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A large tridactyl trackway from the Upper Cretaceous Hell Creek Formation of North Dakota, likely attributable to an adult *Tyrannosaurus rex*

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ABSTRACT—Large theropod tracks are uncommon within the Hell Creek Formation with trackways being exceedingly rare. Until recently the tracks and trackways that have been associated with non-*Tyrannosaurus* tyrannosaurids have not supported a clear comparison with an adult *T. rex*. Here we describe a newly discovered ~7 m trackway comprised of four large tridactyl tracks, each ~1 m in length, from the Upper Cretaceous Hell Creek Formation of North Dakota. The trackway is ~33 m below the Hell Creek/Fort Union Formation contact and is estimated to be ~66.5 Ma. The large size and tridactyl nature of the tracks is consistent with an adult *Tyrannosaurus rex* trackmaker, and numerous *T. rex* skeletal elements and skeletons have been found locally further strengthening the identification of the trackmaker. Stride lengths and foot lengths indicate a walking speed in the region of 1.5–2 m/s, which is consistent with other large theropod trackways. The tracks are preserved as fine-grained sandstone concretions cemented with calcium carbonate that nucleated around footprint depressions and the resultant footprint casts are harder than the surrounding rock. However, the surfaces of the footprint casts are heavily fractured and retain little anatomical detail beyond size and number of digits. Nevertheless, this is an important data point that marks the first report of a trackway that is likely attributable to an adult *Tyrannosaurus rex*.

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INTRODUCTION Fossilized vertebrate tracks are generally found in deposits

devoid of osteological material. This is both because bones and tracks require different preservation regimes, but also because tracks are necessarily made where animals are living, and therefore in areas exposed to scavenging (Falkingham, 2014). As a result it can be difficult to assign trackmakers to any degree of specificity, especially for tridactyl dinosaur tracks, which might be left by a host of theropod and ornithopod trackmakers with shared, conserved, tridactyl foot morphology (Lallensack et al., 2022). The task of assigning trackmakers to tracks is only made more difficult by the fact that "footprints are not feet," and apparent track morphology may differ substantially from foot morphology either due to foot movement and sediment response (Gatesy & Falkingham, 2020; Gatesy et al., 1999; Falkingham & Gatesy, 2014, 2026; Lallensack et al., 2022), or due to preservation (Belvedere & Farlow, 2016; Falkingham & Gatesy, 2020; Falkingham & Lallensack, 2025; Milàn & Loope, 2007). Being unable to confidently link tracks and trackmakers can be frustrating given the potential wealth of information recorded in fossil tracks about locomotor capabilities and behaviors (Falkingham, 2014, 2025; Falkingham & Gatesy, 2014, 2026; Gatesy et al., 1999; Lallensack & Falkingham, 2022; Thulborn & Wade, 1989). Fortunately, there are exceptions where trackmaker identity

can be constrained through a combination of two things; occurrence—tracks and trackmakers occurring not necessarily in the same deposits, but in the same formation and geographic location; and characteristic morphological attributes—number and relative size of digits, for instance. In the case of tyrannosaurs, size and age/locality of tracks are the main factors determining attribution. Despite the relative abundance of skeletal material, the ichnological record for tyrannosaurs remains sparse, with valid specimens restricted largely to the Upper Cretaceous (Campanian and Maastrichtian) of North America and Asia. The first track confidently attributed to Tyrannosaurus rex was described by Lockley and Hunt (1994) from the Maastrichtian Raton Formation of New Mexico, designated as the holotype for the ichnotaxon *Tyrannosauripus pillmorei*. This large (86 cm long) natural cast records a functionally tridactyl morphology and a distinctive posteromedially directed hallux (digit I) impression. Because *T. rex* is the only theropod of such size known from the Maastrichtian of North America, *Tyrannosauripus* is widely accepted as the "gold standard" for an ichnotaxon that can be attributed to *Tyrannosaurus*. Another isolated, probable *T. rex* track was described from the Hell Creek Formation of Montana, where Manning et al. (2008) reported a large (72 cm long) positiverelief siderite-preserved track. That tridactyl track was particularly large, possessed an offset digit II, but recorded no evidence of a hallux impression. The first confirmed tyrannosaurid trackways were reported by McCrea et al. (2014) from the Campanian–Maastrichtian Wapiti Formation of British Columbia. Assigned to the ichnotaxon Bellatoripes fredlundi, these tracks are attributed to non-*Tyrannosaurus* tyrannosaurids (likely *Albertosaurus, Gorgosaurus,* or *Daspletosaurus*) based on their age and size (>50 cm in length). Speeds calculated from the trackways are in the region of 1.8– 2.4 m/s. This site preserves the concurrent movement of three individuals traveling in the same direction, potentially providing ichnological evidence for gregariousness in some tyrannosaurids. One individual in this group displays a pathology—a truncated digit II—marking a rare instance of identifiable injury in the theropod track record (McCrea et al., 2014). A subsequent discovery in the Maastrichtian Lance Formation of Wyoming, the Glenrock Trackway (Smith et al., 2016), consists of three sequential steps attributed to a sub-adult *T. rex* or *Nanotyrannus lancensis* based on size (40 cm long). Speed estimates for the Glenrock trackmaker were calculated at 2.2–3.5 m/s by Ruiz (2018). A trackway recorded from the Hell Creek Formation in South Dakota consisted of large (55–60 cm long) positive-relief siderite casts, and was assigned to *Wakinyantanka styxi* (Lockley et al., 2014). Those authors considered *Wakinyantanka* to have possibly been made by *Nanotyrannus*, given it was too small for an adult *T. rex*.

Globally, the record is expanding. Xing et al. (2019) described a large (58 cm long) tridactyl track from the Hekou Formation of China as a probable tyrannosaurid. This track shares morphological similarities with *Tyrannosauripus* and *Bellatoripes*, such as a wide metatarsodigital pad and pointed claw impressions. Other reports are either contentious or have been rejected.

The ichnogenus *Tyrannosauropus petersoni* (Haubold, 1971) based on Campanian tracks from Utah, is now considered a nomen dubium and is widely reinterpreted as a hadrosaur track due to its blunt digits and lack of distinct theropod features. A purported “pack” of *T. rex* tracks in the Lance Formation described in an abstract by Larson (2003) was later assessed by Lockley et al. (2004) as a “jumble” of poorly preserved tracks with no clear evidence of gregarious behavior. We describe here a trackway found in the Hell Creek Formation, consisting of four large tridactyl tracks. The size, age, and locality lead us to interpret this as a trackway made by an adult *Tyrannosaurus rex*.

GEOLOGIC SETTING AND AGE

The trackway (Denver Museum of Nature & Science [DMNH], Loc. 21732) is located on Dakota Prairie Grasslands administered by the United States Forest Service in Slope County, North Dakota, approximately 4 km northwest of Marmarth, North Dakota (Fig. 1). More detailed locality information is archived at the Denver Museum of Nature & Science. The locality was found by one of us (KMH) in 2025 in the Upper Cretaceous Hell Creek Formation, ~33 m below the Hell Creek/Fort Union formation contact. The contact locally approximates within 1 m below the Cretaceous/Paleogene (K/Pg) boundary, identified by the extinction of typical Cretaceous pollen taxa (Bercovici et al., 2009; Fastovsky & Bercovici, 2016). The stratigraphic position of the trackway was estimated by calculating the difference in elevations between the trackway and the nearest Hell Creek/Fort Union formation contact (~160 m east of the tracksite). A GNSS differential Global Positioning System (GPS; Trimble June T42S models) was used to collect the elevation data, and these data were post-processed using a nearby CORS data station. The difference in elevation is 33 m (track locality has an elevation of 844.96 m and the formational contact, 160 m to the east, has an elevation of 877.94 m). Hicks et al. (2002) and Peppe et al. (2009) analyzed the paleomagnetism of nearby rocks (Bald Butte is 7.6 km to the west; Fig. 1) and identified the 30n/29r magnetochron boundary 26 m below the Hell Creek/Fort Union formation contact. Thus, the trackway is ~7 m below magnetochron 30n/29r. This magnetochron boundary has recently been dated to be 66.436 ± 0.039 Ma in the Denver Basin (Clyde et al., 2016) and 66.311 ± 0.067 Ma in the Williston Basin (Sprain et al., 2018) and the global Geomagnetic Polarity Time Scale age for the 30n/29r magnetochron, which we herein follow (Fig. 1), is 66.398 Ma (Ogg, 2020). Given the locality is ~7 m below the 30n/29r magnetochron, and assuming an average sedimentation rate of 16.6 ka/m (Hicks et al., 2002), the trackway is estimated to have been made ~66.5 Ma (Fig. 1). The tracks of DMNH Loc. 21732 are preserved as internal molds inside four broadly rounded, tridactyl shaped sandstone concretions (Fig. 2). Similar styles of preservation have previously been reported for large dinosaur tracks in various states of greater or lesser weathering of the concretion (e.g., Fanti et al., 2024; Manning et al., 2008; Powers et al., 2023; Therrien et al., 2015). The track concretions are preserved in a ~1 m thick unit that consists of thin (1–3 cm) bands of fine-grained, cross-stratified sandstone interbedded with thin (1–2 cm) mudstone lenses interpreted to represent a crevasse splay overbank deposit. A cross section of the cross-stratified sandstone interbedded with mudstone unit is exposed over 100 m, and no other track concretions are apparent.

DOCUMENTATION

The tracks at DMNH Loc. 21732 were documented digitally using an Artec Leo, which provided a maximum scanning resolution of 0.2 mm, though this was reduced over the large area (~14 m2) scanned. In total, we obtained five high-resolution scans (~1,000,000 polygons, average edge length ~0.2 cm, though meshes were not uniform): the four individual tracks, and a single scan of the entire trackway (Fig. 2). Models were cleaned, measured and visualized in Blender 5.0 (www.blender. org), and made available as supplemental data (Falkingham et al., 2018). Track descriptors, as well as track and trackway metrics, follow those outlined in Lallensack et al. (2025), and methods/locations of measurement for track length, track width, pace and pace angulation, and external trackway width are presented in Fig. 2F and G.

RESULTS

The trackway is 7 m in total length, comprising four large tridactyl pedal tracks, two left and two right (Fig. 2). The tracks are presented in positive relief, consisting of track and infill, both cemented with calcium carbonate and are harder than the surrounding rock.

The foot is presumed to have pressed into the crevasse splay overbank sediments to create a depression, or nucleus, for mineral buildup. While most Hell Creek rocks are unconsolidated soft sediment, post-depositional cementation can occur when groundwater rich in calcium carbonate minerals flows through porous sediment, especially sandstones. A very common feature of Hell Creek sandstones are "sandstones pipes" (Fastovsky & Bercovici, 2016; Hasler & Renne, 2026), where groundwater forms hard cylindrical concretions aligning with paleocurrents. Other concretions occur when minerals crystallize and collect around a nucleus, often a bone of a large vertebrate, cementing the surrounding sand and fine-grained overbank sediment into a hard, compact mass. In the case of DMNH Loc. 21732, nucleation was presumably initiated from the tridactyl tracks forming spherical concretions around them, allowing for their preservation. Differential erosion eventually wears away the softer rock, leaving the durable concretions exposed. Without any hardening process such as the formation of calcium carbonate sandstone concretions or permineralization in ironstone, footprints in soft sediments are unlikely to be found as they would be instantly eroded away. The most heavily eroded concretion ("R2") reveals the fossilized footprint cast inside.

The tracks are tridactyl, more clearly so in track R2 (the other tracks are less exposed, and appear superficially rounder, although generally tridactyl in shape). Tracks are ~0.9–1 m in length and ~60–80 cm in width (measured following the methods outlined in Lallensack et al. [2025]), though the preservation, weathering, and exposure, make accurate and consistent determination of track and trackway metrics difficult (Table 1). We consider track R2 to be clearest, which measures 0.96 m in length and 0.8 m in width. Values are likely to be larger than the trackmaker's foot. Digital impressions are clearest on R2, with the impression of digits II, III, and IV measuring 34, 47, and 30 cm in length (tip to hypex), respectively, and all are ~13 cm in width. The DIII impression of said track may be proximally wider and tapers distally, however the track is heavily weathered and fragmented, so these measurements are only indicative; all the digital impressions in R2 are truncated by weathering. Interdigital angles are confidently measurable for this track, despite the broken surface, and for track R2 are 35° between the impressions of digits II and III and 40° between the impressions of digits III and IV. Track R2 also appears to have a structure at the rear that may be attributable to a metatarsal pad or hallux impression (given the ambiguity here, this structure was included in the measure of total track length).

Stride length is ~4 m (the weathered nature of the tracks makes it difficult to measure stride length accurately and objectively; Fig. 2G). External trackway width (measured between parallel lines bounding the lateral edges of the tracks, see Lallensack et al. [2025], and Fig. 2G) is ~0.8–1 m, and tracks significantly overlap with the midline by 40–50%. Pace angulation (measured from the centroid of each track) is ~167° between tracks L1, R1, and L2, and ~164° between tracks R1, L2, and R2.

DISCUSSION AND CONCLUSIONS

Given the age (~66.5 Ma), locality (Hell Creek Formation, North Dakota), size, and ratio of the tridactyl tracks (100 cm long by 80 cm wide), along with the narrow digit impressions (Fig. 2C, E), and narrow pace angulation in line with other theropod trackways (McCrea et al., 2014) an adult *Tyrannosaurus rex* is the most likely trackmaker. Hadrosaurs from the Hell Creek Formation (e.g., Edmontosaurus annectens) also produce large tridactyl tracks, but with broader digital impressions and tend to be wider than they are long (Díaz-Martínez et al., 2015). Isolated *T. rex* skeletal elements are abundant in the area, and several partial skeletons have also been collected locally (Lyson & Longrich, 2011). The tracks described here, even accounting for the poor preservation and anatomical fidelity, are among the largest tridactyl tracks reported, ruling out most other tridactyl trackmakers. The only other known trackways attributable to tyrannosaurids (McCrea et al., 2014; Smith et al., 2016) are significantly smaller, at nearly half the length of the tracks reported here and must therefore have been made either by a juvenile *Tyrannosaurus* or a smaller related species. This makes the trackway described here the first such attributable to an adult *T. rex.* Other tracks attributed to adult *Tyrannosaurus rex* (*Tyrannosauripus*, Lockley & Hunt, 1994; Manning et al., 2008) are isolated, and do not record locomotor information such as stride length.

Unfortunately, the short length of the trackway combined with the poor preservation of the tracks means there is little locomotor inference to be made from the tracks. A 4 m stride, with tracks 1 m in length, results in a hip height of ~4 m and speed of ~1.6 m/s according to Alexander (1976). Feet smaller than the tracks (i.e., accounting for some level of distortion of the sediment on entry and exit), ~80 cm in length, would increase this speed to 2 m/s. However, given the findings of Prescott et al. (2025) and the caveats of poor preservation and anatomical fidelity, these values are only to be taken as roughly indicative, and the trackmaker was likely moving more slowly than this. Nevertheless, 1.5–2 m/s is not an exceptional, nor unreasonable walking speed for a large animal and is generally in the range of speeds reported for trackways attributed to smaller tyrannosaurs (McCrea et al., 2014; Ruiz, 2018).

The trackway is exposed on the edge of a steep “gumbo” butte, and tracks prior to those reported here, if present, are under considerable overburden. Future excavations may be able to expose more of the trackway and may be able to uncover more features that elucidate foot anatomy and motion or may present trackway parameters that indicate notable locomotor behavior. However, the considerable overburden means that further excavations may be unlikely.

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AUTHOR CONTRIBUTIONS

PLF: Data curation, Formal analysis, Investigation, Methodology,

Writing – original draft, Writing – review & editing; KMH: Conceptualization, Investigation, Writing – review & editing; EMT-G: Investigation, Methodology, Software; ADB: Visualization, Writing – review & editing; TRL: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing

DATA AVAILABILITY STATEMENT

All photographs and digital models used to make measurements and interpretations are openly available via Figshare 10.6084/m9.figshare.31095802 (https://doi.org/10.6084/m9.figshare.31095802). Photogrammetry data of each individual track and of the entire trackway are available here: https://doi. org/10.6084/m9.figshare.31095802

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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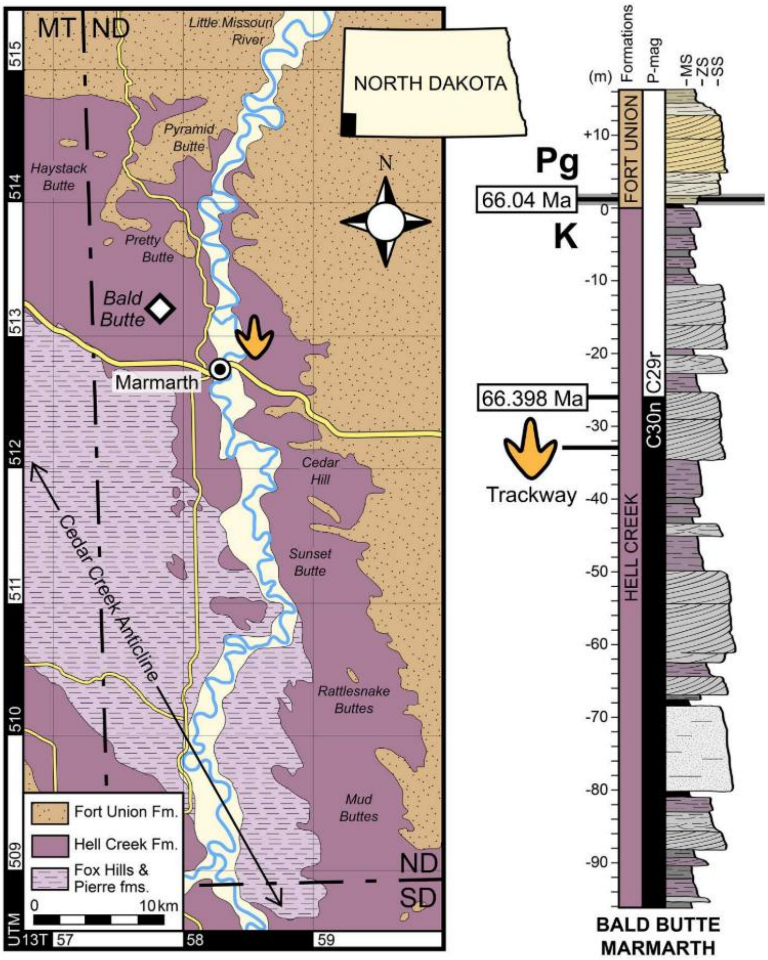

FIGURE 1. Geologic map of the Cedar Creek Anticline and composite stratigraphic section of the Hell Creek Formation (after Murphy et al., 2002) showing the geographic and stratigraphic location of the trackway (DMNH Loc. 21732). Placement of 30n/29r magnetochron within the Bald Butte/Marmarth section is based on Peppe et al. (2009). Map grid is plotted using the Universal Transverse Mercator within grid 13 T. The Global Time Scale (Gradstein et al., 2020) is used for the age of the Cretaceous/Paleogene (K/Pg) boundary and 30n/29r magnetochron. **Abbreviations**: **Fm.**, Formation; **m**, meter; **Ma**, millions of years; **MS**, mudstone; **P-mag**, paleomagnetics; **SS**, sandstone, **ZS**, siltstone.

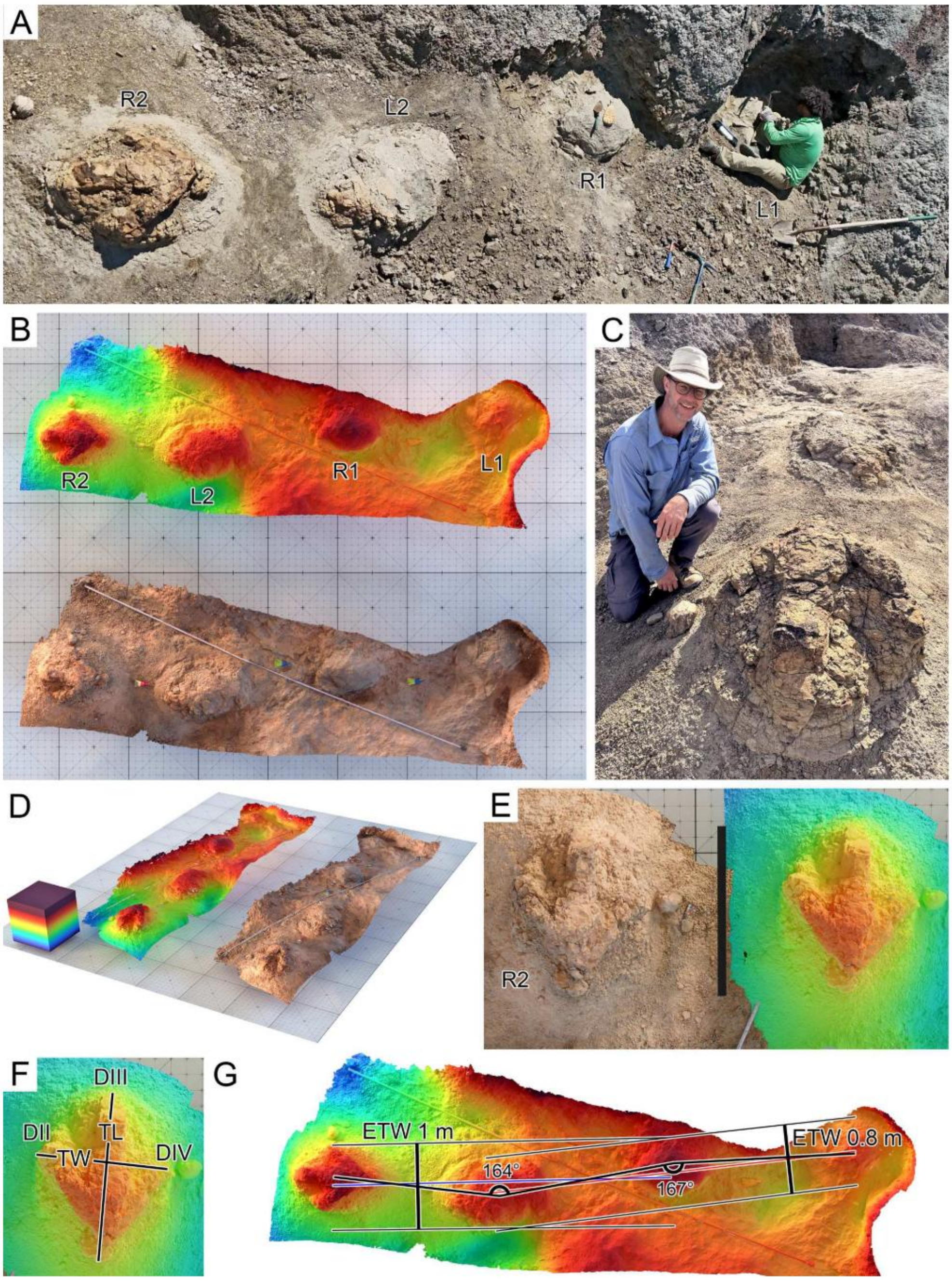

FIGURE 2. **A**, drone photograph of trackway DMNH Loc. 21732, attributed to an adult *Tyrannosaurus rex*. **B**, plan-view false-color (heightmap; top) and true-color (bottom) of the trackway. Grid squares = 1 m. **C**, photograph of R2 and TRL for scale. **D**, perspective view of the false-color (left) and true-color (right) models alongside a false-color scale cube that is 1 × 1 m. **E**, close-up plan view of the true-color (left) and false-color (right) models of track R2, which records most morphology. **F**, close-up view of track R2 indicating where track length (TL) and width (TW) were measured, as well as digits II, III, and IV. **G**, plan-view of height-mapped model indicating where pace and pace angulation (bold line), external trackway width (ETW), and trackway midline (thin lines) were measured. **Abbreviations**: **TL**, track length; **TW**, track width. Scale bar in **E** and **G** equals 1 m.