



## Walking in mud: Remarkable Pleistocene human trackways from White Sands National Park (New Mexico)

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### ABSTRACT

Human tracks at White Sands National Park record more than one and a half kilometres of an out- and return journey and form the longest Late Pleistocene-age double human trackway in the world. An adolescent or small adult female made two trips separated by at least several hours, carrying a young child in at least one direction. Despite giant ground sloth and Columbian Mammoth transecting the tracks between the outbound and return journeys, the human tracks show no changes indicative of predator/prey awareness. In contrast, the giant ground sloth tracks show behaviour consistent with human predator awareness, while mammoth tracks show no such apparent concern. The human footprints are morphologically variable and exhibit left-right asymmetry, which might be due to child carrying. We explore this morphological variability using methods based on the analysis of objective track outlines, which add to the analytical toolkit available for use at other human footprint sites. The sheer number of tracks and their remarkable morphological variability have implications for the reliability of inferences made using much smaller samples as are more common at typical footprint sites. One conclusion is that the number of footprints required to make reliable biometric inferences is greater than often assumed.

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### 1. Introduction

The interaction of two or more animals, as evidenced by their fossilised footprints, preserves a moment in time. Gregarious behaviour has frequently been documented (Hatala et al., 2016b; Roach et al., 2016; Hatala et al., 2017), but multispecies interactions (e.g., Leakey and Hay, 1979), such as predator vs prey, are rare by comparison. When the taxa involved are extinct, such instances offer unique avenues for understanding inter-specific behavioural palaeoecology. Human footprint sites often contain animal tracks (e.g., Aldhouse-Green et al., 1992; Roach et al., 2016; Altamura et al.,

2018) and perhaps most famously at Laetoli (Leakey and Harris, 1987), but demonstrating interaction or even strict contemporaneity is challenging. Most footprint sites are limited by the extent of the exposed ichno-surface which precludes palaeo-tracking over extensive distances (e.g., Ashton et al., 2014). The lack of evidence of interaction is therefore in part a function of preservation and exposure. As a result, our understanding of the behavioural interaction between different animals at various times in the geological record is limited. Such information is relevant to a wide range of questions such as early human hunting practices and their consequence therefore for the extinction of Pleistocene mega-fauna (e.g., Martin, 1973; Guthrie, 2006; Meltzer, 2015; Surovell et al., 2016).

In addition, the sample of fossil human tracks made by an individual track-maker is also typically limited by the size of natural exposures. Inferences are consequently often made, in some cases

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for entire hominin species, on the basis of small track samples, leading to debate. This point is illustrated by the on-going controversy over the biomechanics of the Laetoli track-maker (e.g., Meldrum et al., 2011; Crompton et al., 2012; Bennett et al., 2016a, b; Hatala et al., 2016a). Our understanding of natural track variability, and both the biomechanical and behavioural modifications associated with unstable or slippery surfaces, often the ones that record tracks, hampers these debates (Morse et al., 2013; Bennett and Morse, 2014). The occurrence of a double human trackway extending over at least 1.5 km at White Sands National Park (WNSA; Locality-3) provides a remarkable opportunity to explore intra-trackway variability. This site is distinct from that reported by Bustos et al. (2018) on the eastern, rather than western, side of Alkali Flat. We present new methods for investigating trackway variability and the implications of that variability for biometric and biomechanical inferences. Finally, we explore the behavioural implications that can be deduced from both the human trackway and the mega-fauna that crosscut and are subsequently crosscut by it.

## 2. Geomorphological context and geochronology

Ichnofossils of extinct Rancholabrean fauna occurring at White Sands National Park (WNSA) in New Mexico comprise one of the largest concentrations of Cenozoic vertebrate tracks in North America (Lucas et al., 2007, Figs. 1–3). Tracks and trackways of Proboscidea (mammoth/mastodon), Folivora (ground sloth), Carnivore (canid and felid), and Cetartiodactyla (bovid and camelid) are all known from this site along with humans (Bustos et al., 2018). A fossil mastodon is also known from White Sands (Taylor-Montoya et al., 2015) and may also be present within the proboscidean tracks. Not only do the tracks occur in large concentrations, but they occur over a wide area allowing individual trackways to be followed for extended distances. The unique properties of the site make it ideal to explore the behavioural interaction of different Pleistocene track-makers (Bustos et al., 2018; Urban et al., 2019), including multiple extinct taxa which could not otherwise be observed in the coeval palaeontological record.

Evaporation of saline groundwater from the playa leads to surface gypsum salts which are eroded by the wind to supply the adjacent gypsum dunes (Kocurek et al., 2007, Fig. 1). At times during the Pleistocene the Tularosa Basin was occupied by a large water body (Palaeo-lake Otero; Allen et al., 2009). However, the degree to which (if at all) the centre of this former lake floor has been eroded to the current playa level is unclear, although erosional bluffs occur to the west (Fig. 2). What is evident, is that throughout the Pleistocene, the hydrological budget in the Tularosa Basin led to a range of water levels at different times associated with fluctuations in groundwater, precipitation, and inflow/ outflow to the basin. During the late Pleistocene when the tracks were imprinted, the playa was probably a seasonal patchwork of water bodies of varying size and were occasionally flooded (non-erosively) to form a single lake. It is perhaps significant that the maximum concentration of tracks occurs on the eastern side of the playa (Fig. 2) where a shelving surface would have been regularly, and frequently, transgressed-regressed by flood waters. The local relief (<0.5 m) in this area is more complex than elsewhere on the playa which would leave a diversity of potential water resources during waning floods. The interaction of freshwater, both from the dunes, and a suspected subsurface river (Lost River), with saline ground waters has led to the local formation of calcite/dolomite especially as track infills. Dolomite track infills were likely facilitated by standing water and algal mats (Marty et al., 2009). In some cases, the dolomite forms a hard layer at the base of the true track aiding excavation, while in other cases it infills the track such that the track now forms a pedestal. This contrasts with preservation on the

western side of the playa where tracks have negative relief universally, and the true track surface is more commonly defined by iron and salt horizons (Bustos et al., 2018). The site reported here is located on the eastern side of the playa on the 1189–1193 m surface shown in Fig. 2.

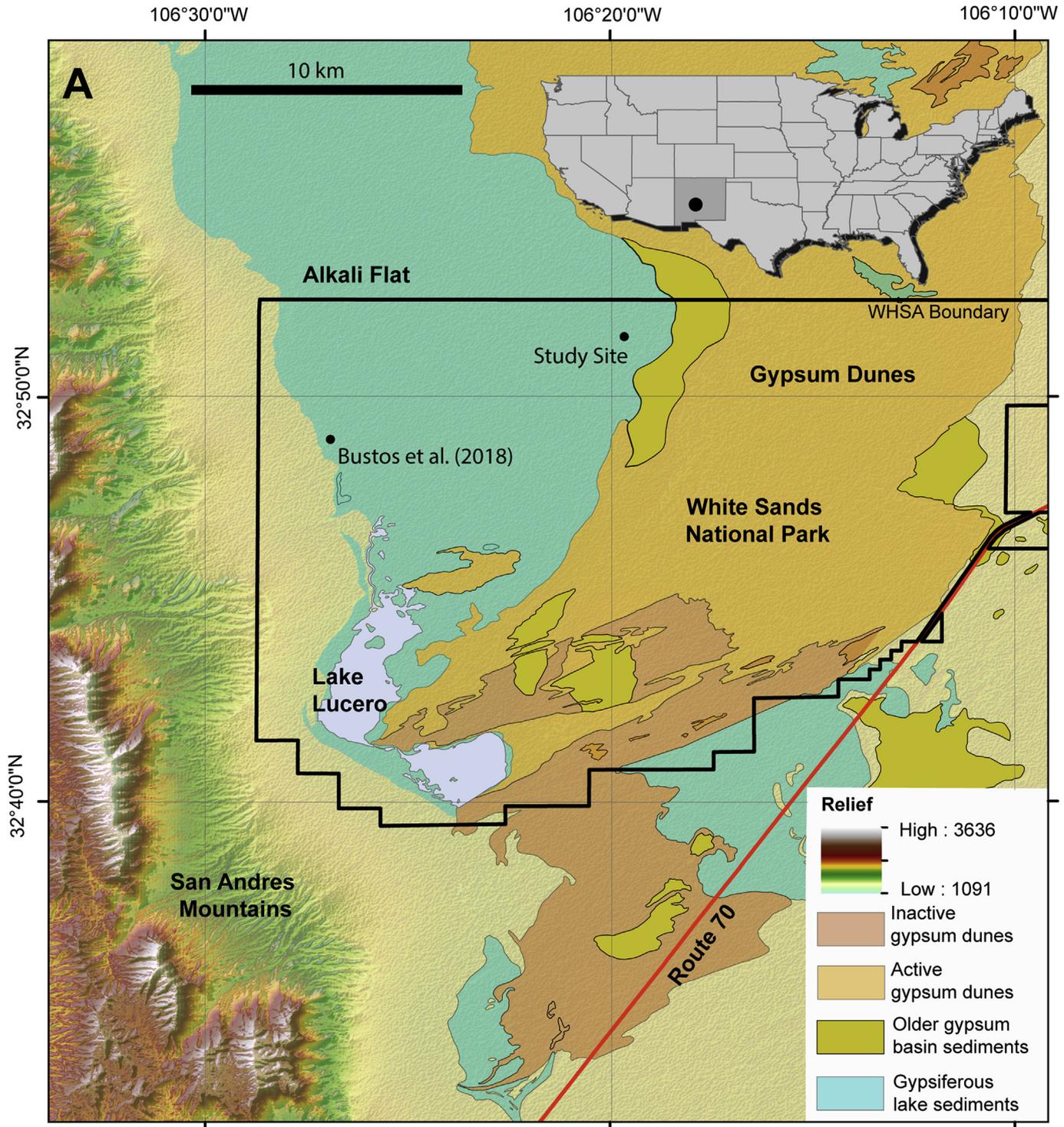
The precise geochronology of the tracks remains uncertain, despite attempts to date them using radiocarbon and OSL methods. Bustos et al. (2018) used summed radiocarbon dates for sloth and mammoth extinction and archaeological sites with established ages for human presence (or time-diagnostic artifacts) to define an overlap between megafaunal extinction and known human presence. This overlap forms the potential track-forming window. The most parsimonious interpretation of this window is that track formation occurred before 10 k BP, however the upper biostratigraphic limit depends on the arrival date for human colonisers in the Americas and more specifically at WNSA. Humans were present in North America sometime before 14.5 kya (Waters and Stafford, 2007; Waters, 2019; Ardelan et al., 2020; Becerra-Valdivia and Higham, 2020). They are known to have been in the Tularosa Basin since at least Clovis times as evidenced by the presence of Clovis (+Folsom) artifacts in private collections and professionally documented archaeological sites from the area (Holliday et al., 2019). Later Paleoindian sites which postdate the demise of ground sloths and mammoth are also present.

## 3. Materials and methods

Tracks were made by unshod humans, and are impressed into thinly bedded gypsiferous and siliciclastic muds and sands. They are visible only under specific moisture conditions which produce colour contrasts between the track infill and the surrounding sediment (Fig. 3A). Repeated field reconnaissance, and both aerial and geophysical survey allowed targets to be identified and excavated (Urban et al., 2018, 2019; Bennett et al., 2019). Once targets were located, they were gridded into 5 m squares and all tracks mapped and measured. Excavation of individual tracks occurred in the following manner. First the tracks were revealed at the surface in 2D by trowelling back the surface to a depth of a few centimetres to reveal the outline based on the colour/texture contrast between the track infill and the surrounding sediment. With the outline established the infill was gently brushed away to reveal the 3D morphology.

A camera elevated on a 5 m pole was used to create orthorectified photomosaics using Agisoft Pro Version 1.4.4 ([www.agisoft.com](http://www.agisoft.com)) prior to and after any excavation. Excavated tracks were digitally captured in close-up via photogrammetry using DigTrace Version 1.8.1 ([www.digtrace.co.uk](http://www.digtrace.co.uk)). A total of 427 tracks were identified (194 S, 233 N) of which 140 were excavated from seven locations (sub-localities A–G, Fig. 4; Supplementary Information). A sample of 90 was chosen from the 140 excavated tracks for analysis. Tracks were excluded due to damage caused by modern overprinting; presence of missile fragments (part of WNSA is a co-use area for military testing); accidental damage during excavation; the presence of roots; hard dolomite infills, and most commonly incomplete tracks.

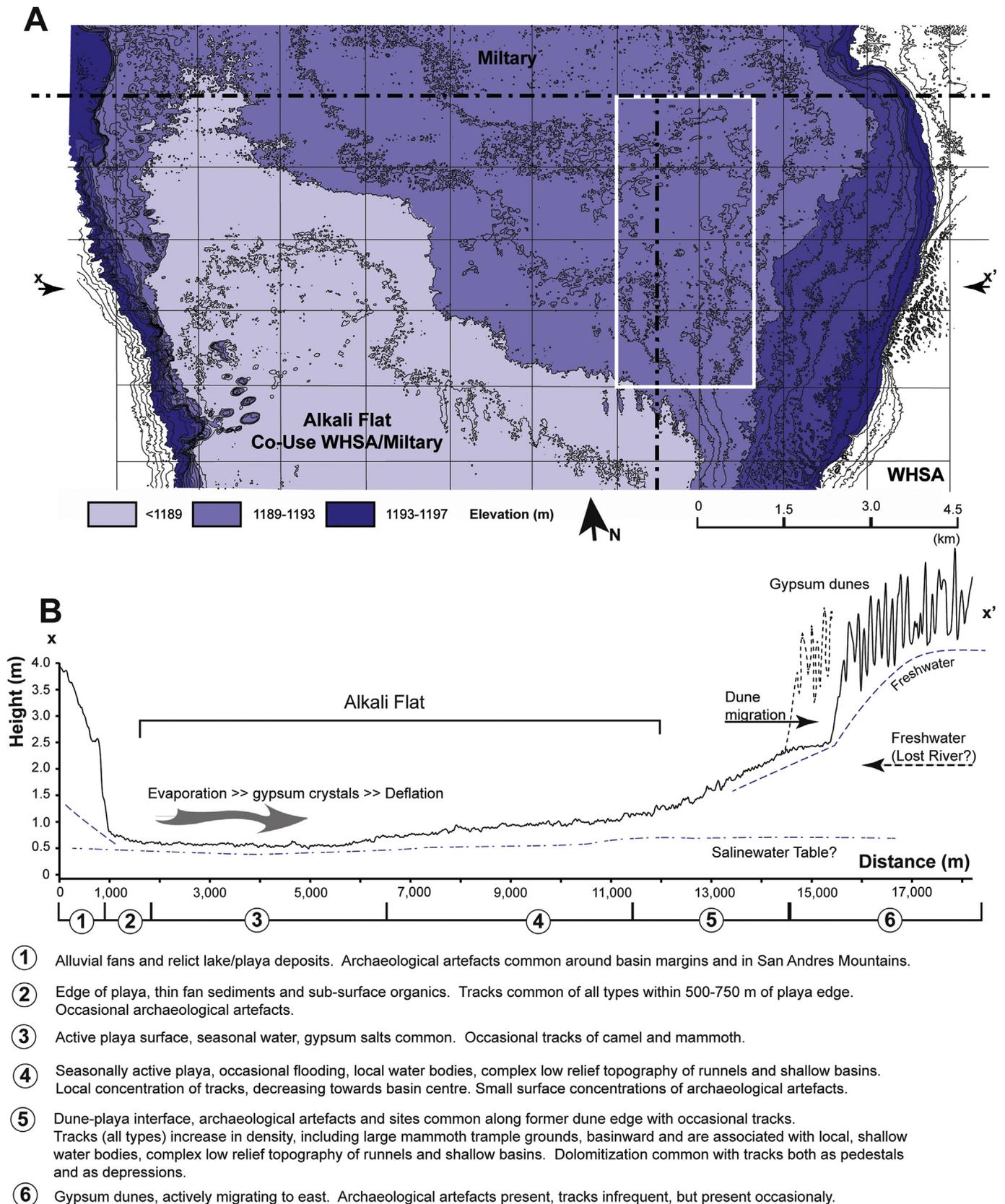
Biometric inferences from tracks were made following the best practice outlined in Bennett and Morse (2014) using two sets of landmarks placed digitally on the 3D models using DigTrace. One landmark set was used to determine the curvature of the longitudinal axis of the foot, defined as the line between the heel and second toe following the mid-line of the footprint and a second set used to determine basic track dimensions (Fig. 5A). Both landmark sets were first used to extract linear dimensions and the landmark coordinates were subject to a Generalised Procrustes Analysis operationalised in PAST Version 4 (Hammer et al., 2001). Measured



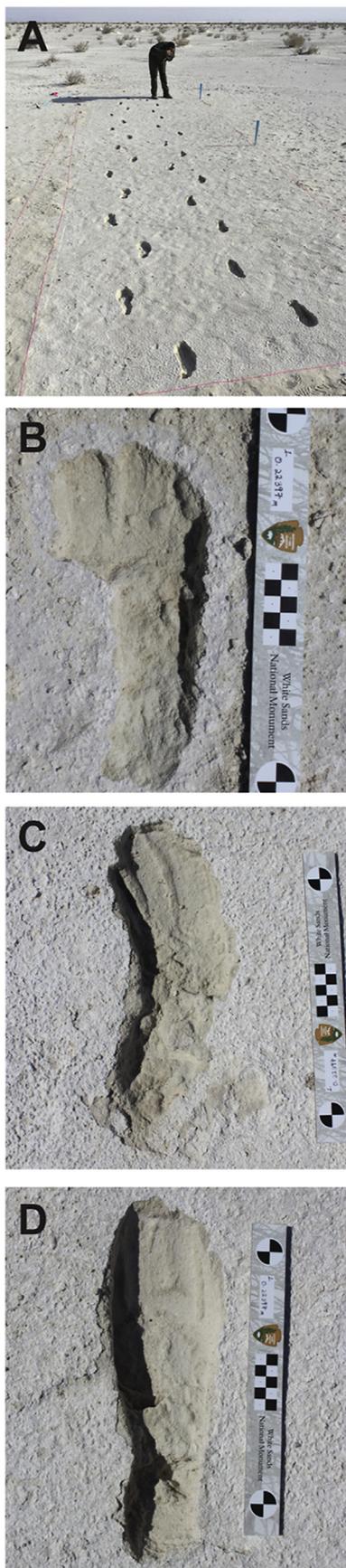
**Fig. 1.** Location map for Locality-3 White Sands National Park, showing the approximate location of the study site. Note that precise latitude and longitude for the site are only available on application to the National Park Service, in accordance with their statutory obligations.

footprint lengths were used to predict stature by applying Martin's ratio (0.15), which has repeatedly been found to positively predict stature in modern habitually unshod populations (Martin, 1914; Hrdlicka, 1935; Dingwall et al., 2013) and has been previously applied at fossilised ichnological localities, such as Laetoli (Tuttle, 1987) and Happisburgh (Ashton et al., 2014). ANSUR II (N = 3982; [www.openlab.psu.edu/data](http://www.openlab.psu.edu/data)) was used to determine hip height from foot length for the walking speed estimates following the well-established methods of Alexander (1976, 1984; see also,

Raichlen et al., 2008; Dingwall et al., 2013). Walking speeds were estimated directly from an 800 m orthorectified mosaic made along a continuous length of the visible trackway. The outline of unexcavated tracks (Fig. 3A) was sufficiently well-defined to allow accurate step and stride measurements to be made. These were calibrated against data from excavated sections and found to be accurate within  $\pm 0.7$  cm. Age estimations for excavated human tracks are based on data from UMTRI/CPSC Child Anthropometry Study (Snyder et al., 1977; N = 3901). For each whole number foot



**Fig. 2.** Summary of topography and geological setting of the tracks in the northern part of White Sands National Park. Elevation data is based in INSAR data; track density is estimated based on field reconnaissance and previous aerial survey. The precise location of the study site is not shown since federal law in the United States prohibit the disclosure of specific archaeological and palaeontological locality information within U.S. National Park Service areas, namely: Archaeological Resources Protection Act of 1979, National Parks Omnibus Management Act of 1998 and the Paleontological Resources Preservation Act of 2009. In general terms the site lies within the area depicted by the red box. Note that Alkali Flat contains unexploded ordnance (UXO) and should only be accessed with permission from the National Park Service. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 3.** Selection of photographs from the double trackway at White Sands National Park. **A.** Location-3A on the double trackway showing both the north and south bound

length in this dataset the associated subject ages were extracted and a mean age, with standard errors, was calculated for that length.

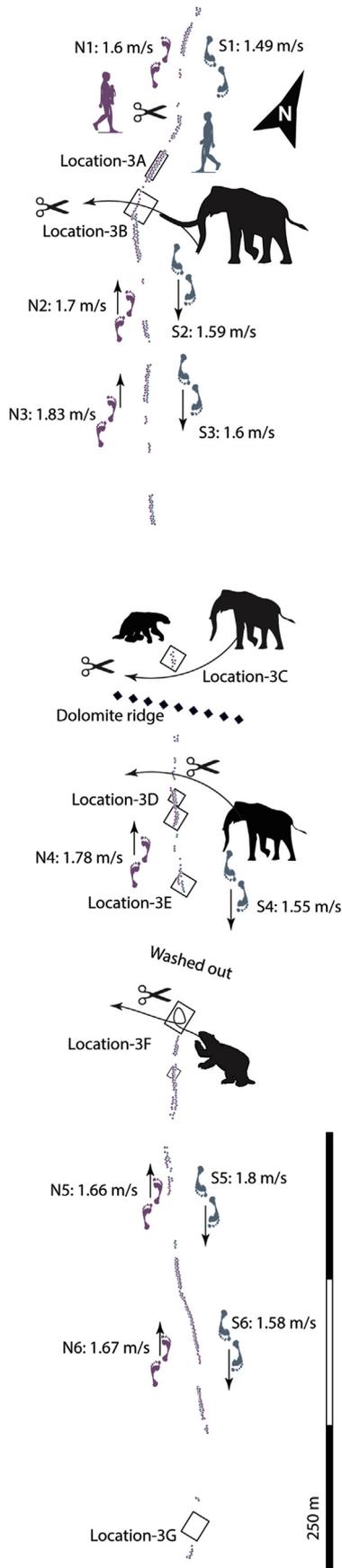
The morphological variability of the tracks was analysed initially from objective track outlines calculated using a modified version of the algorithm developed by Lallensack (2019). This R script automatically selects contours that are representative of the footprint, detects the steepest points along the track wall, and draws an approximating function between these points that serves as an objective outline. The algorithm was optimised to produce outlines that match human-made interpretive outline drawings as closely as possible (Fig. 5B). For the present paper, this involved tuning the script so that it selects a more external outline at the anterior and posterior ends of the footprint thereby capturing heel and toe details more accurately. Along the medial and lateral sides strict tracing of the steepest slope was maintained, however. Footprint length, width, and area are automatically calculated and exported. All outlines were batch-processed using the same settings to allow objective shape analysis. The resulting track outlines were subject to an Elliptical Fourier Analysis coupled with a Principal Components Analysis (PCA) to explore the variation in shape. To facilitate this analysis, all tracks were first brought into common orientation and alignment, by mirroring the left tracks.

An attempt was also made to classify the morphological variability within these tracks into a basic typology using the objective outlines. The first step was to calculate a pairwise dissimilarity measure between each pair of tracks using the area between turning functions (Arkin et al., 1991). The turning function measures the cumulative angle between two consecutive segments of a length-normalised polygon (i.e., segments that share a vertex; Fig. 5C). The starting vertex and the direction of travel (clockwise or anti-clockwise) are arbitrary for closed shapes. For comparison of two shapes, we therefore calculate the area between the turning function (Fig. 5C) of the first shape against all possible turning functions of the second shape and take the minimum distance as the given dissimilarity value. This distance matrix was then used as a basis for a Ward cluster analysis which minimises within-group variance and is recommended by Hammer and Harper (2008) for morphometric data. Using the clusters as a sampling guide 3D median tracks were calculated for each cluster (effectively a morphological type) using the compare function in DigTrace. The compare function uses matched landmarks to co-register a series of 3D tracks and then calculates measures of central tendency for those co-registered tracks (Bennett et al., 2016a; Belvedere et al., 2018; Bennett and Budka, 2018).

#### 4. Double human trackway

This consists of two parallel human trackways that run in a north-north-west to south-south-east direction. The accessible length is approximately 800 m however it extends further to the north for at least another 600 m into the White Sands Missile Range (Fig. 2). The southern end becomes progressively harder to follow as it approaches the former dune line. Both the north- and south-bound trackways show little deviation in direction, although the gap between the two trackways varies from as little as 0.5 to over 2 m and in at least two places the trackways cross (Fig. 4). Push-up structures around the prints are absent (Fig. 3C–E) which suggests that the surface sediment was either compressible, and therefore able to accommodate the foot volume without sediment

tracks and the near-parallel alignment of the two tracks. **B.** Right foot on the south bound trackway (S046). **C.** Typical track on the north-bound trackway showing the curved longitudinal axis. **D.** A straight track on the south-bound trackway.



**Fig. 4.** Summary diagram for part of the double trackway. The individual tracks were surveyed with a Total Station and heel points are plotted for 427 tracks. For walking

displacement, or alternatively that the surface has been lowered after imprinting by erosion (e.g., Wiseman and De Groot, 2018). The track depth is uniform forefoot to heel suggesting a firm sub-surface layer at a depth of 50–65 mm. This transition corresponds to a change from a single massive re-worked near-surface unit (<100–150 mm deep) of gypsum-rich silty fine sand and a sub-base consisting of horizontally stratified and massive units (100–300 mm thick) of silt-rich gypsum with units delineated by discontinuous sand stringers and shallow scours. This sub-base is extremely well-consolidated and resists excavation except with power tools. This sedimentological model applies along the whole length of the trackway. The track-fill consists of a coarse-gypsiferous sand, including in some cases coarse granular gypsum crystals with occasional dolomite clasts at the base. Surface re-working by both wind and insects of the infill has concentrated root fragments and seed heads of native *Allenrolfea occidentalis*. Radiocarbon dating of these fragments gives modern dates within the last 30 years. Ground penetrating radar from various sections of the double trackway (Urban et al., 2019) indicates sub-horizontal layers of sand and silt forming discontinuous sheets at depth. The observed morphological variability is therefore unlikely to be caused by macro-scale sedimentological variations along the trackway unlike that described from a Namibian trackway by Morse et al. (2013). Fig. 6 provides a selection of colour-rendered 3D models of individual tracks from several locations. Thumbnails for all of the excavated tracks can be found in the Supplementary Information (Figs S1 and S2). A typical length of the double trackway is shown in Fig. 7 and the individual tracks are shown in Fig. 6A.

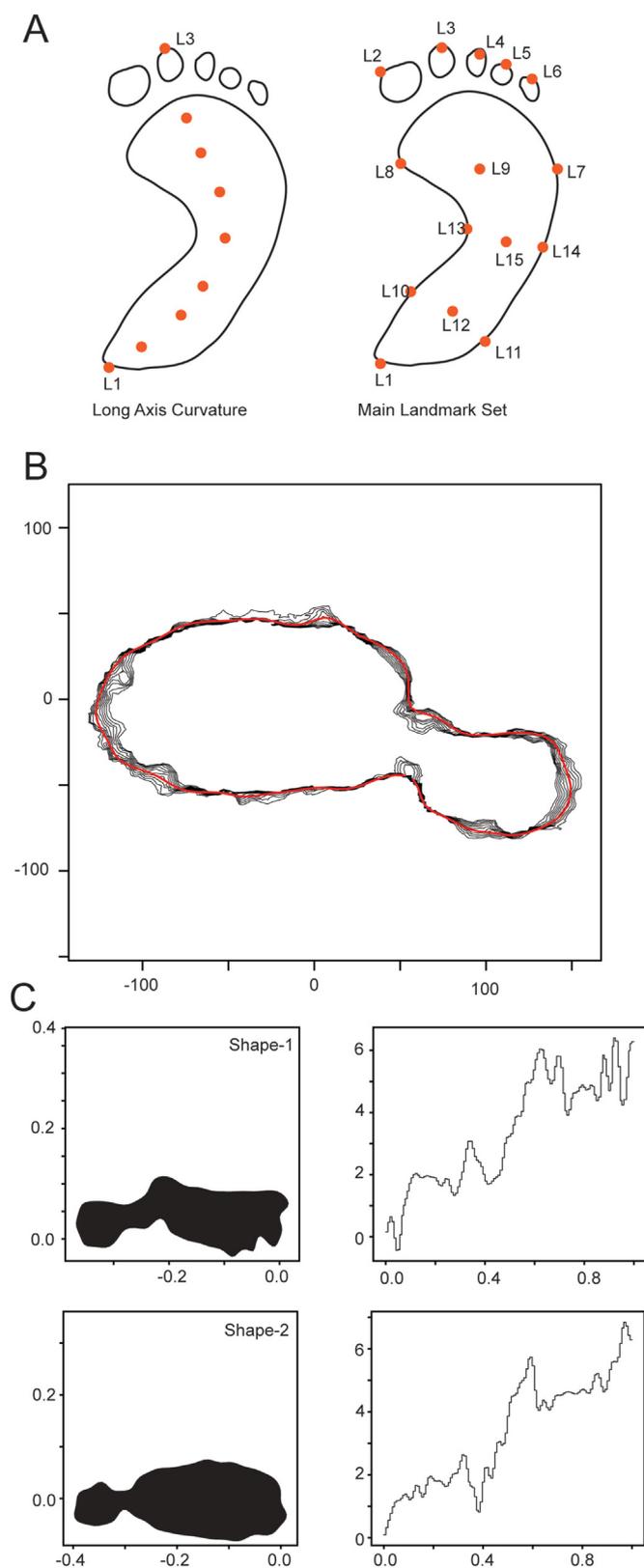
#### 4.1. Child tracks

In at least three locations, the double trackway is associated with individual child tracks (Figs. 6B, D and 7). The best example is a series of partially overprinted tracks, located between the two trackways, at the northern end of Location-3A and at the southern end of Location-3E (Fig. 4). Based on size these tracks were probably made by a child less than three years old, using the growth curve of Snyder et al. (1977) as a guide. A clear trackway of child prints at Location-3A is absent, and the limited impressions suggest that the child was set down briefly by the trackmaker. If the child was carried north-bound then the toes of the child print face those of the adolescent, which is consistent with a front carry. Twisting the child so that they face the same way as the track-maker cannot be ruled out, however. Either way, we hypothesise that the child was placed momentarily on the ground while adjustments were made. The north-bound track does not show parallel steps or signs of trampling associated with a prolonged pause, although the north-bound step length does shorten towards this point, and then lengthen again. The south-bound trackway does not show a step length variation. At the southern end of Location-3E where there is a more complex trampled area including several small child tracks and some adult tracks out of trackway alignment, this might imply a more prolonged rest (Fig. 6D). The exact track sequence is again not clear, since the area has been partially washed out by water from an adjacent scour.

#### 4.2. Double trackway morphology

Classic human track morphology, such as that defined by Kim et al. (2008, *Hominipes modernus ichtnogen*; see also: Lockely et al., 2016) is rare on both the north-bound and south-bound

speed, see Table 1. The scissor symbols indicate locations of cross-cutting relationships between tracks.



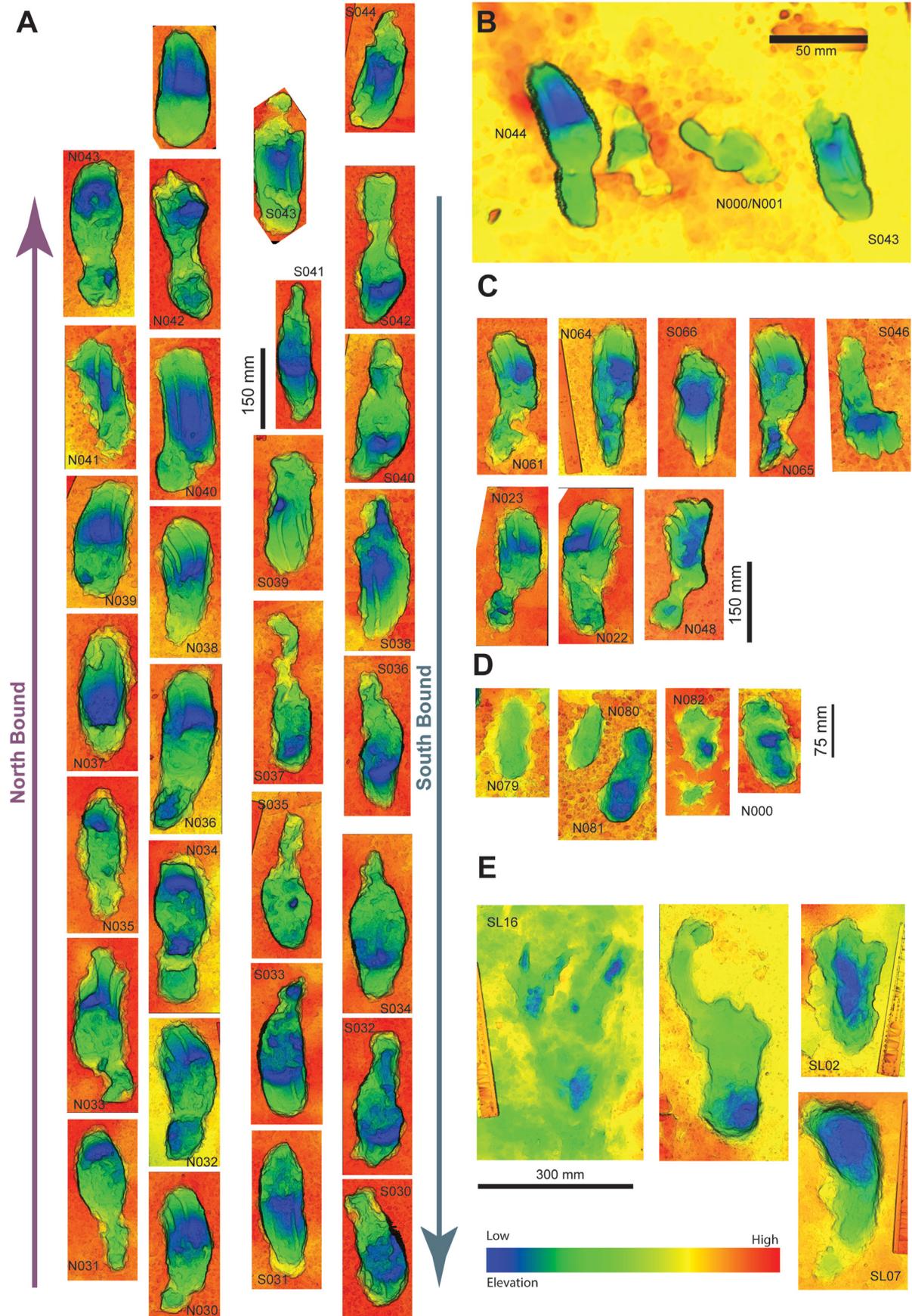
**Fig. 5.** Methods summary. A. The two sets of landmarks used, the first defines the longitudinal axis of a track and was used to determine axial curvature, while the second was used for conventional distance measures. B. Example of an objective track outline determined by the algorithm of Lallensack (2019). C. Illustration of the turning point analysis conducted on the track outlines.

trackways. Track S046 is perhaps the best example (Figs. 3C and 6C). The average length of the tracks (heel to first toe;  $N = 90$ ) is  $233.6 \pm 5.2$  mm for the north-bound trackway and  $247.6 \pm 5.9$  mm for the south bound trackway (Table 1). Using the Snyder et al. (1977) growth data gives a maximum possible age range 12.3–13.6 years for the north-bound trackway and 13.9–14.2 years for the south bound trackway. This should probably be considered a minimum age range, due to the uncertainty with respect to the applicability of a modern growth curve, and the complicating issues of nutrition and ethnic origin (e.g., Roberts, 1953; Katzmarzyk and Leonard, 1998; Ruff, 2002). In addition, footprints may overestimate foot size by the order of 5% (Hatala et al., 2020). Hatala et al. (2020) suggested, using the Snyder et al. (1977) dataset employed here for age estimates, that female feet reach their maximum length at around 14 years (16–17 for males). This was based on a visual inspection of the data, and is not a precise or definitive biological threshold, but age and foot length do become increasingly decoupled from one another after this age. Therefore, while the data is indicative of a track-maker(s) in their early-to mid-teens, if they were female, it is possible that they could be older.

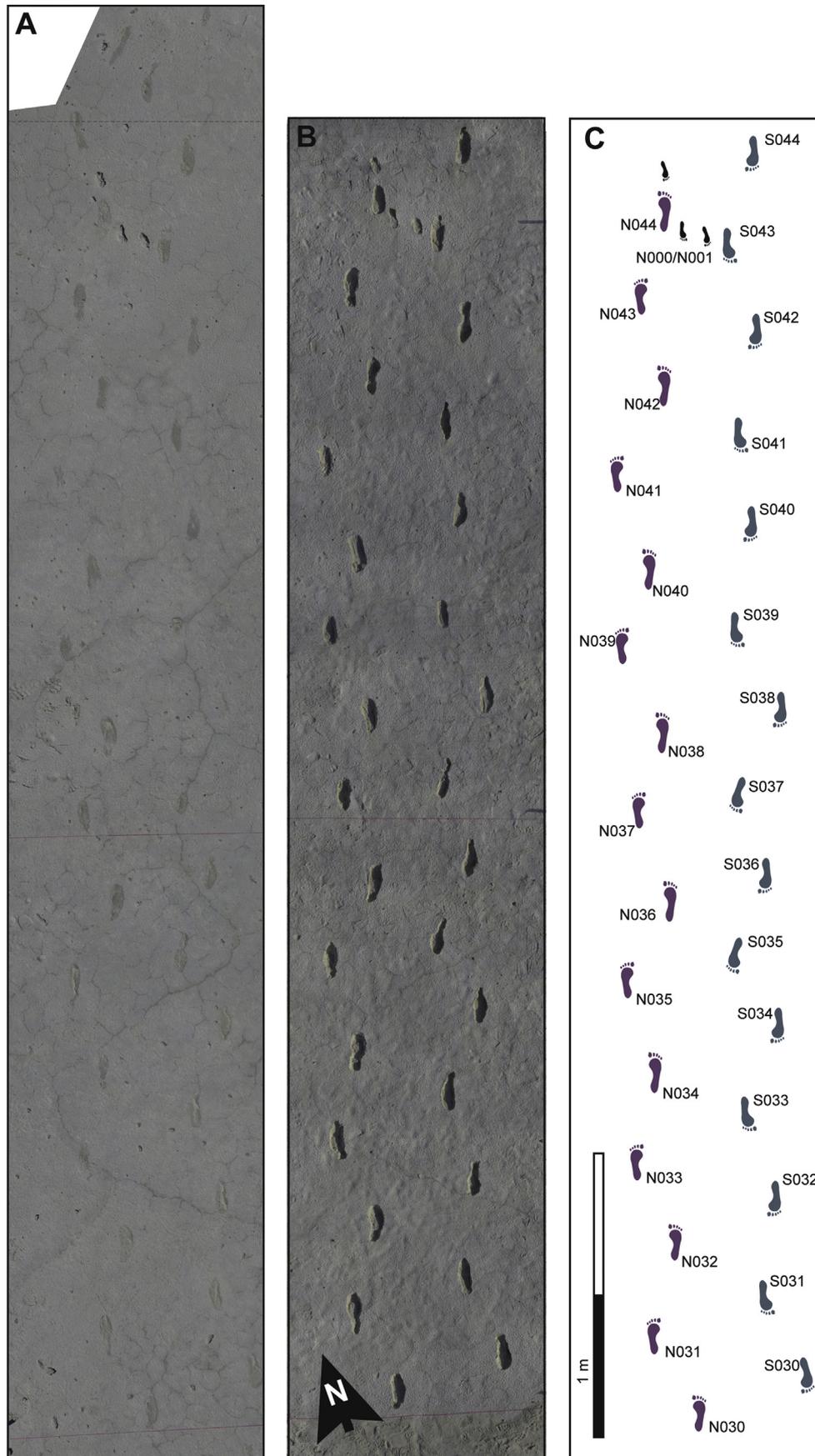
Using placed landmarks (Fig. 5A), we find that the basic dimensions are similar and not statistically different from one another (Fig. 8; Table 1). The variability around each measure is high and the median gives a more stable view of the respective foot dimensions. The right footprint is slightly larger south-bound, both in terms of length and heel breadth, but not in terms of forefoot width. The overall area of the track is also larger for the right foot. North-bound the left foot is longer, with a larger forefoot, and the median gives a larger area. In terms of curvature the north-bound left foot tracks are more curved and also more variable. In summary, north-bound left footprints are slightly larger, while the right foot is typically more curved along the long axis. South-bound there is no real difference in axial curvature, but the right foot is larger in terms of length and area. In other words, the asymmetry is mirrored between the north- and south-bound journeys, although the overall variance is high, precluding recognition of clear statistical differences, despite the large sample.

To further explore the morphology of the tracks, the outlines of 90 excavated tracks were compared using an Elliptical Fourier Analysis (EFA) combined with a PCA (Fig. 9). No statistical separation was apparent for a combined sample with both north- and south-bound tracks included and the first component accounts for 31% of the variance (Fig. 2.5%, 26.9%; Fig. 97.5%, 40.4%, Bootstrapped  $N = 1000$ ). What is present, however, is an apparent asymmetry in the skewness of the distribution of the first principal component when comparing the north- and south-bound trackways (0.51 versus  $-0.59$ ). The north-bound tracks show only a 49% probability of non-normality, while the south-bound have a 93% probability of being non-normal. The tracks of the south-bound trackway are negatively skewed favouring narrower tracks, while the tracks of the north-bound trackway are more symmetrical around the range of shapes present, although in the case of left tracks they show both a greater variance and a slight positive skew (Fig. 9). Variation around the second and third principal components is symmetrical. In summary, the left tracks, north-bound, have a greater tendency toward shapes that are broader, while the right tracks, south-bound, tend towards narrower shapes.

The morphological variability in the tracks was classified into a basic typology using turning point functions derived from the objective outlines. A dissimilarity distance was calculated from the functions for all pairwise combinations of tracks in the sample ( $N = 90$ ). This was then used in a Ward Clustering algorithm to create a dendrogram for both the north and south trackways. A median track was then created by co-registering the component tracks in each cluster using DigTrace (Bennett and Budka, 2018,



**Fig. 6.** Individual colour-rendered models along the double trackway at WHSA. Each 3D model was created, auto-rotated and cropped in DigTrace V.1.8.4 ([www.digtrace.co.uk](http://www.digtrace.co.uk)) and colour-rendered in CloudCompare (<https://www.danielgm.net/cc/>). A. Tracks at Location-3A, see Fig. 7 for actual positions and Fig. 4 for location. B. Child tracks at the northern end of Location-3A, see Fig. 7 for actual positions and Fig. 4 for location. C. Selection of tracks at various locations along the double trackway. D. Child tracks at Location-3E and Location-3A see Fig. 4 for location. E. Sloth tracks at Location-3F, see Fig. 4 for location. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

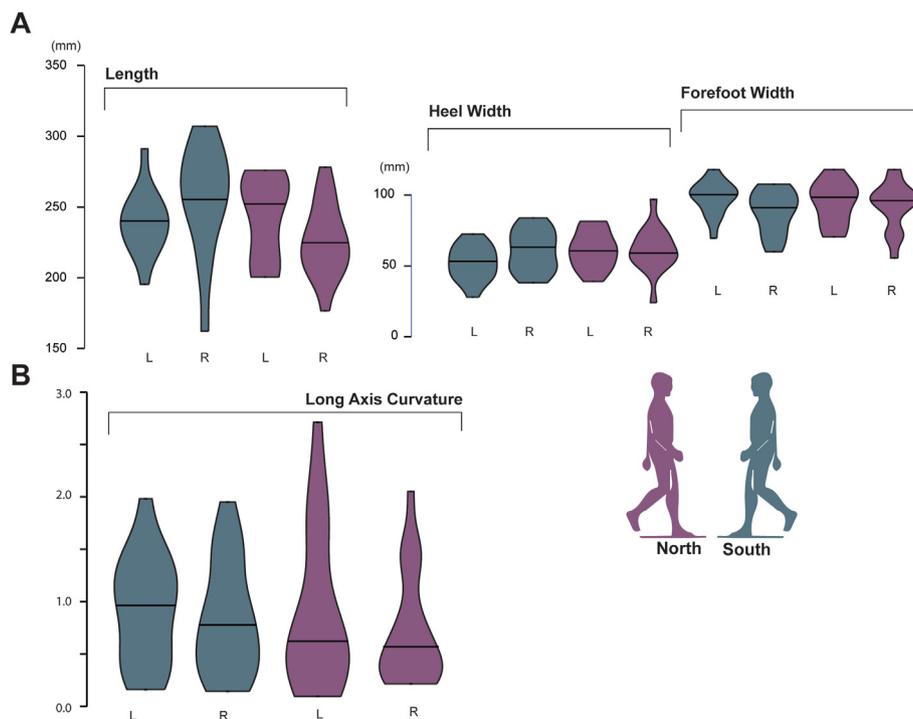


**Fig. 7.** Location-3A on the double trackway at WSHA. The illustrated sections show how uniform the tracks are, but also the morphological diversity present. See Fig. 4 for the location of this section. GPR data for this test section is available in Urban et al. (2019). A. The unexcavated trackway. B. Trackway following excavation. C. Track codes see Fig. 6A for details.

**Table 1**  
Landmark dimensions in mm for the two trackways split by right and left feet.

		Length <sup>a</sup>		Length <sup>b</sup>		Heel Width		Fore Foot <sup>c</sup>		Ball Width		Area <sup>d</sup>	
		R	L	R	L	R	L	R	L	R	L	R	L
South	N	23	20	23	20	23	20	23	20	23	20	23	20
	Min	162.19	195.40	194.00	214.95	38.12	28.00	104.36	113.58	60.05	69.68	9939.94	13764.96
	Max	307.08	306.24	313.29	331.67	84.04	86.52	224.24	188.23	107.76	118.00	29088.23	26105.93
	Mean	250.09	241.96	267.96	274.15	61.53	57.61	159.75	153.43	87.32	95.89	18205.23	18736.26
	Std. error	7.71	6.14	7.77	6.37	2.59	3.64	7.15	4.04	3.08	2.80	1051.64	713.99
	Std	36.99	27.45	37.27	28.51	12.42	16.28	34.28	18.07	14.79	12.51	5043.50	3193.05
	Median	255.21	240.67	281.21	272.70	63.39	55.59	158.90	157.07	91.14	99.68	18852.98	18234.05
North	N	26	20	26	20	26	20	26	20	26	20	26	20
	Min	176.71	168.00	215.84	172.42	24.04	39.00	101.80	116.78	55.54	70.53	13249.73	11196.95
	Max	294.30	289.78	319.70	343.36	97.10	93.09	196.38	177.81	117.98	118.07	29217.73	27722.61
	Mean	236.23	243.01	273.31	264.14	65.30	63.25	144.47	152.46	91.01	91.96	19615.71	18911.07
	Std. error	5.70	7.18	5.26	8.44	3.22	3.24	4.67	4.15	3.32	3.05	756.55	976.25
	Std	29.05	32.10	26.31	38.66	16.41	14.47	23.82	18.57	16.94	13.64	3782.74	4473.73
	Median	233.19	250.13	270.77	275.15	64.93	64.85	147.27	150.53	95.03	91.47	18918.16	19329.31
	Skew	0.12	-0.75	-0.25	-0.78	0.00	0.17	0.32	-0.36	-0.71	0.10	0.66	-0.04

<sup>a</sup> Length based on landmarks [L1 to L3, Fig. 5A].  
<sup>b</sup> Length based on objective outlines.  
<sup>c</sup> Fore foot [L3 to L15, Fig. 5A].  
<sup>d</sup> Area is based on the objective outline.

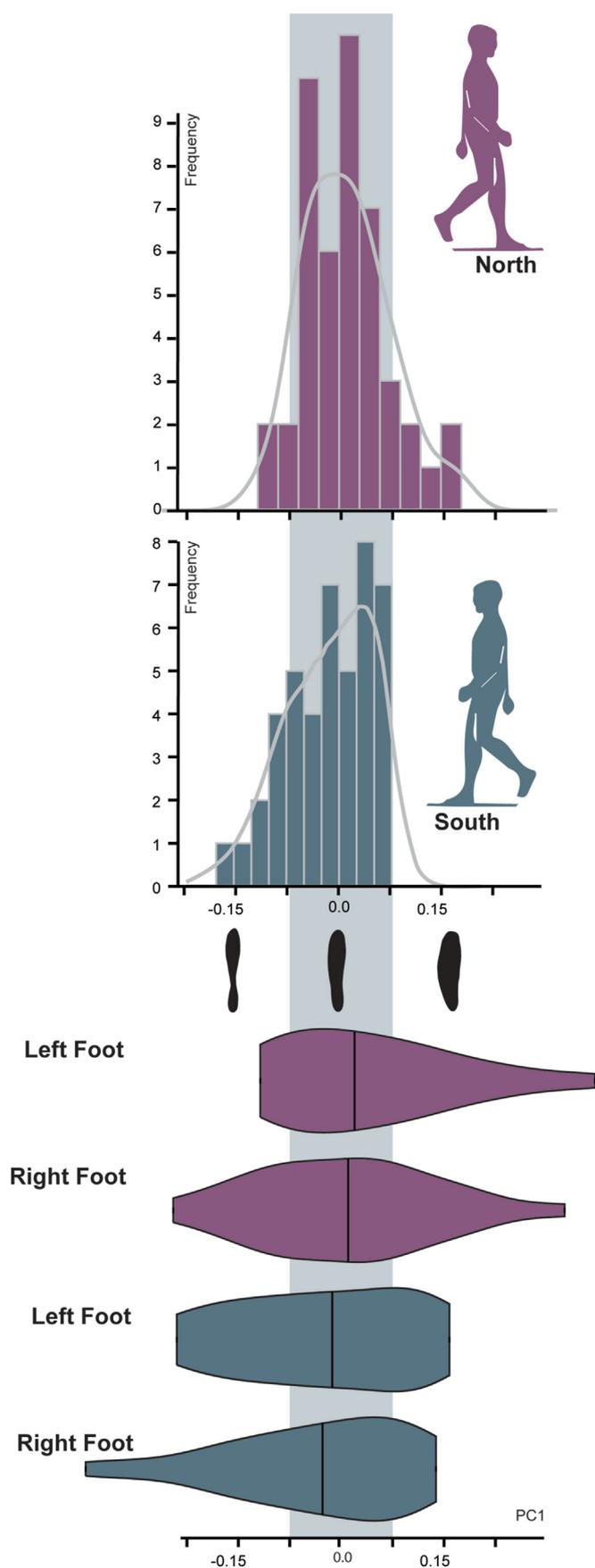


**Fig. 8.** Major track dimensions for a sub-sample of 90 tracks from the double trackway at WHSA. Landmarks for measurements are shown in Fig. 5A. Sampled tracks are shown in Table S1 and S2.

Fig. 10). There are five principal morphological types in the north-bound trackway, with the modal type (Type-N2) distributed 42–48% between left and right tracks, respectively. This track type consists of a broad, gently curved track, with prominent fore-foot slippage and a narrow tapering heel. Two of the other track types (Types-N1 and -N3) are more commonly associated with left tracks and show more angular deviations with an outline apex on the lateral side of the foot associated, one presumes, with lateral slippage along the coronal plane. The remaining two types (Types-N4, -N5) are straighter and with extension along the sagittal plane and tend to be associated with right feet. This is reflected in the slightly

greater length, and variability therein, of the right feet and also reflects the contrasts in track curvature reported in Fig. 8. South-bound there are six morphological types, the modal one being Type-S2 and is associated with an even split between right and left feet. Type-S4 and -S6 are associated with predominately left and right feet, respectively. Three of the types (Type-S3, -S4 and -S5) are associated with tapering heels and have some longitudinal compression parallel to the sagittal plane.

In summary, the north- and south-bound trackways are indistinguishable in terms of broad characteristics, but interestingly are also not identical either. Both trackways, especially the north-



bound one, shows some asymmetry between the left and right feet, especially in terms of variability. The left tracks of the north-bound trackways show evidence of rotational slippage, while the right tracks are more elongated with slippage in the forefoot along the sagittal plane. The south-bound tracks show less rotational slippage and elongated forms are more common.

### 4.3. Trackway kinematics

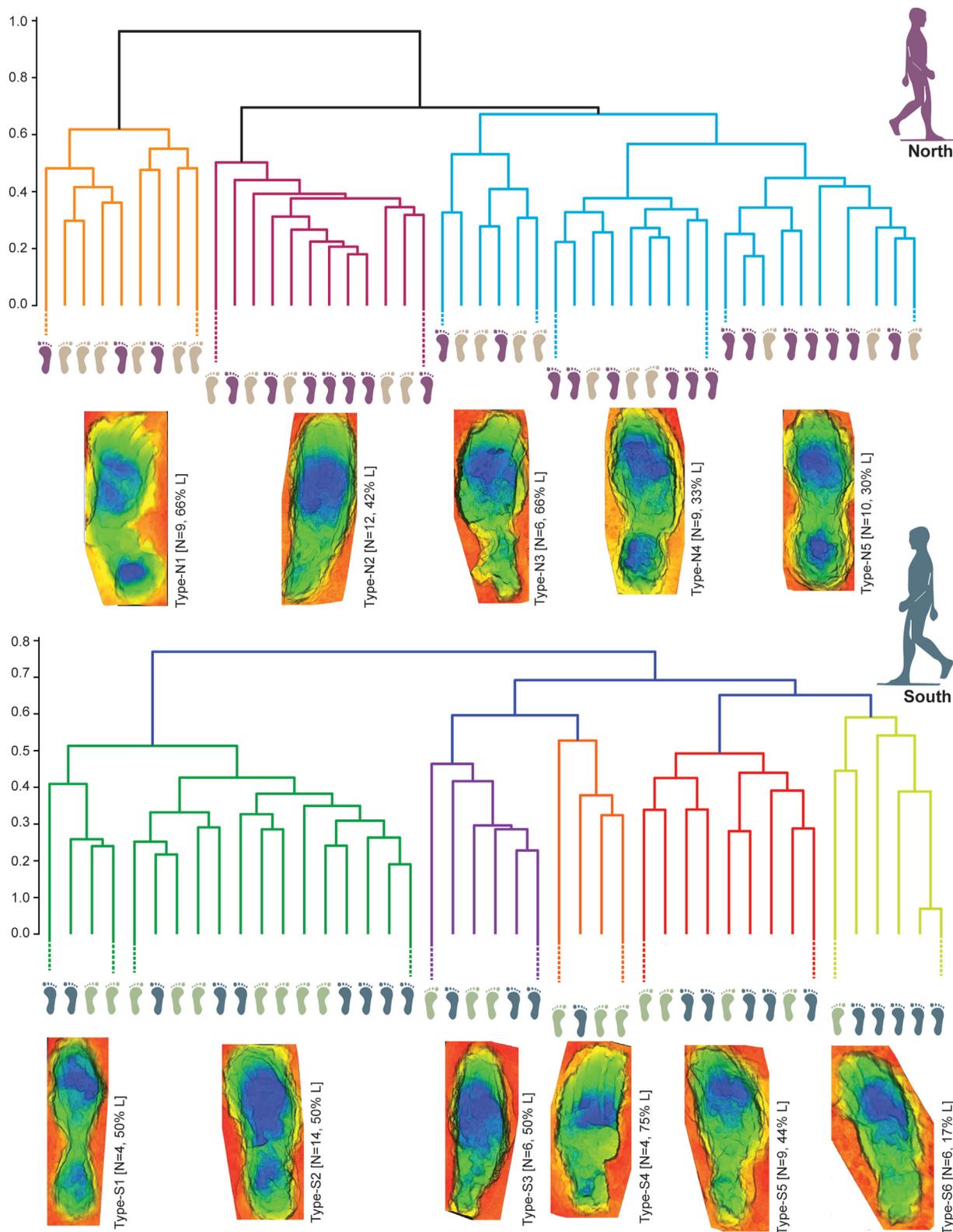
Both trackways show a consistent step and stride length (Figs. 4 and 7 and Table 2), although the width between tracks varies as the individual(s) appear to have picked their way over what must have been slippery terrain. We can estimate the walking speed using an orthorectified mosaic of a large section (800 m) of the track along which unexcavated tracks are visible in particular sections giving us a sample of 427 stride and step length measurements in six sections (Fig. 4). Using the average track length estimates for the north-bound trackway we obtain an average speed of  $1.7 \text{ ms}^{-1}$  ( $N = 233$ ) ranging from  $1.6$  to  $1.8 \text{ ms}^{-1}$ . Estimates for the south-bound trackway range from  $1.49$  to  $1.8 \text{ ms}^{-1}$  with an average of  $1.6 \text{ ms}^{-1}$  ( $N = 194$ ). Both samples are not normally distributed (Shapiro-Wilk  $p < 0.001$ ) both having a slight positive skew (1.072 south and 0.979 north) and while the two speeds are similar south-bound they are statistically lower than those north-bound (Mann-Whitney,  $p < 0.001$ ). The positive skew reflects larger step lengths where the individual(s) is over-reaching to avoid wetter patches/puddles, perhaps. These over-reaching steps are often associated with more irregular morphologies. The Froude Numbers fall below 0.5 normally accepted as the transition from running to walking, although Jordan and Newell (2008) suggest that the transition starts at around  $1.4 \text{ ms}^{-1}$ . Given that the substrate was clearly slippery, as indicated by the morphological variability, the pace is both fast and remarkably consistent over the whole length of the trackway in both directions.

### 4.4. Interaction with Mega-fauna

The two human journeys are bracketed in age, both on geological and human time scales, by the interaction with other animal tracks. A minimum of three mammoth trackways crosscut (or are crosscut by) the double human trackway either obliquely or perpendicular (Fig. 4). A large number ( $>10$ ) of other mammoth trackways can be traced across the axis of the double trackway, although their precise age relationship to it is uncertain. There appears to have been a general east-west movement of mammoths across the site. These tracks are oval to circular in shape with axial-lengths between 350 and 754 mm based on surface expression, which probably exaggerates the true dimensions (Bennett et al., 2019). The tracks are similar to mammoth tracks described previously at WHSA (Lucas et al., 2007) and are ascribed to the ichnospecies *Proboscipeda panfamilia* as defined by McNeil et al. (2007). Mastodon remains are known from the Tularosa Basin, but based on size the tracks seem more likely to have been made by Columbian Mammoth (*Mammuthus columbi*).

Perhaps the best age-relationship between the proboscidean and human tracks is found at Location-3B (Location-3B, Figs. 4 and 11). Here tracks of the north-bound human trackway are deformed and partially closed by deformation in front of a mammoth track (Bennett et al., 2019), the same mammoth track is, in turn, crosscut by two tracks of the south-bound human trackway. Not only does

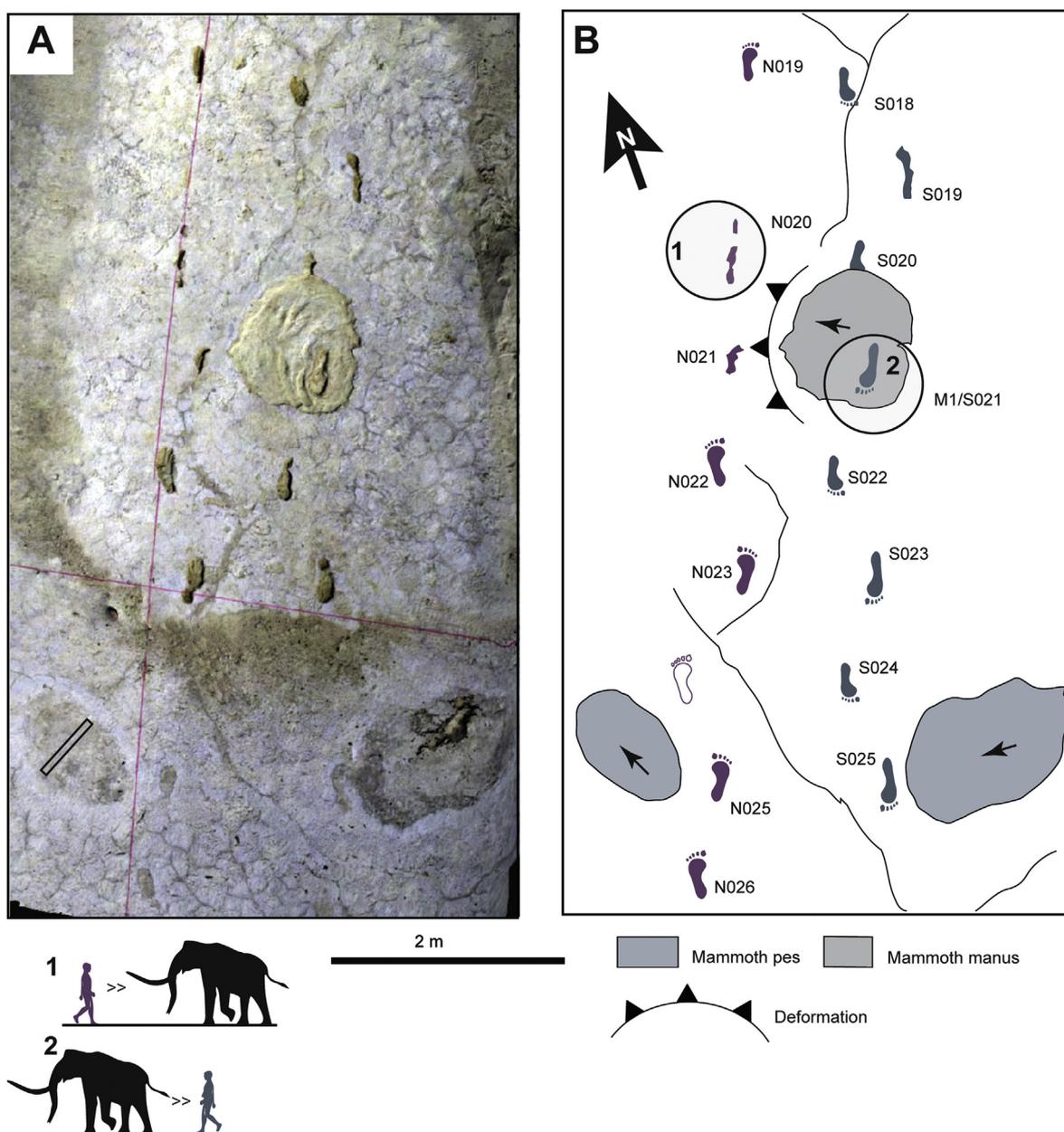
**Fig. 9.** Distribution around the first principal component showing the contrast in skewness between the north- and south-bound trackways. Kernel density is shown in the two histograms and in the violin box plots.



**Fig. 10.** Results of a cluster analysis performed on a similarity distance matrix derived from comparison of turning function data for the track outlines within the sample of 90 tracks. For each major cluster, a median track was created using DigTrace from the component tracks in that cluster. If the percentage of left tracks is greater than 51% then the track is shown as a left.

**Table 2**  
Velocity estimates for the six sections of the double trackway. See Fig. 4 for position of each sampled track section.

Section	Av Track Length	Error	Stride Length	Step Length	Hip Height	Froude Number	Velocity	Max Velocity	Min Velocity
S-1	23	24.76	5.92	132.51	66.43	0.27	1.49	1.54	1.44
S-2	28	24.76	5.92	136.11	67.58	0.33	1.59	1.64	1.54
S-3	48	24.76	5.92	137.80	69.15	0.32	1.60	1.65	1.55
S-4	24	24.76	5.92	135.85	67.48	0.29	1.55	1.60	1.50
S-5	19	24.76	5.92	147.26	73.29	0.40	1.80	1.86	1.75
S-6	52	24.76	5.92	136.91	68.63	0.30	1.58	1.63	1.53
<b>Av</b>	<b>194</b>					<b>0.317</b>	<b>1.601</b>	<b>1.653</b>	<b>1.552</b>
N-1	17	23.36	5.21	134.34	67.34	0.32	1.60	1.65	1.56
N-2	22	23.36	5.21	138.43	69.33	0.37	1.70	1.75	1.65
N-3	56	23.36	5.21	143.93	71.39	0.43	1.83	1.88	1.77
N-4	20	23.36	5.21	142.84	71.41	0.39	1.78	1.84	1.73
N-5	44	23.36	5.21	136.74	68.77	0.35	1.66	1.71	1.62
N-6	74	23.36	5.21	137.39	68.47	0.35	1.67	1.72	1.63
<b>Av</b>	<b>233</b>					<b>0.370</b>	<b>1.708</b>	<b>1.759</b>	<b>1.660</b>



**Fig. 11.** Location-3B interaction of a series of mammoth tracks with the double human trackway. See Fig. 4 for location.

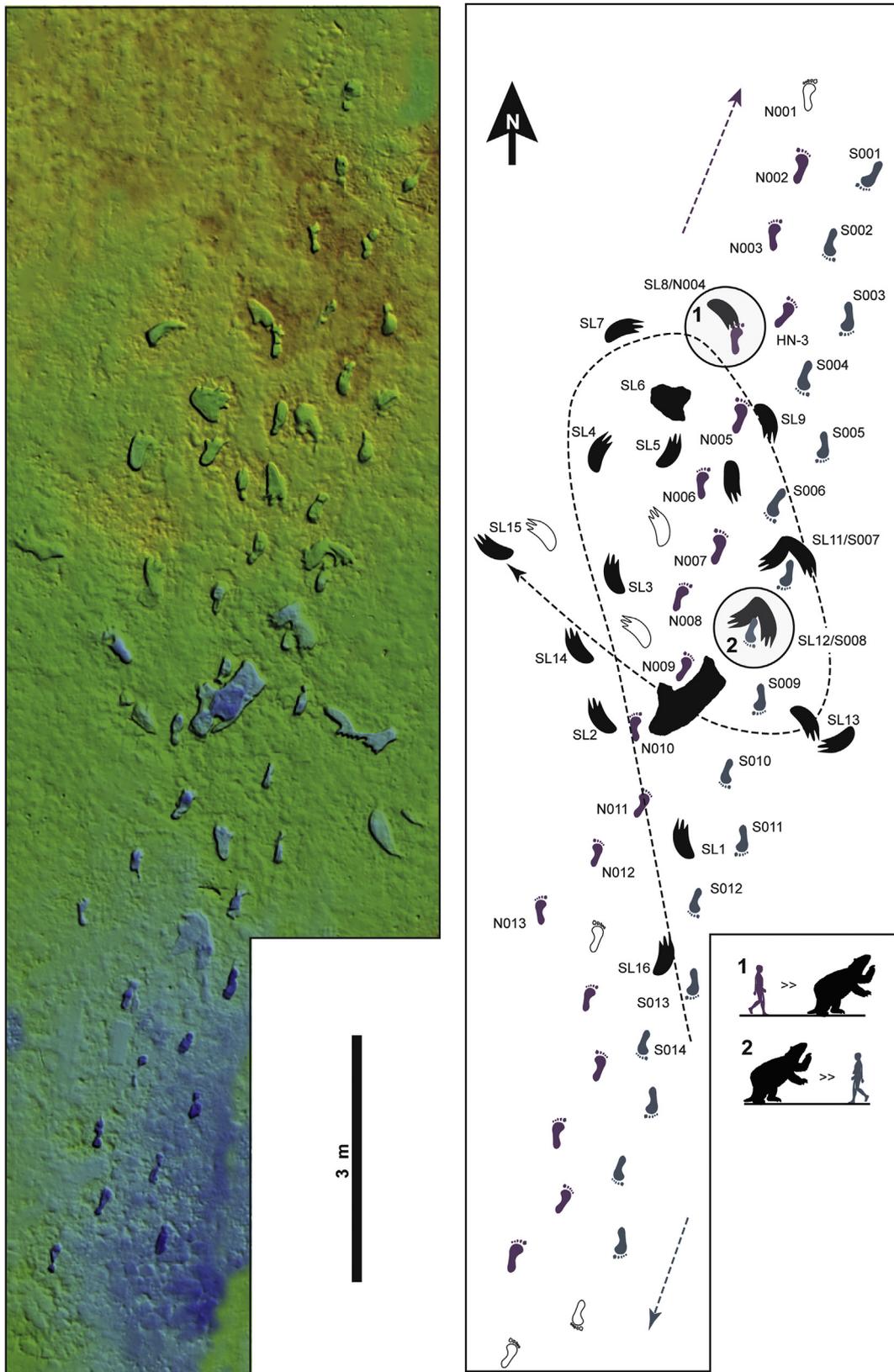
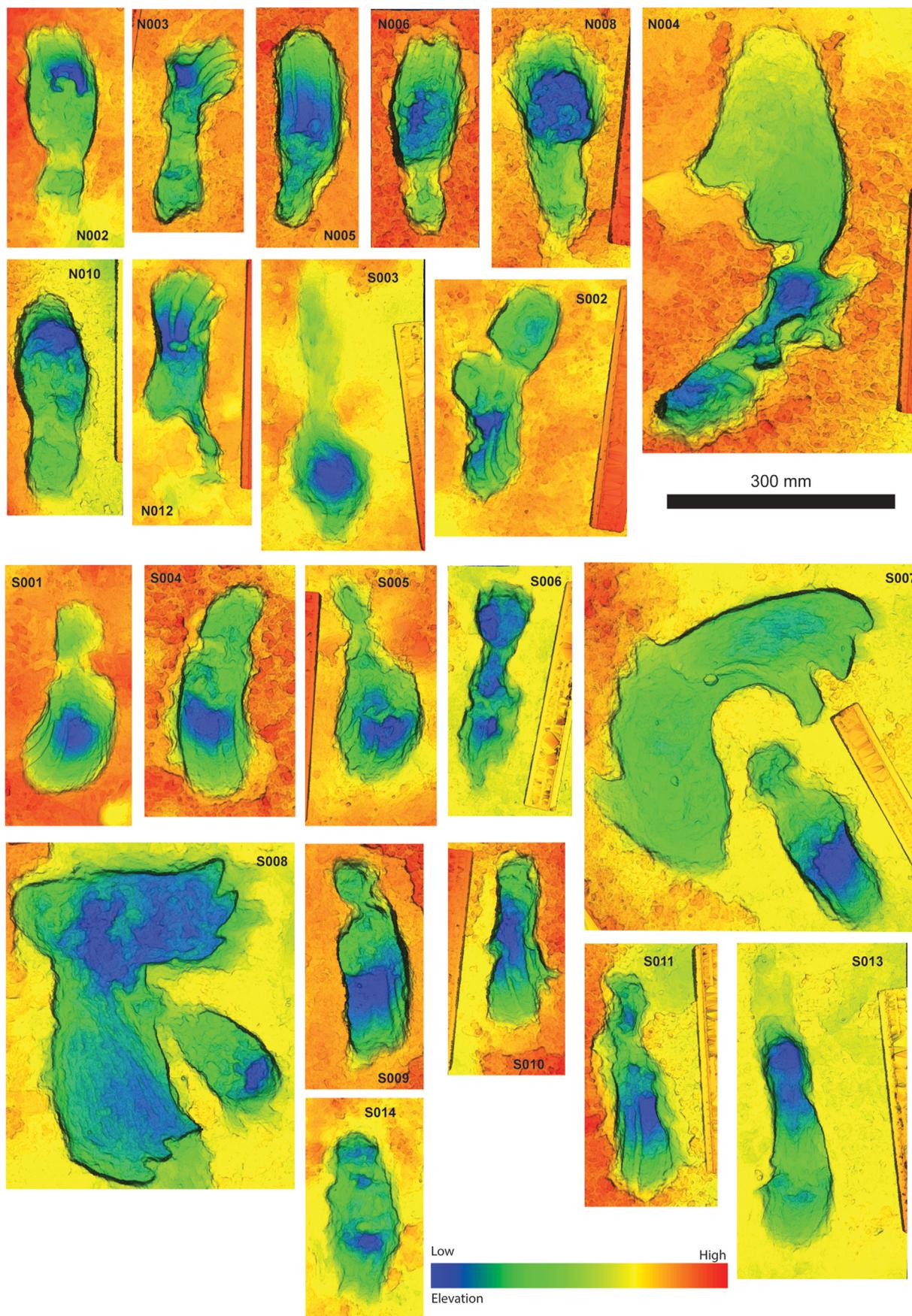


Fig. 12. Location-3F interaction of sloth and double human trackway, see Fig. 13 and 6 for individual tracks.



**Fig. 13.** Colour-rendered 3D models from Location-3F, the index to the tracks is shown in Fig. 12. Each 3D model was created, auto-rotated and cropped in DigTrace V.1.8.4 ([www.digtrace.co.uk](http://www.digtrace.co.uk)) and colour-rendered in CloudCompare (<https://www.danielgm.net/cc/>). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

this tie the two events together in terms of biostratigraphy, but also places a constraint on the time between the two human journeys, likely a matter of a few hours. The mammoth track does not indicate any sort of a reaction on the animal's part to the presence of humans or human tracks. Either the mammoth cannot scent the human trackway, or is not threatened by it. Given the remarkable olfactory ability of modern elephants (von Dürckheim et al., 2018), the former seems unlikely. The pes tracks are 433 and 416 mm long, while the manus is between 724 and 834 mm long. In a range of mammoth track studies in North America (e.g., McNeil et al., 2005; Retallack et al., 2018) modern elephant ontological and body-mass data (Western et al., 1983; Lee and Moss, 1995; Pasenko, 2017) has been used to provide age and size estimates from fossil tracks. This is based on a similarity in patterns of maturation and growth across a range of proboscideans (Roth, 1984) despite some variation (Marchenko, 2003) and was validated by McNeil et al. (2005, 2007), who plotted data from frozen mammoth carcasses (e.g., Vereshchagin and Tikhonov, 1999) on the growth data of Lee and Moss (1995). This implies a shoulder height of at least 2.5 m and a minimum age of 16 years, suggesting the tracks were probably made by a solitary bull.

This contrasts with the behaviour of the giant ground sloth at Location-3F (Figs. 4, 12 and 13). Again, the two human trackways time-bracket the passage of the mega-fauna; north-bound is crosscut by the sloth tracks, south-bound cuts the sloth tracks (Figs. 12 and 13). The ground sloth approaches from the east, perpendicular to the human trackway and does a circular shuffling 'dance' over the north-bound trackway (Fig. 12). The ground sloth tracks are distinctive and have a more plantigrade form than those reported by Bustos et al. (2018) from the west side of Alkali Flat. Overprinting of the manus by the pes is present, with sharp curved extensions to some prints and a manus impression (SL-7, Fig. 6E) is distinct close to the north side of the circular dance (Fig. 12). The lack of manus impressions and the plantigrade nature of the tracks compared to those described elsewhere (McDonald, 2007; Melchor et al., 2015) may indicate that at least initially, the giant ground sloth rose onto its hind legs, perhaps to scent or scout for the human, much as bears do today. The exact locomotion of the animal, however, during this shuffling circular-movement is not clear, but the double placement of tracks to create 'wing-like' impressions is distinctive and suggest small adjustments in foot placement (Fig. 12).

Although Megalonychidae (*Megalonyx*), Nothrotheriidae (*Nothrotheriops*) and Mylodontidae (*Paramylodon*) occur in New Mexico (McDonald and Morgan, 2011), only the latter two genera are known from late Pleistocene faunas. Both *Nothrotheriops* and *Paramylodon* are known from body fossils in the vicinity of Palaeo-lake Otero and both have a pedolateral foot. However, *Nothrotheriops* has a higher arch with just the posterior part of the tubercalcis in contact with the ground while *Paramylodon* has a lower arch with all of the tuber calcis in contact with the ground (McDonald and Morgan, 2011). This might suggest that the track-maker was more likely *Paramylodon*, notwithstanding potential effects due a more upright posture. Sloth tracks of a similar pattern are also found at Location-3C (Fig. 4 and S3), but the temporal relationship to the human trackways is not clear.

## 5. Discussion and implications

The double trackway reported here is remarkable within the human ichnological record, in terms of its length and the number of visible tracks. Morse et al. (2013) describe a trackway of 70 continuous tracks from Namibia over a distance of approximately 300m and Panarello et al. (2017) describe a human pathway extending over several hundred metres at Roccamonfina in Central

Italy, but without continuous visible tracks (see also: Marcos, 2001). Recently, Hatala et al. (2020) described 400 tracks organised into a series of sub-parallel trackways from Tanzania. In relation to these sites the WHSA double human trackway is both extremely long, and unique. It extends for at least 1.5 km and over 427 individual tracks have been recognised and 140 excavated. There are several points worthy of further discussion.

### 5.1. Geochronology

The dating of human tracks, or any other animal trackways for that matter, can be difficult. Exposed track-bearing surfaces often occur without overlying stratigraphic horizons that contain datable materials. Relying on the age of the horizon containing the tracks is frequently necessary, but the exposure-time for track-making and the potential for re-activation of a surface complicate this. To date by co-association with different animal tracks, the trackways must have clear cross-cutting patterns. Dating the tracks at WHSA has so far remained challenging, and even if tracks can be excavated in situ the surface may have been exposed for track-making at successive intervals during the late Pleistocene and any absolute date will therefore only pertain to the trackways dated.

The presence of human tracks from the late Pleistocene remains challenging to some, not least because of the apparent land surface stability it implies. The work of Bustos et al. (2018) demonstrated the co-association of human tracks with extinct ground sloth and here we provide the next best thing to a definitive date, namely two trackways bracketed in age by two extinct mega-fauna (giant ground sloth and Columbian mammoth). The north-bound, outward journey is over-printed by the tracks of mega-fauna, while the return (south-bound journey) in turn over prints the tracks of the mega-fauna. This not only confirms the presence of humans on the landscape of Alkali Flat in the late Pleistocene, but also places the humans firmly in association with the relevant mega-fauna.

### 5.2. Interpretation: tracks and trackways

The two journeys were likely made by the same individual, given the similarity in absolute track dimensions, and the consistency of stride and step lengths in both trackways. We cannot exclude the possibility, however, of two individuals, but they would have to have been almost identical in stature and foot size. We can show that whoever made the return journey did so at a slightly slower pace (by circa.  $0.1 \text{ ms}^{-1}$ ). Geologically the surface is similar along the length of the trackway examined, consisting of re-worked silty, fine gypsum sands overlying a firmer in situ sublayer. This textural similarity does not preclude local variations in moisture content however, and therefore surface consistency experienced by the trackmaker. It is also possible that surface moisture content varied between the two journeys, for example the surface could have either improved through drying, or deteriorated due to rainfall (e.g., Wiseman and De Groote, 2018). It is also worth re-stating that the surface is flat, with only local gradients of a few degrees in vicinity of the dolomite ridge shown in Fig. 4. The periodic occurrence of well-defined and clearly impressed child tracks without evidence of their own trackway, or that of another carrying adult, suggests that an additional load was carried on at least one of the journeys. There are any number of reasons for temporary placement of the child on the ground, not least of which was the slippery surface which must have been an effort to walk over. In light of these factors it is not surprising that the morphology of individual tracks is so variable.

Morse et al. (2013) showed how subtle variations in substrate are reflected in track morphology, although linked to variation in track depth (i.e., sediment strength). Tracks associated with weaker

(i.e., damper) substrate regions were much deeper. The mid-foot and hallux are known to display different amounts of flexion while walking on different materials, helping to maintain stability especially on more granular, and less uniform, substrates (D'Août et al., 2010; Hatala et al., 2018). Walking speed is also a factor in determining the shape of track outlines as suggested by Dingwall et al. (2013) and by others (e.g., McClymont et al., 2016; Hatala et al., 2013). Relevant here is also a more general change in body posture and gait associated with movement over slippery terrain. Clinical trials suggest that a crouched gait offers greater biomechanical stability by restricting joint rotational movements (e.g., Hickes et al., 2008) and some studies have demonstrated that humans will flex their limbs when anticipating falls during movement across slippery and/or uneven surfaces (e.g., Cham and Refern, 2002). In addition, there is a tendency for people to hold the upper body and arms in a more rigid fashion reducing, for example, arm swing, on unstable terrain. Marigold and Patla (2002) report a series of experiments in which subjects were asked to walk on a runway partially composed of rollers to induce a potential slip. On first encountering the slip, the response was to tense the muscles, raise the arms and modify the limb swing. As the participant became aware of the stability issues, they started to modify their behaviour by reducing the braking impulse, landing more flat-footed and raising the centre of mass. A shift in the medial-lateral centre of mass also occurred to bring it over the unstable foot. Anyone who walks regularly on unstable terrain will recognise these responses, raising the arms, flexing the joints, adopting a more crouched stance, reducing the load in anticipation of placing the foot in soft ground and varying the step length to avoid that ground. All of these actions will manifest in some way in the track shape, although currently there are no published studies available to indicate precisely how. In theory both feet should experience these dynamic influences equally, that is there should not be any systematic asymmetry in morphology between right and left tracks. An injury, pathology, or an asymmetrical carried load (i.e., a child) might lead to a left-right contrast in morphology, however.

While not statistically significant, we do see systematic evidence in the double trackway of left-right morphological asymmetry. The left footprints north-bound are a little longer, have larger contact area, are more variable, and show evidence of rotational slippage with the foot moving laterally away from the track-maker's mid-line. The right footprints are straighter with prominent slippage (distal to proximal) in the forefoot causing compression of the heel. This asymmetry might be indicative of load carrying on the left side, perhaps on the left hip. A person carrying a child will adjust the load and swop hips and arms from time to time, but the experience of most parents is that they have a favoured side when carrying a child. The increased contact area, variability, and tendency for lateral slippage away from the mid-line might be evidence of this. Spinal or limb pathology in the trackmaker cannot be ruled out, but the asymmetry does not occur in the same manner during the return journey, assuming that it is the same individual, of course. If we were observing pathology in this instance, then we would expect to see the same asymmetric footfall pattern in both the out-bound and in-bound trackways.

South-bound the tracks are narrower and do not show the same pattern of left-right asymmetry. In this case the right foot is subtly larger, and with greater variance than the left. In general, the heels of the tracks are narrow and more pinched. The rotational slippage and outward movement parallel to the coronal plane is less marked and might suggest the absence of the child. The narrower hindfoot probably reflects suction below the heel, causing the side-walls to close. This type of suction is a phenomenon that has been noted at other footprint sites (e.g., Ileret, Bennett et al., 2009) and is akin to the problem one experiences when withdrawing a foot from a

rubber boot. The fact that this is more prominent on the return, or southern journey, might imply that the surface properties had changed slightly causing it to adhere to the sole of the foot. The morphological asymmetry described here is undoubtedly subtle and within the morphological variance of the track population as a whole, it is, however, systematic. While potential load carrying is an intriguing idea there could be multiple causes. As such, tracks like this are difficult to interpret definitively. One implication of these data is that the ichnological community lacks modern analogue information with which to interpret this type of variability. Most gait studies are conducted in the artificial environment of modern gait labs, where the substrates are not natural, being usually composed of flattened material or instruments walkways, and inclement weather is absent. What we need going forward is a set of actualistic experiments in natural environments to better understand how humans walk on slippery, unstable, mud-rich surfaces which are the conditions that tend to preserve footprints (e.g., Leakey and Harris, 1979; Bennett et al., 2009; Ashton et al., 2014; Wiseman and De Groote, 2018; Hatala et al., 2020). In fact, we would rally the biomechanical and ichnological communities over this issue, especially in light of the increasing number of footprint sites that are emerging around the world.

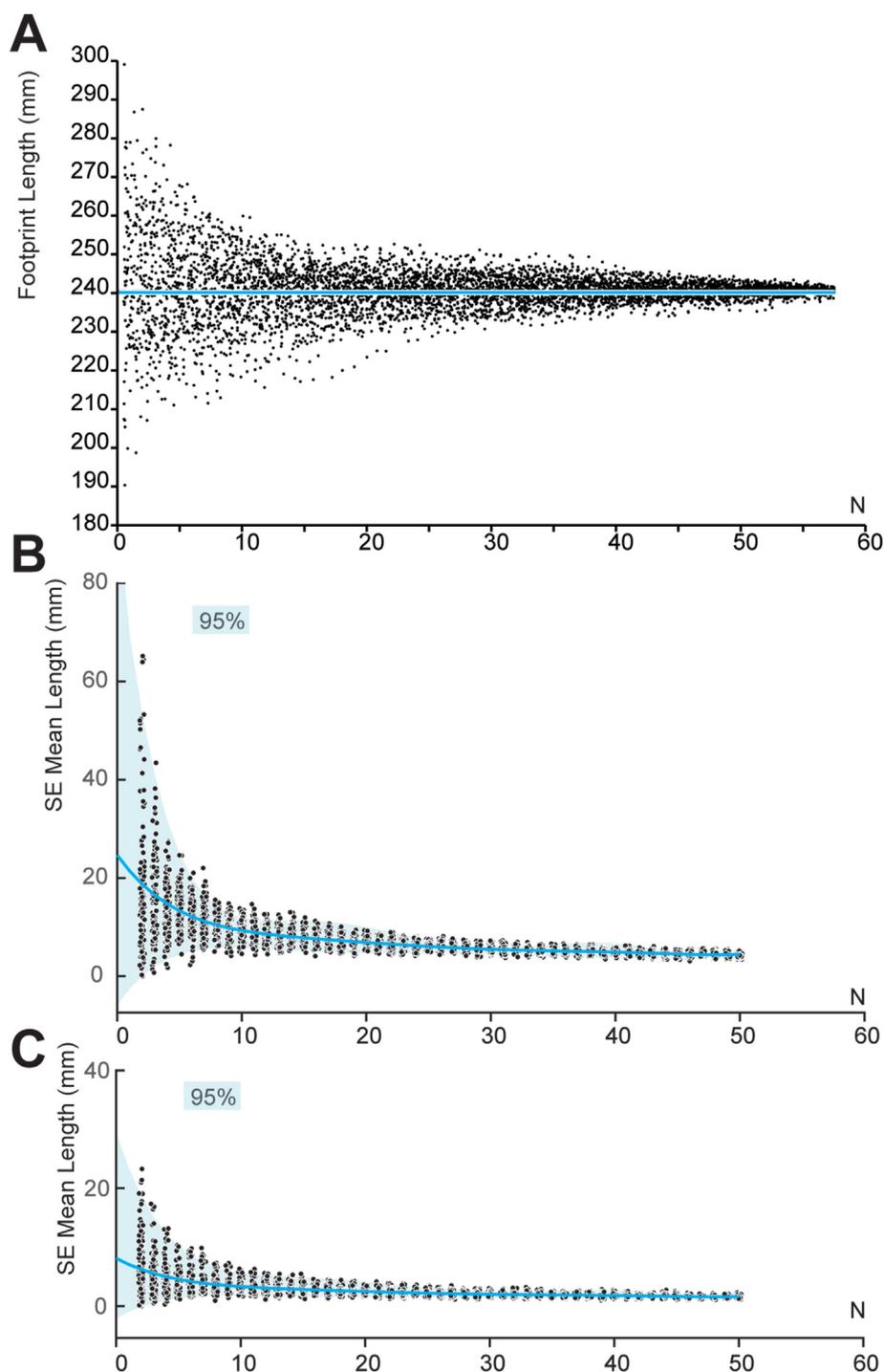
The track-maker(s) was/were clearly moving from unknown location A to B, with haste and apparently with a child. This was a potentially dangerous landscape with potential carnivores, although familiarity tends to mitigate perceptions of risk. Sole trackways like this appear relatively rare, however, in terms of what has been mapped and excavated at WHSA so far (Bustos et al., 2018; Urban et al., 2019). Most track assemblages consist of mixed-age groups which implies that this journey was perhaps unusual, as does the haste in which it was conducted. We simply do not know the reason for this journey and the challenge with any ichnological interpretation like this is to find the line between 'palaeo-poetry' and evidenced fact. What we can evidence is:

An individual set out alone across a potentially dangerous landscape, carrying a child. The journey took them at right angles to animals coming to, and from, ponded waters on the salt flats. The surface while flat consisted of soft mud and was slippery. They walked in a straight line with a clear destination in mind, possibly another family or hunting group camped several miles away. The individual walked at a steady, but fast, pace stopping occasionally to adjust the child in their arms. It would have been an exhausting walk and their feet slipped and slid in the mud. Later they returned south and followed their earlier trackway in reverse, which had been overprinted in the interim by the tracks of giant ground sloth and mammoth.

In terms of other animal behaviours, the mammoth trackway deviates little when it encounters the human trackway, but the tracks of the giant ground sloth appear to show a predator awareness. The animal's path is interrupted, it appears to rise on its rear feet, perhaps to scent the air before carrying on its journey. The interactions described here is best described as a passive response, in contrast to the active interaction (i.e., stalking/hunting) described by Bustos et al. (2018) on the basis of tracks elsewhere at WHSA. However, it is important to note that it would not have been necessary for the individual to stop to examine the sloth or mammoth tracks to know how recently they had passed by. The appearance of the tracks and the fact that they overprinted the north-bound journey would have been sufficient to allow the individual to share actionable information with other members of their group upon return to camp.

### 5.3. Trackway sampling

Human footprints in the geological record were once thought to



**Fig. 14.** Trackway sampling curves. A. Bootstrapped sample of track length for the WHSA double trackway. As the sample size increases the variance falls. B. Variation in Standard Error (SE) with sample size for the WHSA double trackway. Note the wide variance within the 95% confidence area. C. Variation in Standard Error (SE) for the Namibian long trackway reported by Morse et al. (2013). The variance is much less within this trackway and demonstrates that the variance is potentially specific to each trackway or substrate.

be relative rare, but a plethora of recent discoveries (e.g., Masao et al., 2016; Helm et al., 2018; McLaren et al., 2018; Duveau et al., 2019; Hatala et al., 2020) have changed this view. The trackways reported here have important implications for the interpretation of this growing body of evidence. The degree of morphological variability is considerable and significantly greater than that reported from other long trackways such as that discussed by Morse et al. (2013) from Namibia. It is common to make biometric inferences such as stature, body mass, sex, and minimum group size (e.g., Dingwall et al., 2013; Masao et al., 2016; Duveau et al., 2019;

Villmoare et al., 2019) from footprints. Biomechanical inferences are also frequently made about whole species from limited track numbers (e.g., Bennett et al., 2016b; Hatala et al., 2016; Raichlen et al., 2017). The morphological diversity found in the double trackway at WHSA challenges the reliability of doing so based on small samples, especially on soft, slippery substrates. Unfortunately, those are the ones that often preserve tracks best. The point reinforces the conclusion of Bates et al. (2013) that shallow footprints, essentially those in drier firmer substrates, record most anatomical and biomechanical data, while deeper tracks do not.

We can illustrate the implications of this for the sample size necessary to make robust biomechanical inferences or to determine minimum number of track-makers from a trampled zone. Using 60 track lengths from the double trackway one can bootstrap 100 averages for successive sample sizes 2 to 60 based from randomly chosen tracks. The results of this are plotted in Fig. 14A and show classic decrease in variance with increasing sample size. Using 5 and 2.5% variance around the mean gives minimum sample numbers of 24 and 44. The point is perhaps better made by considering the Standard Error (SE). We first generate 100 bootstrapped samples of track length (with replacement) for values of N in the range between 2 and 60. We then calculate the SE for each bootstrapped sample corresponding to a particular value of N, deriving the mean and standard deviation of these SE values. Fitting polynomial curves to the means and 95% confidence intervals obtained for each SE population for a value of N, you can calculate the SE range for any sample size (Fig. 14B). An error curve for the Namibian trackway of Morse et al. (2013) is shown in Fig. 14C for comparison. This type of analysis can be easily conducted for any population of tracks and indicates the potential 95% confidence SE for different samples sizes. The variance in SE by sample size is a function of the trackmaker's specific biomechanics, speed of travel, and the substrate. Three things are evident from this analysis: first, the general use of 5% variance around a mean (e.g., Duveau et al., 2019) in minimum trackmaker estimates should perhaps be nuanced in light of variability data and may be site-specific. More generally, information about the substrate upon which tracks were made is critical, and inferences based on small samples, or even individual tracks, should be treated with caution.

#### 5.4. Method development

The double trackway and the analytical methods used here to explore it, namely the use of objectively derived track outlines, opens up an alternative approach the analysis of vertebrate footprints especially where a combination of two- and three-dimensional tracks are available. In parts of the double trackway, for example, the outline of individual tracks is surprisingly clear (Fig. 3A) and could be easily and accurately digitised from a vertical photograph. While this is not the case with all the tracks at WHSA, others can be made visible by trowelling back the surface. Given that excavation may accelerate erosion and track loss the advantages of not excavating are clear. The use of outlines may provide a way of analysing tracks at WHSA, or similar locations, without excavating, in just the same way that the use of Ground Penetrating Radar can (Urban et al., 2019). There may be other applications within vertebrate ichnology more generally. Wiseman et al. (2020) used landmarks placed around the outline of 2D and 3D models to explore the nature of the Happisburgh footprints in the UK assigned to *Homo antecessor*. Due to inclement weather the Happisburgh tracks where never successfully captured in 3D before they were lost to coastal erosion and, therefore, a mixed-approach was essential. A similar analysis could have been undertaken using track outlines which was initially developed by Lallensack in 2019 but refined for human inchofossils here. Gierliński et al. (2017) also used a mixed method (2D and 3D) to study the Trachilos tracks in Crete. Again, this analysis could have used outlines with the advantage of avoiding potentially subjective landmark placement. Whilst we are still to fully explore the validity of this method – which is beyond the scope of the current study – it does show potential for the assessment of fossil footprint data especially where a mix of 2D and 3D data is available.

## 6. Conclusions

The double trackway reported here is remarkable within the human ichnological record for its length and also for the morphological diversity of the individual tracks. We draw the following conclusions:

1. Both the outward and return journeys were likely made by the same individual, an adolescent or small adult female (?) that appears to have been carrying a small child (<3 years old) on at least the north-bound (outward) leg. The journey was made with considerable haste over difficult and slippery terrain with little deviation in direction. The individual had a known destination in mind. The speed at which the journey was made may speak to either urgency of mission or the perceived risk of the journey given the presence of large mega-fauna on the landscape including carnivores. The trackmaker clearly follows their own path on the way south providing evidence of cultural behaviour (tracking) while moving through the palaeolandscape.
2. The double trackway is clearly age-bracketed by its association with extinct mega-fauna, namely Columbian mammoth, and giant ground sloth. This clearly establishes the human tracks as being of late Pleistocene age.
3. The individual tracks show considerable intra-trackway variability which can be ascribed to the speed of travel and the slippery conditions. The left foot on the north-bound journey shows a slightly larger contact area and dimensional variability. This may be indicative of the child being carried more often on the left side. The tracks of the south-bound or return journey especially those of the right foot are more elongated and narrower. This may be due to a drying substrate and adhesion below the foot.
4. In terms of method development, the use of objectively determined track outlines shows merit as an alternative to more traditional landmark-based geometric morphometrics or whole foot analysis. This increases the toolkit available to ichnologists. Moreover, it has particular potential where a combination of 2D and 3D data is available. This would allow the analysis of unexcavated tracks at locations like WHSA where clear outlines exist. Excavation is by its nature destructive and strategies that allow morphological analysis while avoiding excavation have relevance to conservation management.
5. Finally, the double trackway reported here adds to the growing ichnological record of human and megafaunal activity at WHSA. The number and extent of the tracks present is exceptional within the ichnological record. It is worth noting however that other playas, both gypsiferous and not, occur throughout the American southwest and all may contain a rich ichnological record just waiting to be explored.

## Author statement

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2020.106610>.

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