D model (0.2 mm contour interval) of left pes track, L 9 track (in R 9, L9, R 10 sequence) showing digit traces (left) and configuration of trackway segment (compare with Figure 3). Outline was drawn from contours by ML. **E,** Best fit outline drawn from 3D contour map of left pes track 9 using the algorithm of Lallensack (2019). Compare numbered tracks with Figure 4. See text for details.

Overlapping photographs of one of the few tracks with pes digit traces (Fig. 6) were used to create a virtual 3D model of the in situ track (left pes 9), following the photogrammetry methods outlined by Xing et al. (2018; Lallensack et al., in press). Here, 23 photographs taken with a smart phone (camera XT1565-4.67 mm lens) were added to Agisoft Metashape Professional (v.1.6.3). The models were repositioned to the center of the Cartesian coordinate system using Meshlab (Cignoni et al., 2008), and then the surface topography was visualized using Paraview (v. 2020.06; Ahrens et al. 2005) and CloudCompare (v. 2.10.2; http://www.cloudcompare.org/) filters.

The outline of left pes 9 was drawn using three methods: first, by tracing directly from the outcrop (Fig. 6B right); second, by drawing an outline on the virtual 3D contour map (Fig. 6D left); and, third, by running the digital data through the algorithm of Lallensack (2019) to draw a best fit outline (Fig. 6E).

RESULTS

When first visited by the authors, the number of tracks and potential trackmakers represented at the WGHDT was uncertain, especially in the "looping" area of the site when only partially exposed. The notion that the prints all represent a singular looping trackway was hypothesized by one of us (RT), and upon repeat visits to fully expose the sequence we have established that a single trackway is represented, consisting of a continuous sequence of 134 pes footprints (67 right and 67 left = 134 visible steps). Although there is local overprinting of a short segment of the trackway (between R 43 and R44) where the trackmaker crossed its own trackway (between R 19 and R 20), there are no "missing" tracks due to erosion of the track-bearing surface or intervals where tracks are not visible due to poor quality of original preservation. Thus, this is the longest continuously exposed sauropod trackway in North America. Although Mazin et al. (2017) reported what they described as "the longest known sauropod trackway" (155 m long) from the Jurassic of France, the French trackway represents a larger individual (pes length ~1.00 m) with fewer individual steps (longer paces) than recorded in the Colorado trackway sequence (LP1- LP56). Thus, the WGHDT represents the trackway with the most continuously observed and documented steps (paces) in the global record. As noted, we infer that all tracks are pes prints that completely overprint their corresponding (previously registered) manus tracks, and that hypothetically the trackway represents 268 track registrations. As noted below, the French trackway includes segments where the pes did not overstep the manus tracks, and other segments where only the pes tracks are visible having overstepped manus tracks.

One of the most obvious features of the WGHDT trackway is the 180+° turn registered by the trackmaker at the northern margin of the site (Figs. 2B,3B). There is, as noted below, only one previous report, from the Lower Cretaceous of China, of a sauropod trackway that made a 180+° turn (Xing et al., 2015a). However, in the case of the Chinese example, the track-bearing surface was in a working quarry and has since been destroyed, leaving only a photographic record, which does not yield detailed measurements. Thus, the WGHDT is the world's only example of a sauropod trackway, still preserved in situ, which records a complete reversal of direction. As discussed below, changes in trackway direction can be analyzed using the concept of tortuosity (Benhmou, 2004).

The best preserved WGHDT pes tracks have a diagnostic, bluntly triangular shape with narrower heel and wider anterior margin: e.g., left pes L 34 (length 30.0 cm width 26.0 cm): Fig. 7. Generally, the track length is more variable than the width in the measured tracks (Table 1), probably due to the combined influence of the forward motion of the pes through a yielding substrate, where the tracks registered deeply, and the prior registration of the manus before it was overstepped by the

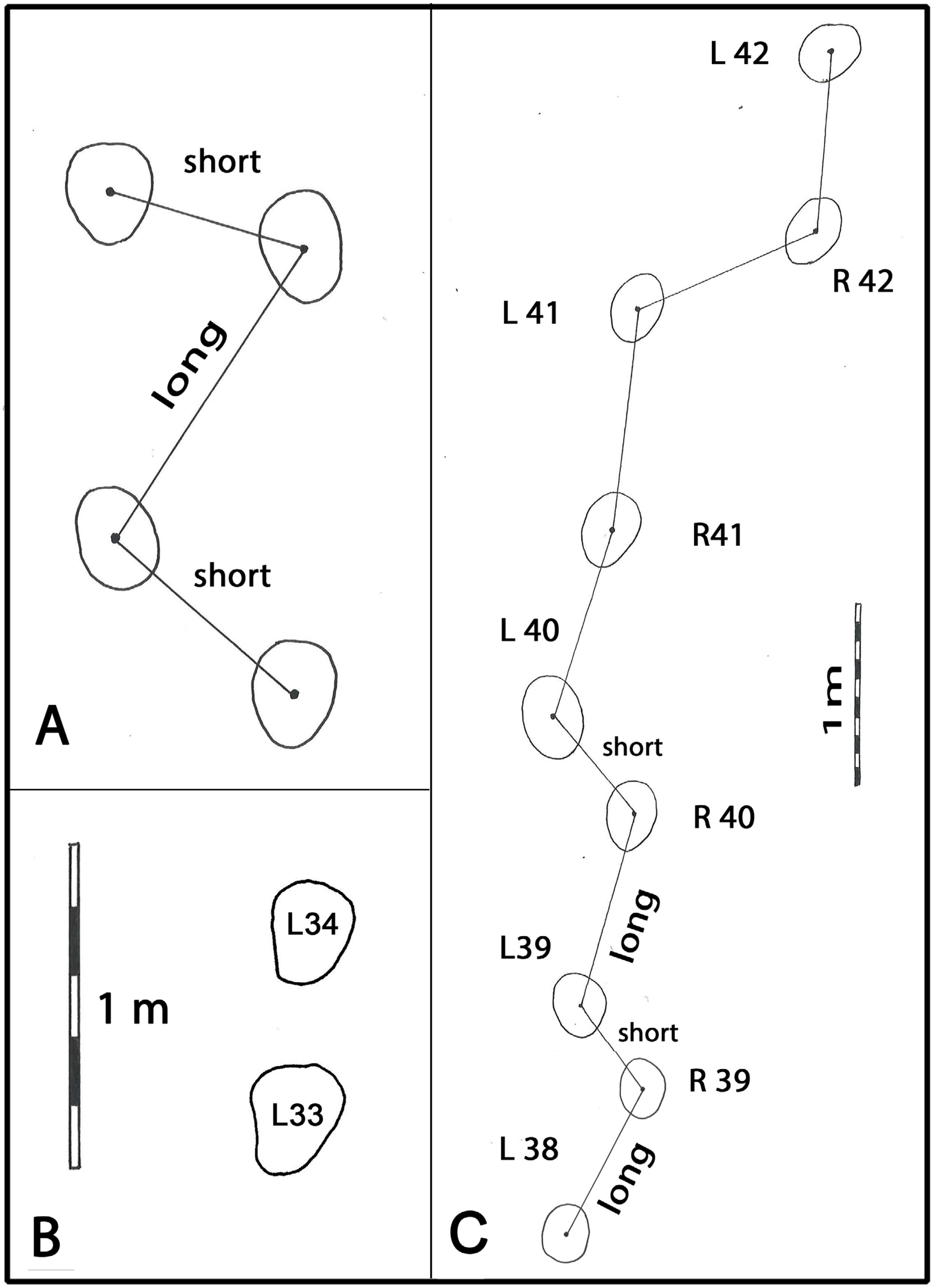

FIGURE 7. **A,** Tracks in series R 54-L 54-R 55-L-55 (see Fig. 4) exhibit alternating short-long-short steps typical of this section of the trackway. **B,** isolated tracks L 33 and L 34, at same scale as A**.** Note subtriangular shape regarded as diagnostic of sauropod pes. L 34 is the smallest track measured and probably the most representatuve of true size**. C,** Tracks in series L 38 – L 42 (see Fig. 4) initially show alternation of long-short steps, after left turn, then show elongation of step, particularly between R 41 and and L 41.

pes. Thus, the mean track lengths and widths (~37 and ~28 cm respectively: Table 1) compute as ~23% longer, but only ~8% wider than the smallest tracks such as L 34. These mean values highlight the aforementioned greater, and quantifiable, exaggeration of track length as a result of motion in the direction of progression and/or registration of the manus.

The pes length of ~30 cm indicates relatively small sauropod trackmakers. Other morphometric parameters are typical of sauropods. For example, despite the variation in trackway direction, which affects step, stride, pes angulation and trackway width, mean pes pace angulation (114°) is typical of sauropods. Mean track width is 38% of mean outer trackway width (OTW) and mean inner trackway width is 68% of track width. The former measurement (pes width /OTW) was described as the "pes trackway ratio" (PTR) by Romano et al. (2007) is 0.38 for the WGHDT trackway, which indicates a medium gauge trackway, close to the value (35%) representing the transition to wide gauge. We recognize that these values are derived from a trackway with sub optimal preservation and deep tracks. It is possible that the relatively wide gauge represents a response to walking on a soft/saturated substrate.

Due to the poor preservation of the individual footprints, inferred to represent deep (~10-~15 cm) pes overprints on manus tracks, it was not necessary, or ichnologically advisable, to measure and average the length and width of individual footprints, as such a compilation would include extramorphological tracks that are larger than the smaller tracks that more accurately represent foot size. Thus, we infer that the most accurate measures of pes size are obtained from smaller prints and those with steep side walls: see measurements in Table 1. However, even with poorly preserved tracks, it was possible to use track mid points (Figs. 6-7) to obtain accurate step, stride and pace angulation measurements, and show local variation along the trackway, especially where the trackmaker changed direction. We also obtained inner and outer trackway width measurements (Figs. 6-7). The accuracy of these latter measurements is slightly influenced by two factors: (1) original gait of the trackmaker (Figs. 6 and 7), and (2) the selection (tracing) of the best position of individual track outlines. In cases where the inferred outlines may over represent track size (width), outer trackway width measurement may also be exaggerated, and the inter-trackway width may be less than would register on an optimal substrate.

According to Lockley et al. (1994) trackway gauge (Farlow, 1992) helps differentiate narrow gauge trackways including *Parabrontopodus* (Lockley et al., 1994) and likely representing diplodocid sauropods, from wide gauge trackways (*Brontopodus*, Farlow et al., 1989), likely representing brachiosaurids, both of which are known from the Morrison Formation. The former ichnogenus typically has a small manus (greater heteropody) and the latter a larger manus (lesser heteropody). Given that the WGHDT trackway lacks manus tracks one of two diagnostic features (manus size) is not available to help apply either of these two ichnotaxonomic labels. As noted above, the gauge of the WGHDT trackway falls technically in the medium category (sensu Romano et al., 2007), which, considering the poor preservation, is not determinative of a confident identification either as *Brontopodus* or *Parabrontopodus*.

There are many segments of the trackway where there are pronounced alternations between long and short steps (Fig. 8). For example, in the sequence R54-L55 the short steps (R-L ~ 76 cm) contrast with the long steps (L-R ~112 cm), a long/short ratio of 1.47 or difference of 47% (Fig. 8A). The pace angulation between R54, L54 and R55 is 98°, but between L54, R55 and L55 it is only 73°, one of the lowest on record for sauropod trackways. As noted below, this irregular gait may be the result of the trackmaker's response to a soft substrate.

The sharp turn made by the sauropod trackmaker (Figs. 2-4, and 6) begins after tracks R30 and L30 in the northernmost portions of the generally linear south-to-north segment of the trackway, veer to the left (west) as the trackmaker registered the tracks here designated as R 31 to L 33 (Fig. 7C), after which the trackmaker veered south (Figs. 4 and 7C). Tracks in the sequence L 38 to L 40 show an alternating long-short sequence similar to that shown in the R 54 to L 55 sequence (Fig. 7A). There is then a short segment (R 41- L 42) where the trackmaker's step lengthened, before the trackmaker veered to the east, crossing the recently registered portion of the trackway (Fig. 4). Interpretations of these changes in direction and the corresponding variations in step, stride, and pace angulation are discussed below.

TRACKWAYS OF TURNING SAUROPODS

There are relatively few documented examples of dinosaur trackways that indicate pronounced changes of direction. As there are no criteria for what consititutes a "significant" change of direction, we arbitrarily select a turn of ~45° or more as a pronouced change in direction of progression, or otherwise follow published sources that refer to such turns or changes in direction. There is no terminology for changes in direction in common use in the ichnological literature, although the term "tortuosity" was borrowed from the ecological literature (Benhamou, 2004; Nams 2005) to described variably-oriented, large tetrapod Pleistocene trackways from New Mexico (Bustos et al., 2018). We also note that documenting trackways that indicate changes of direction may be difficult on small surfaces, or where trackways of similar type intersect. Among known examples of such "tortuous" departures from relatively "straight line" progression are two theropod trackways that turned progressively through almost 90°, including a Lower Cretaceous example from Inner Mongolia (Li et al., 2009), and another from the Early Cretaceous of Shaanxi Province, China (Xing et al., 2018). To date, however, examples of turning sauropod trackways appear somewhat more frequently documented and include four examples from three sites in China and two examples from the western USA: one in Utah and the Ouray (WGHDT) site described here. Thus, there are a total of six examples documenting sauropods that changed direction significantly. In an unpublished thesis, Lim (1990) mapped Cretaceous sauropod trackways from Korea that revealed modest departures (~20°-30°) from straight line progression. These are under investigation by one of us (ML) and will be described elsewhere.

In approximate order of discovery, the tortuous Chinese and American trackways are represented by a Late Jurassic sauropod trackway from the Salt Wash Member of the Morrison Formation, near Moab, Utah, that turned to the right ~65° (Lockley and Hunt, 1995; Fig. 8A herein). The tracksite, originally named the Valley City site, was renamed the Copper Ridge Dinosaur Trackway site and developed as one of five interpretive dinosaur tracksites, destinations, by the Bureau of Land Management (BLM). The next four documented, turning sauropod trackways come from three sites in China as follows: (1) a pair of trackways from the Early Jurassic of Sichuan Province, China (Lockley and Matsukawa 2009; Xing et al., 2016b), one of which shows a ~145° turn to the left, whereas the other turns right through only 30° (Fig. 8B); (2) a Lower Cretaceous trackway from Shandong, China (Xing et al., 2105a), which indicates a turn of nearly 180° (Fig. 8C), but does not intersect itself; and (3) a turning sauropod trackway from the Early Cretaceous Zhaojue site of Sichuan Province, China (Xing et al., 2015b) that turns through a little more than 180°, thus crossing its own trackway (Fig. 8D). This latter site representing a fluvio-lacustrine succession of "thick sandstones with minor siltstones and shale and … thick brick red siltstones containing thin sandstone layers" (Xing et al., 2014, p. 80) was located on a steep quarry face and has since been destroyed; see Xing et al. (2015a) for the photographic record.

The Ouray tracksite represents the sixth documented report of a turning sauropod trackway and most closely resembles the Early Cretaceous trackway from Sichuan Province, which, after heading north, turned in a very tight right hand (clockwise) loop through 180+° before crossing its own trackway and heading south. The turn registered by this Sichuan sauropod (Fig. 8) was even sharper or "tighter" than that of the WGHDT trackmaker, crossing its own trackway within 5 meters of the turn round point rather than within ~15-20 meters at the WGHDT. Unfortunately, the lack of morphometric data for the Sichuan trackway makes interpretation of any potential relationship between trackmaker size and turning radius impossible. Such 180+° turns are rarely recorded, and given the size of sauropod tracks and trackmakers, a certain minimum area suitable for track registration is required in order to increase the chances that such evidence of complete turns will later be exposed, allowing for unambiguous interpretation. For example, the Sichuan trackway (Fig. 8D) was recorded on an exposed surface of ~2000m^2, now collapsed, and the West Gold Hill trackway, which turns in a tight left hand (counter-clockwise) loop, is on a surface of ~3000m^2. In both cases, the turn around traces were registered on localized parts of the exposed surface but could easily have been obscured or lost to erosion, had the preserved surface been smaller. In fact, this was the case in the present study, as we were uncertain as to how many trackways were present before the turn-around point in the trackway was fully uncovered.

DISCUSSION AND CONCLUSIONS

The single sauropod trackway represented at the WGHDT is unique for two unambiguous reasons. First, it is composed of 134 consecutive right-left footprints, which represents a larger number of pes tracks than hitherto recorded in any single sauropod trackway in the global track record. Second, this is one of only two sauropod trackways that does a 180+° turn to completely change direction and cross its own trackway. Of these two tortuous trackways, the first to be reported, from China (Xing et al., 2016b), was not accompanied by precise measurements due to its inaccessible location on a steep face in a working quarry, and, in any case, was destroyed, so it is no longer available for study. By contrast, the WGHDT tracksite is the only such global example available for further study.

The frequency of examples of sauropod or other dinosaur trackways that show pronounced or tortuous changes in direction

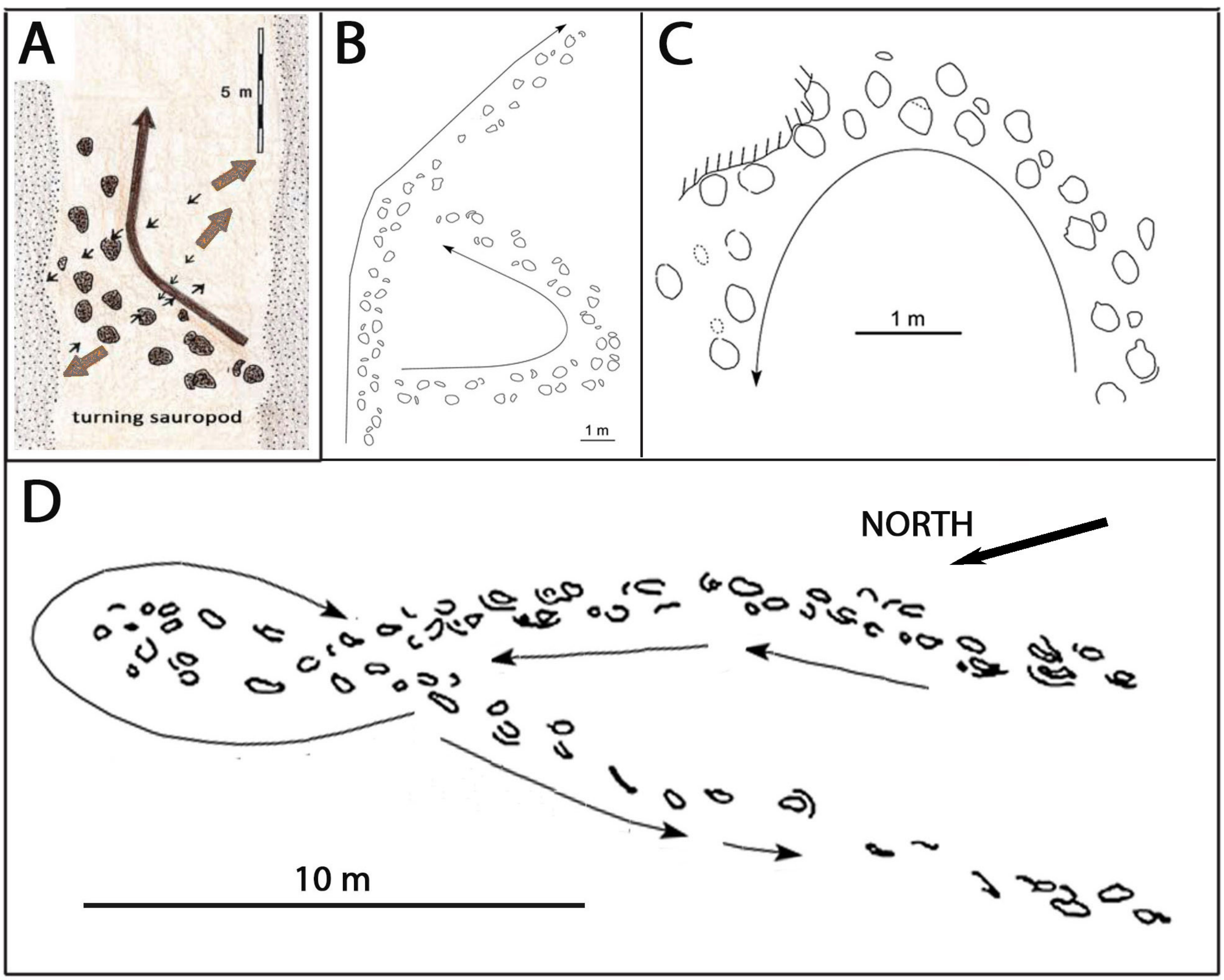

FIGURE 8. **A**, Turning sauropod from Upper Jurassic Morrison Formation of the Moab area, Utah, after Lockley and Hunt (1995; Hunt-Foster et al., 2016). **B**, Two turning sauropod trackways from the Early Jurassic of Sichuan Province, China (Lockley and Matsukawa 2009; Xing et al., 2016b). The right trackway shows a very tight left turn **C**, A turning sauropod trackway from the Early Cretaceous of Shandong Province, China (Xing et al., 2015a); **D**, A turning sauropod trackway from the Early Cretaceous of Sichuan Province, China (Xing et al., 2015b), exhibiting the off-tracking phenomenon of the manus with regard to the pes. Tortuosity can be calculated using the ratio of direct (DL) distance between the first and last registered tracks to trackway length (TL): see text for details.

TABLE 1. Morphometric parameters of selected tracks from sauropod trackway from West Gold Hill Dinosaur Tracksite. OTW and ITW represent outer and inner trackway widths respectively. All measurements except Pace Angle in cm. As only one trackway is represented, speed was estimated using the formula of Alexander (1976) as between 2.21 and 2.58 km/hour using hip height estimates of 4.0 and 4.45 x footprint length. The smallest track, L 34 (bold) is likely the most representative of foot size: see text.

Track number	Length (L)	Width (W)	L/W	Step	Stride	Pace Angle°	OTW	ITW
R 9	33	26	1.27					
L 9	37	29	1.28	95	145	110°	78	22
R 10	38	28	1.36	82				
R 16	37	29	1.28					
R 18	38	29	1.31					
R 26	32	29	1.10					
L 26	34	24	1.42	82	139	118°	70	19
R 27	32	24	1.33	84				
L 30	38	28	1.36					
R 31	41	25	1.64	88		100°		
L 31	41	29	1.41	74		157°	47	
R 32	38	28	1.36	106		95°		
L 32	39	28	1.39	70				
L 34	**30**	**26**	1.15					
L 36	32	27	1.19					
L 38	37	31	1.19					
R 39	38	29	1.31			115°	74	11
L 39	42	28	1.50	67	160	130°	64	7
R 40	38	27	1.41	108		126°	68	6
L 40	44	32	1.38	71	160	123°	71	7
R 41	41	29	1.41	108				
L 41	40	28	1.43	125	203	118°	88	31
R 42	40	28	1.43	109	180	120°	83	26
L 42	38	30	1.27	101				
R 54	33	27	1.22					
L 54	33	25	1.32	76		97°	87	33
R 55	35	26	1.35	112		73°		
L 55	33	28	1.18	76				
mean	**36.86**	**27.78**	**1.33**	**90.8**	**123.4**	**114°**	**73**	**18**

is difficult to assess or compare with trackways with directed, linear configurations that show no significant deviations. As intimated above, the chances of preserving trackways with such changes in direction likely depends on the size of the exposed bedding plane, and the trackmaker's ability to make tight turns. Any inferences about why a dinosaur would change direction are necessarily speculative. However, there are indications that some large vertebrates are less prone to meandering progression than others. For example Webb (1972, p. 102) stated that the pacing gait of the narrow bodied camel was a "major disadvantage" because "maneuverability is reduced" and "it cannot change direction" as easily or as often as broader "barrel chested" ungulates. Lockley (1999, fig. 8.4) illustrated the trackway of a wildebeest that showed the trackmaker turned through 180+° to cross its own trackway, presumably representing a trackmaker less averse to changing direction.

Bustos et al. (2018) documented a large (~60,000m^2) New Mexico tracksite that reveals trackways of large Late Pleistocene tetrapods, namely those of large ground sloths, that show significant changes in trackway direction on the order of ~90°. However, in this case the changes in direction are purported to have been caused by humans that were supposedly hunting the sloths. These authors followed Benhamou (2004) in defining "tortuosity" as the measured ratio of direct length (DL) to cumulative track length (TL). So, a straight, non-deviating trackways has a tortuosity of value of 1.0, but a highly convoluted one approaches a value of zero.

Other measures of tortuosity have been discussed by Nams (2005, p, 180), who theoretically defined the "fractal D" as "between 1 when the path is straight and 2 when the path is so tortuous as to completely cover a plane." In the case of the WGHDT trackway, the direct (DL) distance between the first registered track (R1) and the last (L67) is ~ 60.0 m, whereas the trackway length (TL) is 96.3 m. This gives a moderate tortuosity ratio (DL/TL) of 0.62: i.e., approximately midway between a straight line (DL=TL) and extreme tortuosity. Thus, trackway tortuosity can be measured independently of any speculation as to why any given trackway departs from a straight line or what Nams (2005) calls a "directed walk." Tortuosity values can be explained on a variety of spatial scales pertaining to a track maker's behavior in departing from a directed walk in order to forage, or perhaps to avoid obstacles or other animals in the environment. However, as intimated above, with the exception of the putative sloth-human interactions reported from the Pleistocene of New Mexico, proposing causal reasons for such deviations or changes in directions in the case of sauropod trackways or any other tracksite examples are necessarily highly speculative without other corroborative contextual evidence.

However, despite this caution, we know that trackway orientations are often controlled or influenced by features in the physical environment such as shorelines (Ostrom, 1970; Lockley, 1986), which may influence the consistency of the substrate. In the case of the WGHDT, the tracks are consistently quite deep, which could indicate that the substrate was saturated (possibly subaqueous) and not firm or resistant to compaction, as is more typical of wet but well drained sand. However, without detailed sedimentological evidence of changes in sedimentology across the site, the possibility that the trackmaker changed direction in response to its perception of changes in substrate consistency is purely conjectural. A sedimentological analysis of the ripple-bearing surfaces and variability in track preservation at the WGHDT could help understand the dynamics of trackway registration.

Future studies may allow more detailed documentation of the tortuosity observed in dinosaur and other tetrapod trackways from the global track record, in comparison with those of extant tetrapods. Such studies could shed light on changes in gait as trackmakers deviate into more or less tortuous paths. Thus, for example, the WGHDT location has the potential for a further detailed analysis of "step-by-step" variation in the progression of an individual trackmaker, including the dynamics of turning and the pattern of alternating long and short steps, and possible relationships to a soft substrate.

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