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The taphonomy of human footprints in an estuarine setting: implications for quaternary track-sites in intertidal zones

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ABSTRACT

The purpose of this paper is to understand the preservation of human footprints formed in estuarine settings, with a specific focus on survival time and morphological modification. To this end, we conducted a taphonomic study by creating five trackways at two different sites on the intertidal mudflats of a modern estuary in North Wales. Trackways were monitored across multiple tidal cycles using photogrammetry to create timelapsed orthomosaics and digital elevation models. Our results exhibit a pattern of morphological footprint decay for individual tracks, while showing persistence at the same time. Under progressive influence of the tides, anatomical detail decreases, push-up ridges erode, and footprint outlines become wider with eventual sediment infill. Despite this, individual tracks remain identifiable and biometric inferences (e.g., foot length) are consistent throughout, with intra-trackway variability comparable to changes observed over time. Estimates for a complete removal of the tracks at the study sites are after five to seven days (10–14 tidal cycles). This will vary between sites as with variations in sediment properties, local hydrodynamics, and track orientation. We suggest that tidal duration is critical for footprint preservation and stress that taphonomic processes are different at sites with aeolian sediment formation. While site-specific, our results offer broader insights into the formation and survival of Quaternary footprints in dynamic coastal environments.

1. Introduction

Fossil footprints occur around the coastline of Northwest Europe (Burns et al., 2022). Mesolithic examples have been reported from the Severn Estuary (Bell, 2007) and along the Sefton (Formby) Coast in the UK (Roberts et al., 1996; Roberts, 2009; Burns, 2021). Discoveries on the coast of Normandy of Neanderthal footprints (Duveau et al., 2019; Mercier et al., 2019) as well as examples from Spain (Neto de Carvalho et al., 2020, 2023; Mayoral et al., 2021, 2022; García Rincón et al., 2022) and Portugal (Neto de Carvalho et al., 2025) have increased the number and significance of Europe's coastal footprint sites (Fig. 1; Table 1). Sites are preserved in a variety of coastal sediments ranging from peat[1] (e.g., Kenfig; Bennett et al., 2010), to fine grained silts deposited in interdune and estuarine settings (e.g., Formby Point; Roberts et al., 1996) and fine, sandy mud (Duveau et al., 2019; Neto de Carvalho et al., 2020). Further afield, a rich ichnological resource has been discovered in aeolian sediments of the Cape Coast at Nahoon Point and Langebaan (Mountain, 1996; Roberts and Berger, 1997; Roberts, 2008; Jacobs and Roberts, 2009), with other notable coastal examples being Brenton-on-Sea, Goukamma, Kleinkrantz, or Woody Cape (Helm et al., 2018, 2020, 2022, 2023a, 2023b), as well as the most recently discovered Larache site on the Northwest coast of Morocco (Sedrati et al., 2024). The increasing number of coastal footprint sites discovered in recent years is intriguing for several different reasons. It evidences the importance of coastal resources and communities in the Holocene and Pleistocene (Bell, 2007; Helm et al., 2018; Duveau et al., 2019; Neto de Carvalho et al., 2020, 2025). But it also poses an essential mystery of preservation — how did these sites survive on the coast after their initial formation?

Footprint formation requires several elements. Firstly, a ductile substrate which has strength properties that are just right for the footprint preservation. Too weak and the surface can't be traversed; too

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[1] The sediment description "peat" has been used as a rather loose term (see also Waller and Kirby, 2021) to describe track-bearing layers at Holocene coastal sites. We regard the substrate at most UK footprint sites as organic clay rather than actual peat.

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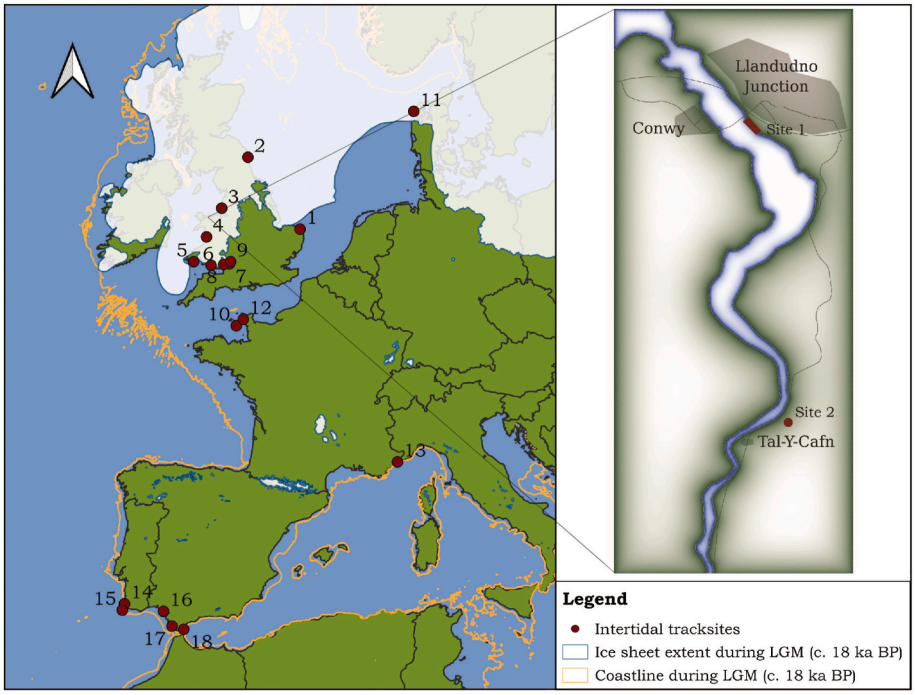

Fig. 1. Distribution of coastal footprint sites in Europe dating from the late Pleistocene to the Neolithic Period, with a close-up of the location of the two study sites at the mouth of the Conwy Estuary in Wales. 1 Happisburgh, 2 Low Hauxley, 3 Formby Point, 4 Dovey Estuary, 5 Lydstep Haven, 6 Kenfig, 7 Redwick, Peterstone and Goldcliff East (Severn Estuary), 8 Uskmouth and Magor Pill (Severn Estuary), 9 Oldbury (Severn Estuary), 10 St. Ouen's Bay (Jersey), 11 Lodbjerg Dunes, 12 Le Rozel, 13 Terra Amata, 14 Monte Clérigo, 15 Praia do Telheiro, 16 Matalascañas, 17 Cape Trafalgar, 18 Gibraltar. Basemap: Natural Earth, Feature Layer: University of Koeln (http://booksite.elsevier.com/9780444534477/).

strong and no trace is left; and too elastic and the impression is lost after formation. These Goldilocks conditions vary with an animal's weight and the sediment properties (Falkingham et al., 2011; Bennett and Reynolds, 2021) and lead to selective footprint preservation by an animal's weight. It is not surprising therefore that the footprint record does not reflect the faunal assemblage deduced from conventional skeletal fossils (Roach et al., 2018). Secondly, a hiatus of some kind is required between footprint formation and burial. Exposure to air, sun and salt may harden a surface through dehydration and/or cementation, but this takes time (Morse et al., 2013). Different studies have also demonstrated how geochemical activity and bacteria in microbial mats stabilize footprint surfaces which can aid the preservation of vertebrate tracks (e.g., Kvale et al., 2001; Melchor et al., 2006; Scott et al., 2008, 2010; Marty et al., 2009; Carmona et al., 2012; Carvalho et al., 2013; Díaz Martínez et al., 2018; Cuadrado et al., 2021; Quijada et al., 2025). Thirdly, there must be an optimum level of trampling. Too little and the footprints are so rare they are hard to find, but too much and they will be lost under the footfall of later animals (Laporte and Behrensmeyer, 1980). Finally, burial is needed, ideally by a different sediment type, or after a sufficient break, so that the surface contact between sedimentary events is clear (e.g., Laporte and Behrensmeyer, 1980; Cohen et al., 1993; Marty et al., 2009; Bennett and Morse, 2014, pp. 131 Fig. 5.19). Coastal environments, excluding aeolian ones, have an additional challenge, namely the fluctuation of the tides. Ideally, you want footprint formation to occur just after an extreme high tide so that the sediment is "prepped" for imprinting (i.e., moist) but for the site not to be immediately inundated by another tidal cycle. The fact that there are so many coastal footprint sites speaks to the frequency with which these conditions have been met in the past, but also the sheer number of footprints that are left in such environments. The last point is made by a simple calculation in which the average person leaves over 200 million footprints in a lifetime (Bennett and Reynolds, 2021).

Fig. 2A scopes some of the variables that are relevant to the preservation of coastal footprints prior to burial in none aeolian situations. Wiseman and De Groote (2018) noted how the morphology of footprints made in sand trays deteriorated with exposure to meteorological conditions. Rainfall will cause rapid disintegration but equally, dehydration and/or wind erosion will have a similar adverse effect (e.g., Laporte and Behrensmeyer (1980); Marty et al. (2009); Scott et al. (2010); Bennett and Morse (2014), p. 130. Inundation by standing or flowing water will also in theory cause rapid loss of morphological definition (e.g., Scott et al., 2010; Bennett and Morse, 2014, p. 128 and literature cited therein). A particularly important variable here for coastal sites is tidal duration, or more precisely the lack of it. Ideally, you want a surface that is at the extreme of the tidal range. In the 1980s the concept of tidal duration was introduced as an explanation for the shore normal gradient of shore platforms (Trenhaile and Layzell, 1981; Carr and Graff, 1982; Trenhaile, 2000). Tidal duration is the percentage of time a specific tidal height experiences inundation; the shape of the curve changes with a site's specific tidal regime (Fig. 2B) and different shapes of curve have different implications for footprint taphonomy. Other variables (Fig. 2A) include the substrate properties, organic sediment content, vegetation cover, current velocities, wave conditions, water depth and of course the amount of animal trampling (e.g. Morse et al., 2013). We stress that preservation in aeolian situations involves a different set of variables and is therefore not covered in this model. At some coastal sites the salt from sea fog, spray and dew are also likely to be important in the rapid cementation of exposed sediment surfaces (Morse et al., 2013). Frost may also be a variable in aeolian coastal settings (Bustos et al., 2018). Although far from the coast, the surface of gypsum dunes becomes fixed by frost to a depth of a few millimetres. Drifting sand can then inundate

[2] Data available here: https://ntslf.org/tides/uk-network/data-availability (last accessed on 25th July 2025).

Table 1
List of coastal footprint sites around Europe with a focus on the depositional setting. See Fig. 1 for site locations.

No.	Site Name	Country	Substrate	Depositional Environment	Landscape	Citation
1	Happisburgh	United Kingdom	laminated silts and sands	mudflats	upper estuary	Ashton et al. (2014)
2	Low Huxley	United Kingdom	peat		intertidal zone	Eadie and Waddington, 2013
3	Formy Point (Mesolithic)	United Kingdom	laminated, muddy sand-silt	Backbarrier lagoon mudflats	coastal zone	Roberts (2009); Burns (2021)
	Formy Point (Neolithic)	United Kingdom	silt-fine sand	Backbarrier lagoon mudflats	coastal zone	Roberts (2009); Wiseman et al. (2022)
4	Dovey Estuary	United Kingdom	peat		estuary	unpublished
5	Lydstep Haven	United Kingdom	peat	thin peat layer above clay, covered by sand	intertidal zone	Murphy et al. (2014)
6	Kenfig	United Kingdom	peat	salt marsh or fen environment	intertidal zone	Bennett et al. (2010)
7	Redwick (Severn Estuary)	United Kingdom	peat, filled with silt	peat bog at transition to transgressing saltmarsh silt	estuary	Bell (2013); Barr and Bell, 2016
	Peterstone (Severn Estuary)	United Kingdom	laminated silt	silts cut by palaeochannels	estuary	Barr and Bell, 2016
	Goldcliff East (Severn Estuary)	United Kingdom	peat, filled with silt	peat bog near silt-filled palaeochannel	estuary	Scales (2003); Bell (2007); Barr and Bell, 2016
8	Uskmouth and Magor Pill (Severn Estuary)	United Kingdom	peat	peaty bog overlain by tidal silts	intertidal zone	Aldhouse-Green et al. (1992)
9	Oldbury (Severn Estuary)	United Kingdom	peat	thin peat shelf	estuary	Barr and Bell, 2016
10	St. Ouen's Bay	United Kingdom	peat		coastal zone	Patton (1993)
11	Lodbjerg dunes	Denmark	peat	fan deposit	dune system	Milàn et al. (2007)
12	Le Rozel	France	fine sand, sandy mud	coastal environment, creek	palaeodune system	Duveau et al. (2019)
13	Terra Amata	France	beach sand	coastal deposits	coast; Paillon river delta	De Lumley (1966), 1967
14	Monte Clérigo	Portugal	aeolianite	beneath alluvial fan deposits, colluvial deposits	dune system, coastal	Neto de Carvalho et al. (2025)
15	Praia do Telheiro	Portugal	aeolianite	colluvial layer	dune system, coastal	Neto de Carvalho et al. (2025)
16	Matalascañas	Spain	sand	fluvio-deltaic coastal plain	dune system, coastal	Neto de Carvalho et al. (2020)
17	Cape Trafalgar	Spain	aeolianite	coastal deposits	palaeodune system, coastal	Neto de Carvalho et al. (2022)
18	Gibraltar	Spain	medium-coarse sand	Leeward aeolian deposits ramped against cliffs and in caves	cliffs and caves	Muñiz et al., 2019

that surface without disturbing it (Bustos et al., 2018).

Compared to other branches of geoscience and archaeology there are relatively few taphonomy studies with which to examine these types of questions. Marty et al. (2009) photographed a series of coastal footprints post formation and as mentioned above Wiseman and De Groote (2018) observed footprint degradation when exposed to ambient weather. Most recently, Quijada et al., 2025 conducted field experiments at different locations in coastal environments in Argentina, documenting (shod) human tracks to infer how microbial mats impact the characteristics of vertebrate tracks during their formation and afterwards. Cohen et al. (1993) provided a systematic study of footprint taphonomy and survival on the shore of Lake Manyara in Tanzania. While probably the best taphonomy footprint study to date, its relevance to estuarine and coastal locations of northwest Europe is perhaps limited. In this context, we report a series of simple experiments undertaken on the mudflats of a modern estuary in Wales to explore the processes involved in footprint taphonomy. We created four long trackways on an intertidal mudflat in Wales, which were documented over five days to study survival time and morphological modifications that may occur during this process and theoretically at least be preserved in the fossil record. A different volunteer created a fifth, shorter trackway at a different location on the river estuary, which received a more detailed documentation over four days. Based on these experiments, we show case some of the different analytical approaches available for the study of footprints.

2. Study site

Sites chosen for this study lie on the eastern side of the Conwy Estuary in North Wales (Fig. 1). Site 1 is located adjacent to the RSPB Nature reserve close to Llandudno Junction and opposite from Conwy Castle (Fig. 3A and B). The choice of location was based on ease of access to estuarine muds at low tide. The test trackways were created in the intertidal zone on the east side of the river in between the RSPB car park and Conway Road. From the footpath (Llwybr Moryd Conwy Estuary Trail) that runs parallel to the estuary, you climb down rip-rap rocks and walk over degraded salt marsh (~10 m) which rests on a 0.5 m deep clay layer the edge of which is being eroded by high tides. At this point you are standing on the estuary which slopes westward (0.6°) initially as a sandy surface, with fragments of eroded clay, but quickly grading to a dark organic rich, silty fine sand and clay. Beyond this slope at low tide are horizontal, ripped sand bars with occasional drainage troughs. The dark organic-rich, silty clays were selected for the experimental trackways.

Site 2 lies 1 km south of Tal-y-cafn on the east bank close to the A470 (Fig. 3C) and can be accessed by short footpath crossing the railway. Here, the channel is steeper, entirely composed of estuarine mud overlying bedrock.

3. Methods

These experiments were conducted in accordance with Bournemouth University's ethical policy and approval number 59816. The main

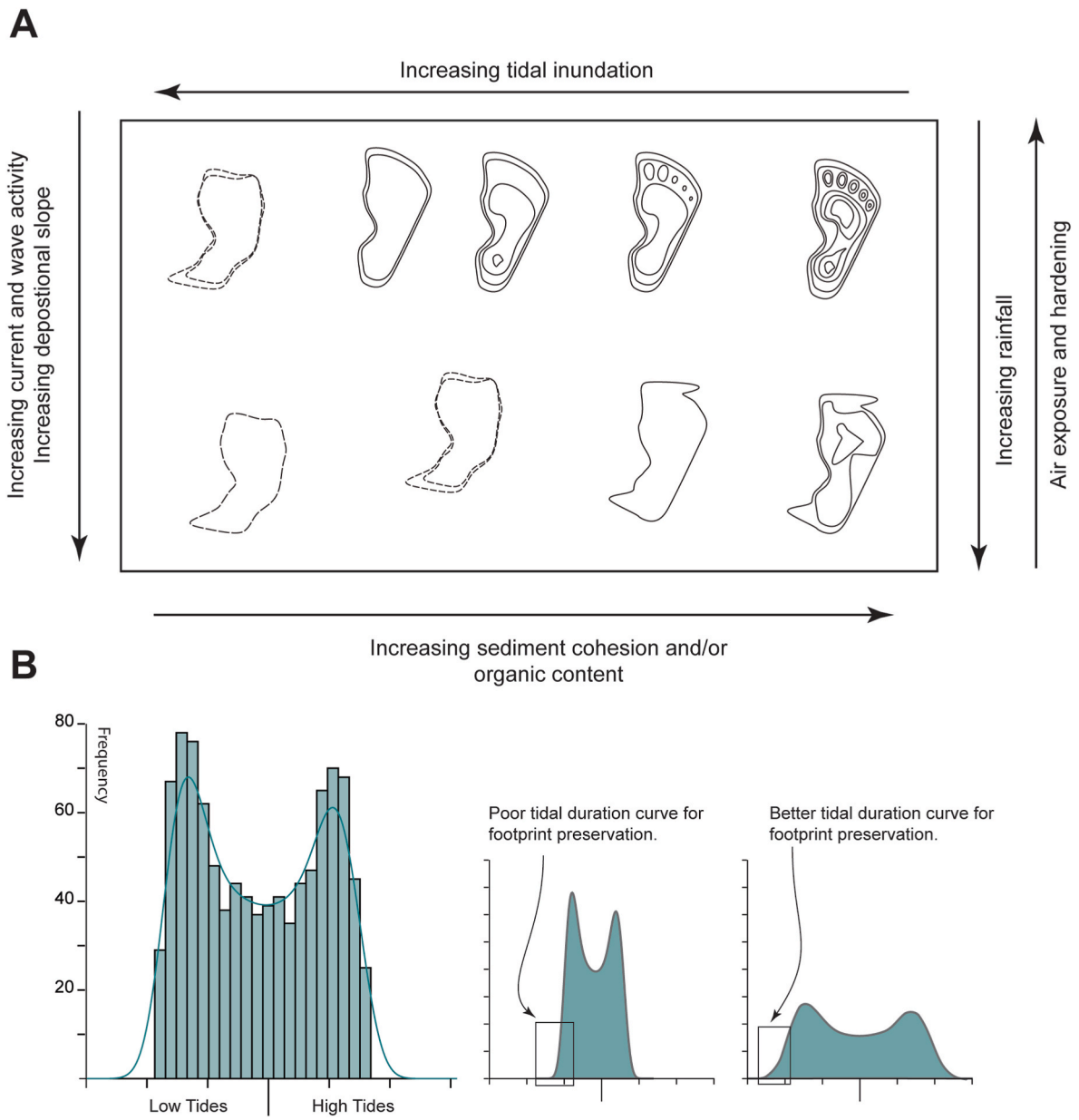

Fig. 2. Conceptual model of estuarine footprint taphonomy. **A.** Matrix showing the interplay of different variables. **B.** The role of tidal duration in footprint taphonomy. The histogram on the left is based on data from Liverpool (Albert Docks) for the year 2023.[2] Here, the x-axis represents the duration of each tidal phase (time spent exposed at low tide or submerged at high tide), and the y-axis represents how often each duration occurred. The graphs on the right have been stretched to show different scenarios. The flatter curve (right) is better for footprint preservation because the extreme tidal ranges occur but infrequently. An initial high tide may prepare the surface for imprinting but the chance of sustained inundation subsequently is low. In the middle example, the tide is frequently at its maximum range and therefore the number of inundations a potential tracked surface may experience is higher.

experiment involved a female volunteer (117 kg, height 1.7m, foot length 230 mm, walking speed 1.1 m/s) walking on the silty clay mudflats at the main site (Site 1) during low tide (Figs. 3 and 4). This created a trackway of 91 m in total and of triangular shape, in which the outward (northwards) path ran parallel to the river (SE-NW), with a return path diagonal to the river (NWW-SEE), and a short side to the south that connected the two paths. The trackway was created in the afternoon of a dry day with a mix of sun and clouds in mid-February 2025. High tide had been at 13.30 that day and the trackway was created at 17.00 h. The freshly made tracks were characterised by deep imprints, with high push-up ridges, visible toe imprints, and ejecta in the form of muddy clumps both in front and behind the tracks. Eight ground control points (GCPs) were placed around the trackway and trackway morphology was documented using a GoPro 10, elevated on a monopole, using the time-lapse function. The ground control points were located using a GNSS unit (Leica GS15). The GoPro 10 images were used to create both digital elevation models (DEMs) and orthomosaics in Agisoft Metashape[3] (version 2.2.0).

Twelve hours later the trackway was documented again via GoPro 10 images for photogrammetry, and this was repeated the same afternoon. This resulted in three, including the initial, orthomosaics/DEMs after each tidal cycle, thereafter the tidal cycles only permitted daily monitoring (i.e., after two cycles; Fig. 4). The weather was fine aside from rain on the morning of Days 3 and 5 (after three and seven tidal cycles).

In April 2025, a further set of footprints was monitored over five tidal

[3] www.agisoft.com (last accessed on 28 July 2025).

Fig. 3. Site locations. A-B. Main site opposite Conwy Castle looking north and south. Note the footprints in the foreground of (B) which have survived two tidal cycles. C. Location south of Tal-y-cafn looking north.

cycles at Tal-y-cafn using fixed pegs as control points and 3D capture via Scaniverse on iPhone-15 using photogrammetry through the "detail mode" in the app (male volunteer; 92 kg, height 1.8m, foot length 255 mm, 0.9 m/s).

Co-registered DEMs for each of the five trackways in this study were subtracted from one another in ArcMap and QGIS (Fig. 5). Footprint measurements were made from orthogonal photographs and foot length was from the heel to the first toe and foot width was measured across the maximum width of the ball of the foot. Rather than placing traditional landmarks, which can lack precision in deep footprints, we adopted an alternative approach to examine the shape of individual tracks. This is based on creating polygons which define the outline of a print. This work was conducted in the VGG Image Annotator (VIA) produced by the Oxford Robotics Group.[4] Detailed polygons of between 20 and 25 points were used. This data was then extracted from the output files for analysis using a python script. Because the number of nodes per polygon varies, they were re-sampled to minimise shape variance and give 50 uniformly spaced nodes per polygon (Fig. 6). Left feet were reflected to right feet in this analysis taking care to correct the winding direction and all polygons were then normalised to the centroid. Mean shapes and variance were examined at this stage. Additionally, a Procrustes-based ANOVA was performed to examine statistical variance between pre-stated groups. While strictly speaking the polygon nodes are not fixed landmarks they are used in palaeontology as "pseudo-landmarks" because they are evenly spaced along the shape boundary and resampled geometrically (Dujardin et al., 2014; Rolfe et al., 2021). Further, we are not making any anatomical inferences from them directly, which normally requires anatomically recurrent landmark placements. In practice the approach is like classical work that places landmarks on 2D images (Bennett et al., 2009; Wiseman et al., 2020) and has the added advantage of being applicable to footprints which have degraded morphology such as those in this study. The scripts used in this work can be found on GitHub (see data availability statement).

4. Results

The substrate at Site 1 consists of a cohesive mud that grades towards the river floor where compact sands and muds outcrop. Shoreward this is covered by a 50 to 100 mm thickness of sand towards the highwater mark where a shallow cliff (<0.5 m) of presumably Holocene laminated clays is eroding to produce silty mud which in places drapes the sand. Trackways 1W and 2 have massive mud as the substrate. Trackway 1E progresses from the north from mud to mud covered by sand, while part of Trackway 1S has underlying mud, sand and then a thin veneer re-worked mud. In the case of Site 2 soft, massive mud prevails overlying at depth an irregular surface of pebble gravel.

All the experimental tracks involve displacement of sediment, rather than simply formation by plantar compression. This displacement is manifested by rim or push-up structures around the tracks which are typically between 50 mm and 80 mm deep. Anatomical definition is present in all the tracks when first made (cycle 0) inclusive of clear heel impressions, toe grooves in the distal wall, in some cases toe pad definition, evidence of medial longitudinal arch, sediment ejecta to the front of the tracks (Figs. 7–9). Rim structures show extensional fractures (Fig. 8B) and bulging side walls (under the weight of rim structures) are evident in some tracks. Figs. 8 and 9 show the typical transition in foot morphology during repeated tidal cycles. The first tidal cycle reduced the elevation and morphological definition of the rim structures around each footprint. This involved opening of the extensional fractures and de-roofing of the anticlinal structure within rim ridge. The tracks were orientated parallel to the strike of the slope and therefore draining water would have traversed the short axis of the footprints. As such, the ridge would have been an upstanding obstacle to drainage. Some sedimentation within the tracks does not appear to have taken place as part of this process, and the true track surface persisted through several tidal cycles before infill occurred. We speculate that turbulence within the track caused by water flowing over it may have helped prevent sedimentation. After six to seven tidal cycles the morphology of the tracks has clearly degraded (Figs. 7–9), and outlines are only partially preserved, but they remain identifiable as footprints. Comparison of the mean tracks for tidal cycle 0 and tidal cycle 7 constructed from a dozen tracks in Trackway 1E makes this point (Fig. 7G and H), as do the other pairs of tracks in Fig. 5. One might expect that deeper tracks should have a greater preservation potential than shallower ones, at least in terms of anatomical detail but, again, as the paired tracks in Fig. 7 show this is not necessarily the case. It is important to note here that the mud is cohesive, and this may not apply to footprints left in non-cohesive materials such as loose sand or silt. Sedimentation within a track leading ultimately to its disappearance only began after three to five tidal cycles.

There are a few exceptions to this, however. Trackway 1S traversed ground consisting of massive mud, an upper sand layer over which there was a drape of re-worked mud. Erosion of this upper re-worked mud cause the rapid loss of some of these footprints, within a minimum of two tidal cycles. Survival as one might expect is dependent on the sedimentary stratigraphy present and the cohesion within each sediment layer.

Individual footprints tend to follow an individual taphonomic trajectory and all the studied trackways show an increase over time (i.e., with each tidal cycle) in intra-trackway morphological variability. The polygon shape and associated 95% ellipses around polygon nodes (Fig. 4) illustrates this point. This increased variability is one reason why

[4] www.robots.ox.ac.uk/~vgg/software/via/(last accessed on 29 July 2025).

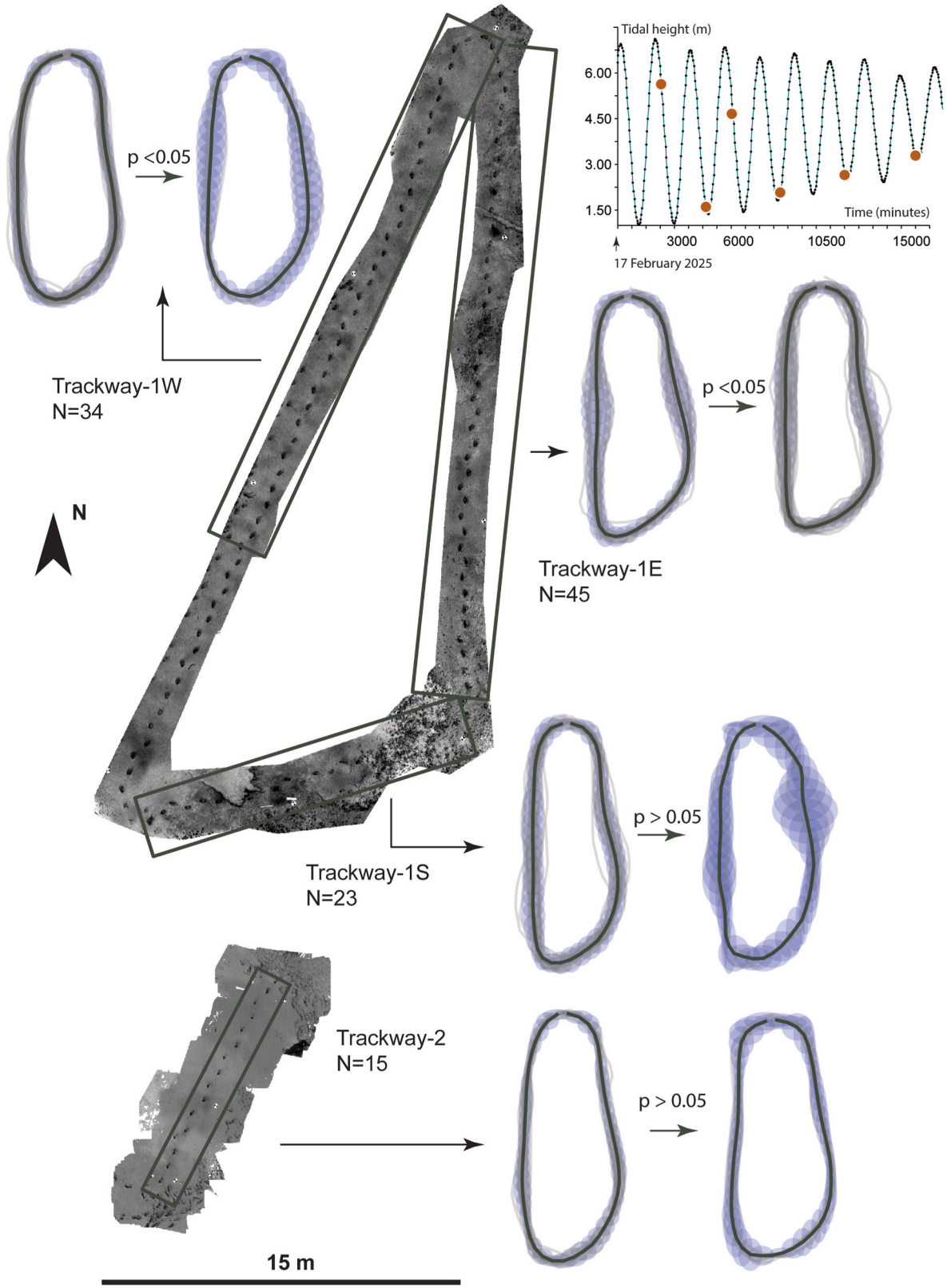

Fig. 4. Orthomosaics of the footprint trackways at Site 1, February 2025, close to Llandudno Junction, created from photogrammetry in Agisoft Metashape. The inset shows the sampling times in relation to the tidal cycles. Also shown are the average shapes for the first and last set of observations presented as polygons and 95% confidence ellipses around the points. The significance values refer to a Procrustes ANOVA performed on the data.

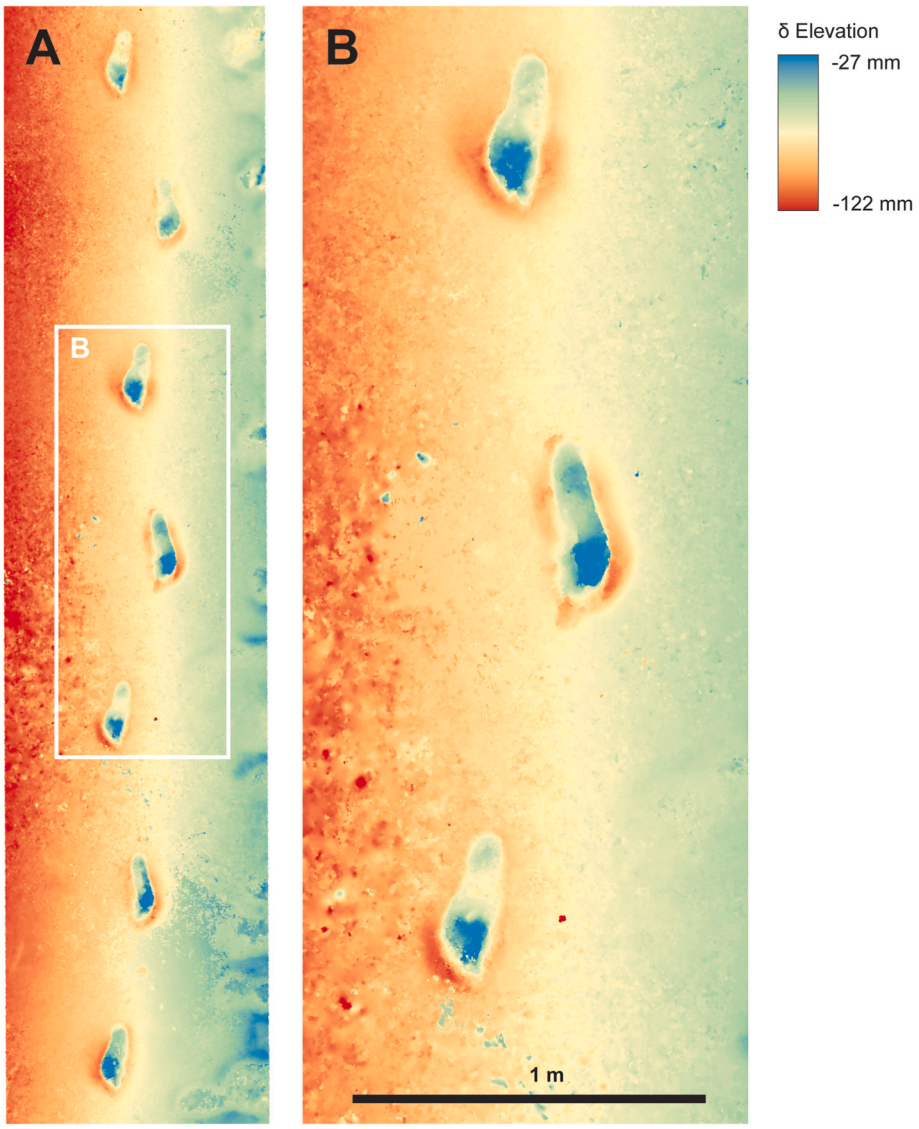

Fig. 5. Raster difference between Cycle 0 and Cycle 7 for part of Trackway 2 at Site 1. The blue end of the spectrum demonstrates the gain in elevation over time, that is the track infill, and the red end of the spectrum is the decreasing elevation, showing a loss of push-up ridges around the tracks.

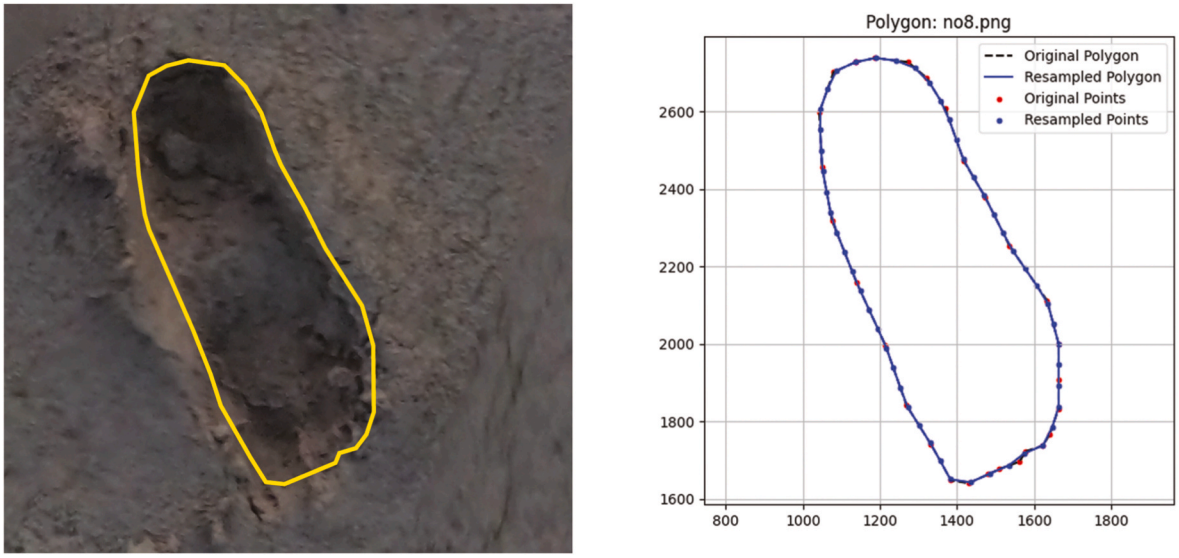

Fig. 6. Left: Polygon with 20-25 points around a track in T1E at Site 1 after its creation on the first day, i.e. with no tidal impact. Right: The polygon of the same track resampled with 50 nodes using a python script.

the morphological difference between the first day and last day of the experiments is not always statistically significant. Of the four trackways at Site 1 (T1E, T1W, T1S, T2), only two show a statistically significant difference using a Procrustes ANOVA (Fig. 4). The individual taphonomic trajectory potentially reflects the stochastic nature of the combination of variables at play around each footprint, namely subtle differences in the morphology of each print may pose different flow obstacles and therefore turbulent response. While the tracks are shore parallel, and the water protected from swell waves, it is possible that the wave base of local waves created by wind blowing across the estuary may have also touched the sediment surface at different points. As one might expect, there are more variables at play than the simple rising and falling of the water level over the tracks.

Fig. 10 shows the net gain/loss in width and length for all the footprints in this study. Length shows a slow decline, while ball width shows an increase. Consequently, the width to length ratio increases over time and notably this is most marked during the first tidal cycle (Figs. 10–12). The cross-sections in Figs. 11 and 12 are typical of the process at work here, which can also be seen in the paired tracks of Fig. 7. In the case of the width profiles, erosion on the upslope side of the track occurs rapidly as the rim structure is removed. Again, we hypothesise that water turbulence draining over the track is responsible. In specific tracks that do show elongation, this is linked to breaching of the forefoot or heel by water causing it to be diverted parallel to the long axis of the footprint. There are anecdotal observations to suggest that track orientation to the draining water may play a part here. The tracks in Fig. 13A, B were made shore normal, as the volunteer squelched out to make the initial line of tracks at Site 2. The rim structures here remained intact over the monitoring period and once the heel had been breached (Fig. 13B) so that water could drain through the track easily its morphology did not change dramatically. Infilled tracks observed by one of the authors in January 2025 show localised ripple formation (Fig. 13C and D) which only occurred in tracks orientated shore normal. Future experiments could explore the role of track orientation to the water drainage direction.

Despite gradual decay, the tracks show a remarkable level of perseverance across the length of the experiment and, projecting forward, we anticipate that complete removal would take at least five to seven days and therefore 10–14 tidal cycles are needed to remove them completely. While identifiable, we need to consider the reliability of inferences over this time (Table 2). Comparison of intra-trackway variability with that for a single track over time indicated that the standard errors are in fact

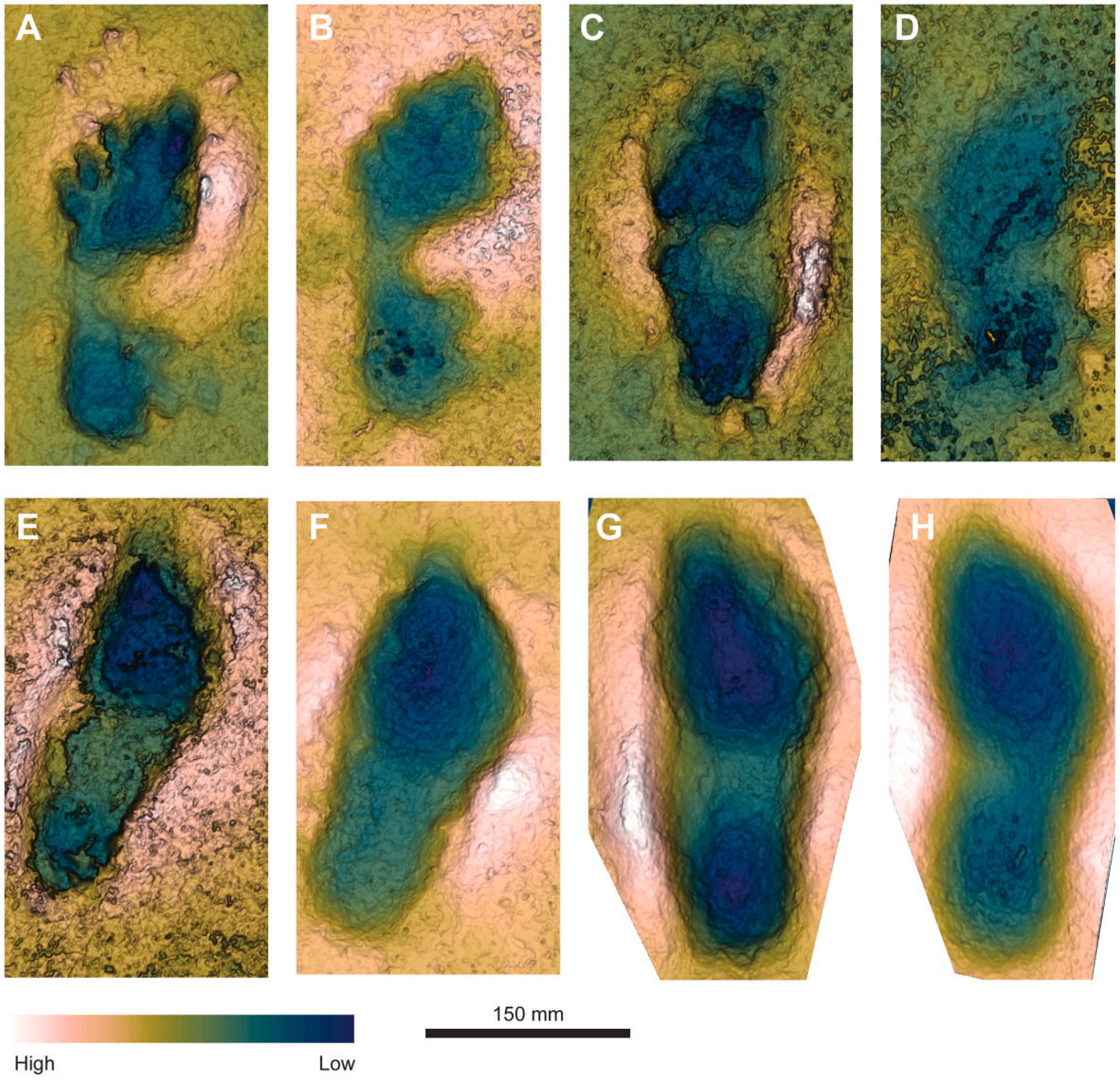

Fig. 7. Close up 3D models of tracks for Trackway 1E at Site 1 from tidal cycle (TC) 0 to TC 7. A-B, C-D and E-F paired tracks. G-H are mean tracks constructed from 12 tracks selected from the trackway at TC 0 and after TC 7. Images are colour rendered by depth in CloudCompare (version 2.12.4) after automatically rotating to the orthogonal plane. The mean tracks were constructed using Track Transformer (Bennett et al., 2016).

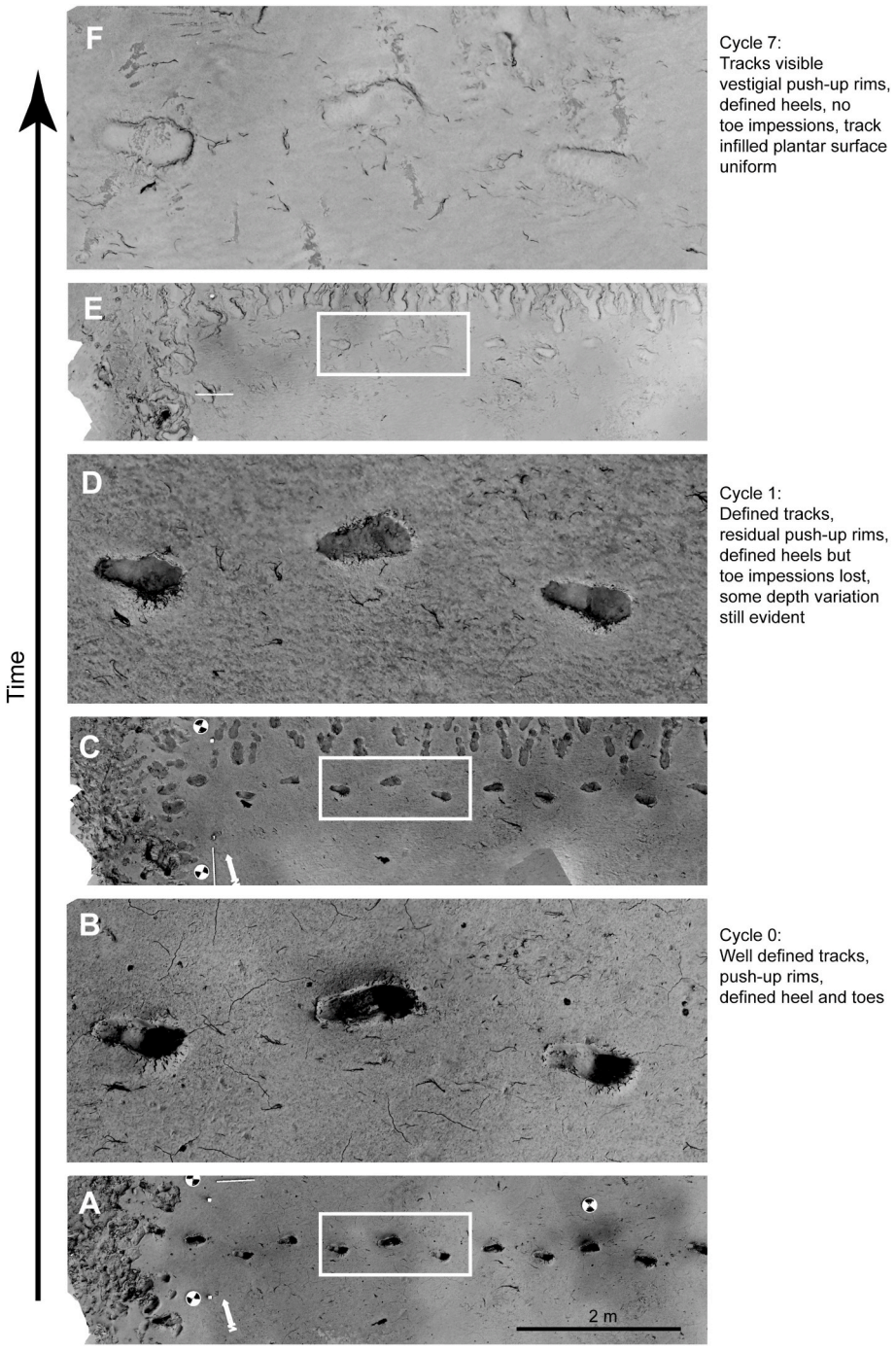

Fig. 8. Trackway 2 (T2) at Site 1 showing the same tracks at various scales through the main tidal cycles.

surprisingly similar. In a less cohesive and firmer substrate this may not be the case but in estuarine mud observations are similar whether made immediately after formation or after seven tidal inundations. As Fig. 13E illustrates, even after multiple tidal cycles the tracks remain visible and identifiable as human as the final state just prior to complete removal illustrates in Fig. 13F–H.

Although the length to width ratio increases with the passage of time, speed estimations also remain reliable, since the distance from heel to heel remains approximately the same even if the size and shape of the track change. The estimated speed of the volunteer creating T1E is 1.238 m/s measured after its creation and 1.243 measured after seven tidal cycles, based on an equation offered by Ruiz and Torices (2013). This has important implications for Quaternary trackways showing that biometric inferences are likely to be reliable even after morphological decay.

5. Discussion

The results presented here show how track morphology changes over progressive tidal cycles, and it is one of the first comprehensive studies into the taphonomy of human footprints. The survival or "preservational window" (sensu Díaz-Martínez et al., 2021) for the tracks is between five and seven days (10 to 14 tidal cycles), and during this period reliable estimates of track and gait dimensions can be made. Detailed anatomical/biomechanical inferences, such as depth to pressure substitution (Bates et al., 2013), are not possible after the first tidal cycle.

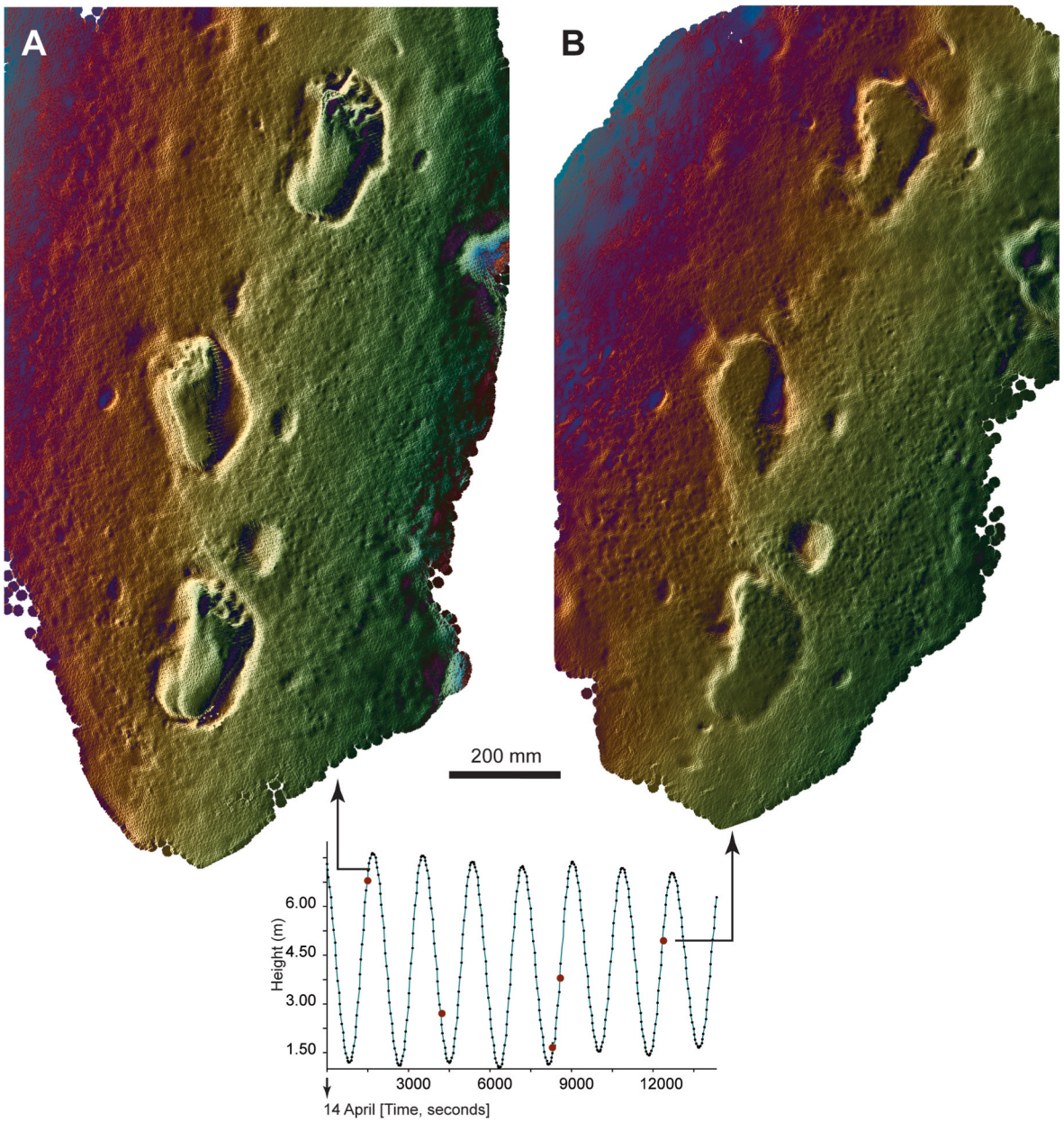

Fig. 9. Results from Tal-y-cafn (Site 2) showing a false colour comparison between tidal cycle (TC) 0 (A) and TC 5 (B). The footprint models were captured using Scaniverse on iPhone-15, converted to 2D raster in QGIS with a hill shade superimposed on a DEM using the difference blending mode. Models were georeferenced using 3D printed pegs which remained in place throughout the experiment. Note the tracks were made parallel to the slope.

Track morphology is a function of substrate (Morse et al., 2013) and shallow tracks in less cohesive sediment are unlikely preserved long despite being biomechanically more valuable (Bates et al., 2013). It reinforces the fact that the observation made here are potentially both site- and occasion-specific, a function of the sedimentary properties and the weather/wave conditions that existed during the experiment. Increased rainfall plus wind, and therefore wave conditions, would accelerate footprint loss and the rapidity of morphological degradation. Despite this the observations do provide a starting point from which to consider footprint preservation in coastal and estuarine settings. To be clear, a different set of variables would be at play in aeolian coastal situations such as those of the South African Cape (Helm et al., 2018, 2020, 2023a, 2023b). The full impact of footprint orientation with respect to the shoreline is also something that we believe needs to be explored in the future.

Our observations suggest that a track, oriented shore parallel in an estuarine setting with moderate to little wave action or current velocity, will follow a series of morphological decay patterns summarised in Fig. 14. Initially, the push-up structure degrades rapidly facilitated by radial, extensional fractures across it. These fractures are associated with the deformation of the sediment which are exploited by moving water. After an initial tidal cycle, the remnants of this structure can sometimes be seen as two concentric track outlines, one representing the outer edge of the push-up ridge and the other the inner edge. As morphological decay progresses with continued tidal inundation, the upslope wall of the track is eroded, and visible drainage rills appear. The depth of the track remains largely as in the original footprint, although the morphological detail such as toe pads and scrapes becomes less clear. In time, after approximately six to seven tidal cycles, the footprint resembles a shallow basin with a single outline that is broader than the original track. Footprint length remains remarkably constant during this decay. The final stage is a smooth sediment surface in which the track

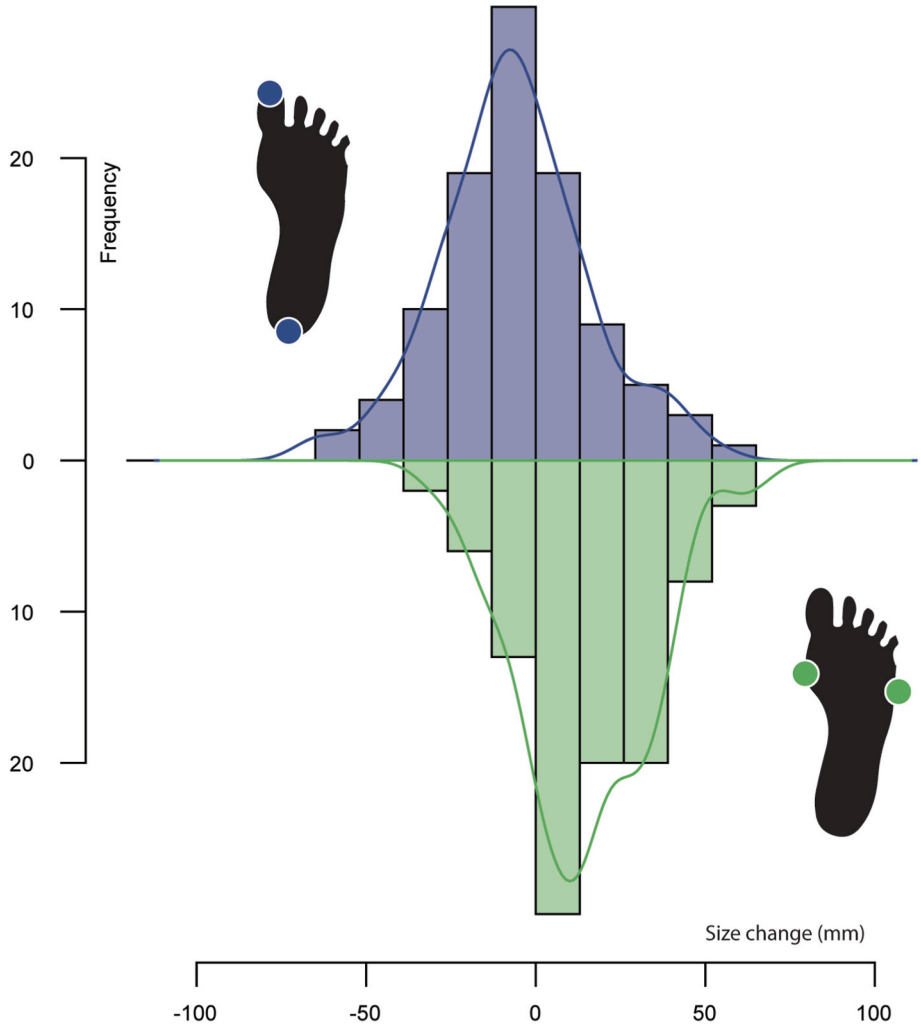

Fig. 10. Histogram showing the positive or negative change in foot size during the experiment over all trackways. Width shows a positive increase and length shows a decrease. Overall, the width to length ratio increases. Most of this increase occurs during the first tidal cycle.

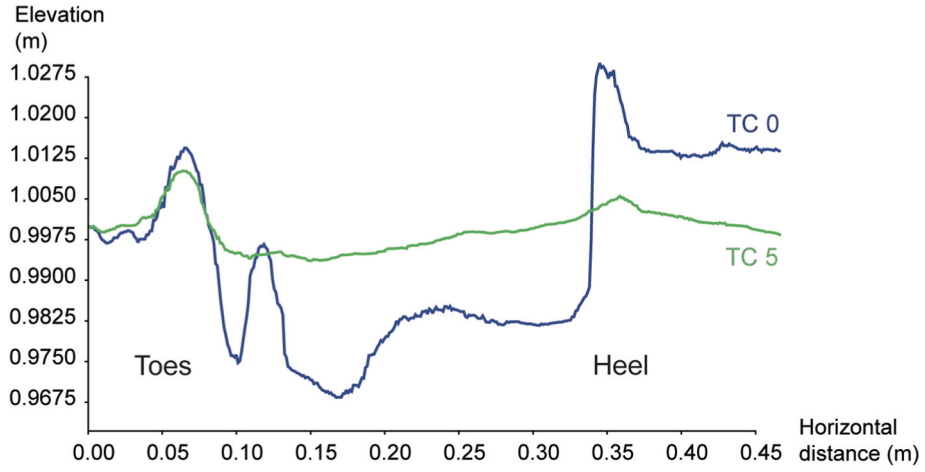

Fig. 11. Longitudinal cross section for the bottom print (right foot) in Fig. 9 after its initial creation (TC 0) and after the fifth cycle (TC 5).

outline can sometimes be traced by a line which is either slightly depressed or visible as an edge associated with a textural sediment change. We do not propose this model as anything other than a site-specific one that pertains to the conditions during our study. The important transferable point here is that a footprint can survive several tidal cycles and while anatomical detail may degrade the trace is clearly a human track, and basic inferences made from it are surprisingly consistent over time, even as the print itself degrades.

In terms of the conceptual model of footprint preservation outlined at the start of this paper (Fig. 2), we suggest that tidal duration is critical

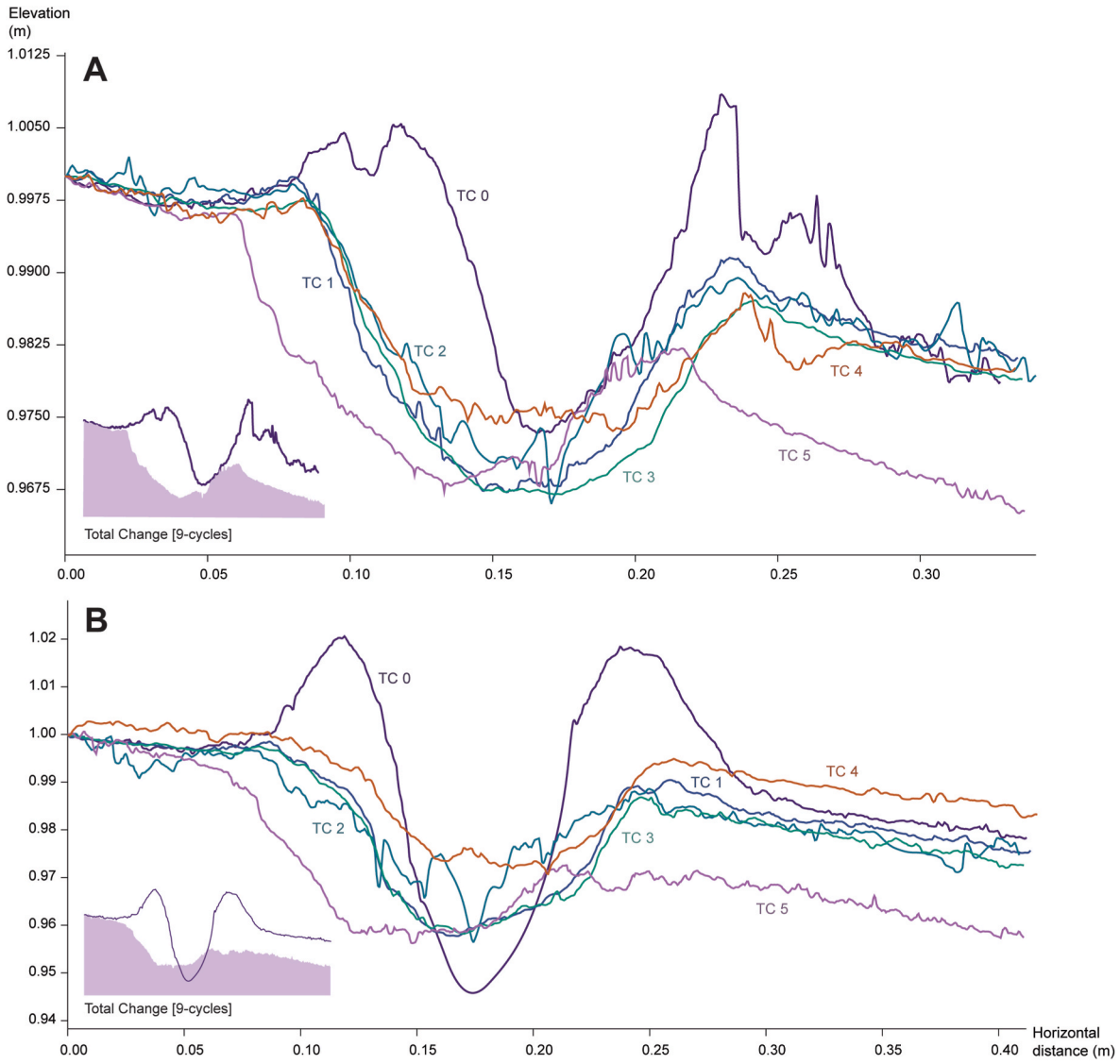

Fig. 12. Transverse cross-sections through two monitored tracks from Site 2 over five tidal cycles (TC 0-5). Note the significant change in track width during this time. Compare this with the cross sections in Fig. 11.

to the survival of the trace. A track that is made in an intertidal zone, where inundation occurs over a period between approximately one and five tidal cycles, is likely to be ideal for preservation. Fig. 15 shows two previously unreported tracks from Talacre on the North Wales coast that are likely of Mesolithic age based on similar discoveries across Liverpool Bay on the Sefton Coast (Roberts, 2009; Burns, 2021; Wiseman et al., 2022). While these tracks have clearly been eroded and currently contain pebbles and shell fragments, they are identifiably human tracks which have survived multiple tidal inundations. The key difference here is the consolidation of the sediment and/or an element of hardening. We emphasize the importance of the hardening step in footprint preservation. At any point during the morphological decay identified from our observations, interruption by a cessation of tidal inundation and/or a period of "baking" would lead to preservation.

6. Conclusion

Quaternary track-sites with human footprints, specifically in coastal environments, have increased over the past years. Despite a few notable exceptions (Cohen et al., 1993; Marty et al., 2009; Wiseman and De Groote, 2018; Quijada et al., 2025), very few studies have specifically addressed the taphonomic processes affecting footprint preservation. Yet, such work is crucial for improving our interpretations of fossil footprints. We hope that the present study represents a step toward more systematic investigations in this area.

Our taphonomic study of experimental estuarine footprints reveals a clear pattern of morphological degradation over the course of six to seven tidal cycles. The initial tidal cycle significantly reduces anatomical detail and lowers associated push-up structures. This is followed by a progressive widening of the trace, culminating in infilling. As expected,

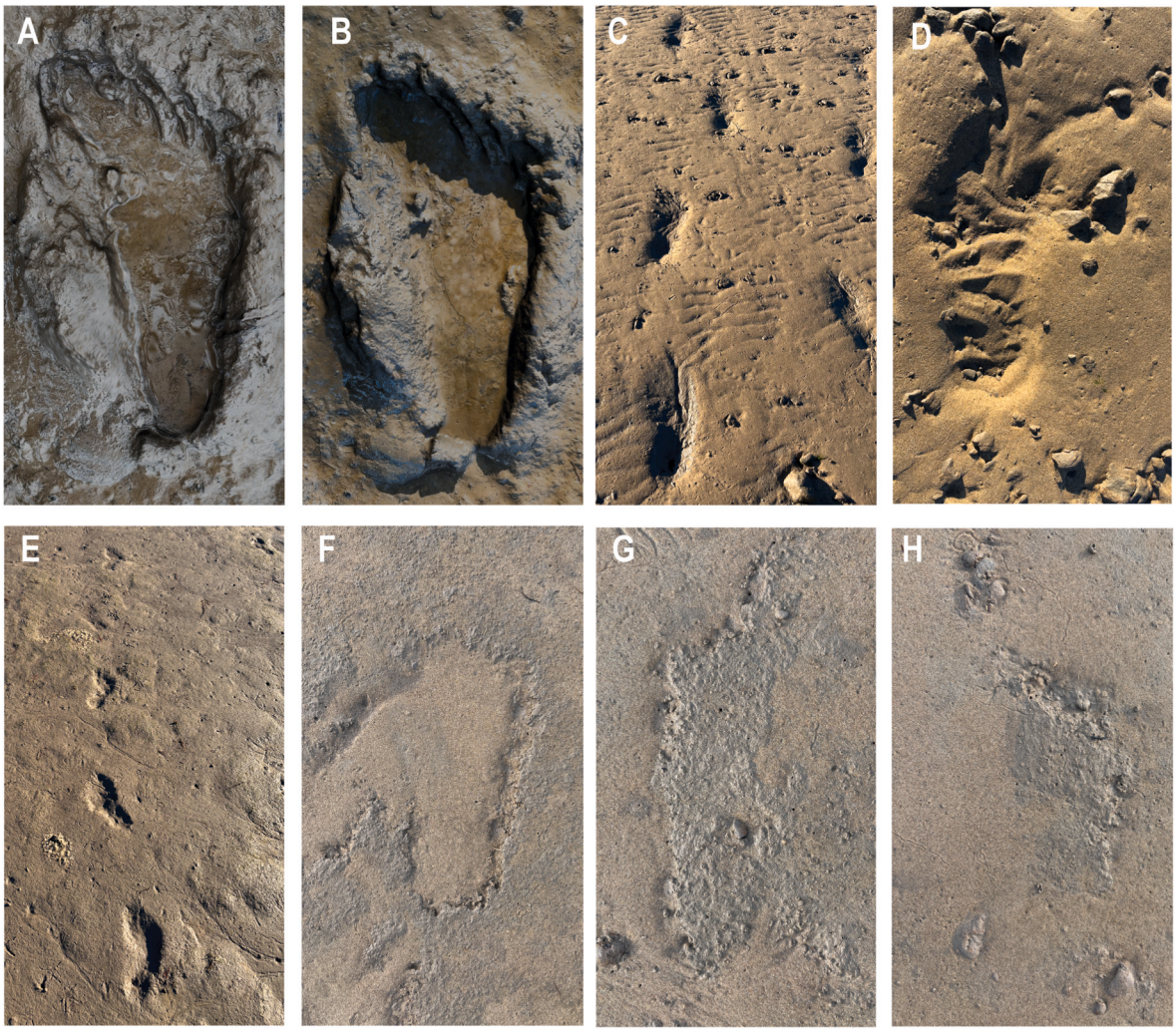

Fig. 13. Observations of different tracks and trackways on the mudflats at Site 2. A-B: Two tracks orientated shore normal after three and after five tidal cycles. Note how the push-up structures remain and how the breaching of the heel rim allowed water to drain after the fifth tidal cycle (B). C-D: Tracks oriented shore normal with localised ripple formation at infilled tracks. E-H: Tracks can remain visible and identifiable as human after multiple tidal cycles even before removed completely (F-H).

Table 2
Means, and standard errors (SE) for foot length for each trackway (T1E, T1W, T1S, T2) at Site 1. Left: Before tidal inundation and after seven tidal cycles. Right: For specific footprints that were preserved well enough to allow measuring after each tidal cycle. Foot lengths were measured from heel to first digit. TC = tidal cycle, with initial creation of the trackways on Day 1 as TC 0.

	Mean	SE		Mean (N)	SE	Min. SE	Max. SE
T1E TC 0	270.3	3.3	**T1E TC 0–7**	269.1 (33)	5	1.8	11.3
T1E TC 7	263.2	3.8	**T1W TC 0–7**	276 (13)	4.7	2.2	11.8
T1W TC 0	277.3	2.4	**T1S TC 0–7**	282.7 (2)	6.7	6.4	4.9
T1W TC 7	276	5.3	**T2 TC 0–7**	271 (6)	6.2	3.9	7.9
T1S TC 0	281.3	4.2					
T1S TC 7	284	22					
T2 TC 0	288	4.6					
T2 TC 7	266	4.6					
T1E TC 0	270.3	3.3	**T1E TC 0–7**	269.1 (33)	5	1.8	11.3
T1E TC 7	263.2	3.8	**T1W TC 0–7**	276 (13)	4.7	2.2	11.8
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T1S TC 0	281.3	4.2					
T1S TC 7	284	22					
T2 TC 0	288	4.6					
T2 TC 7	266	4.6					

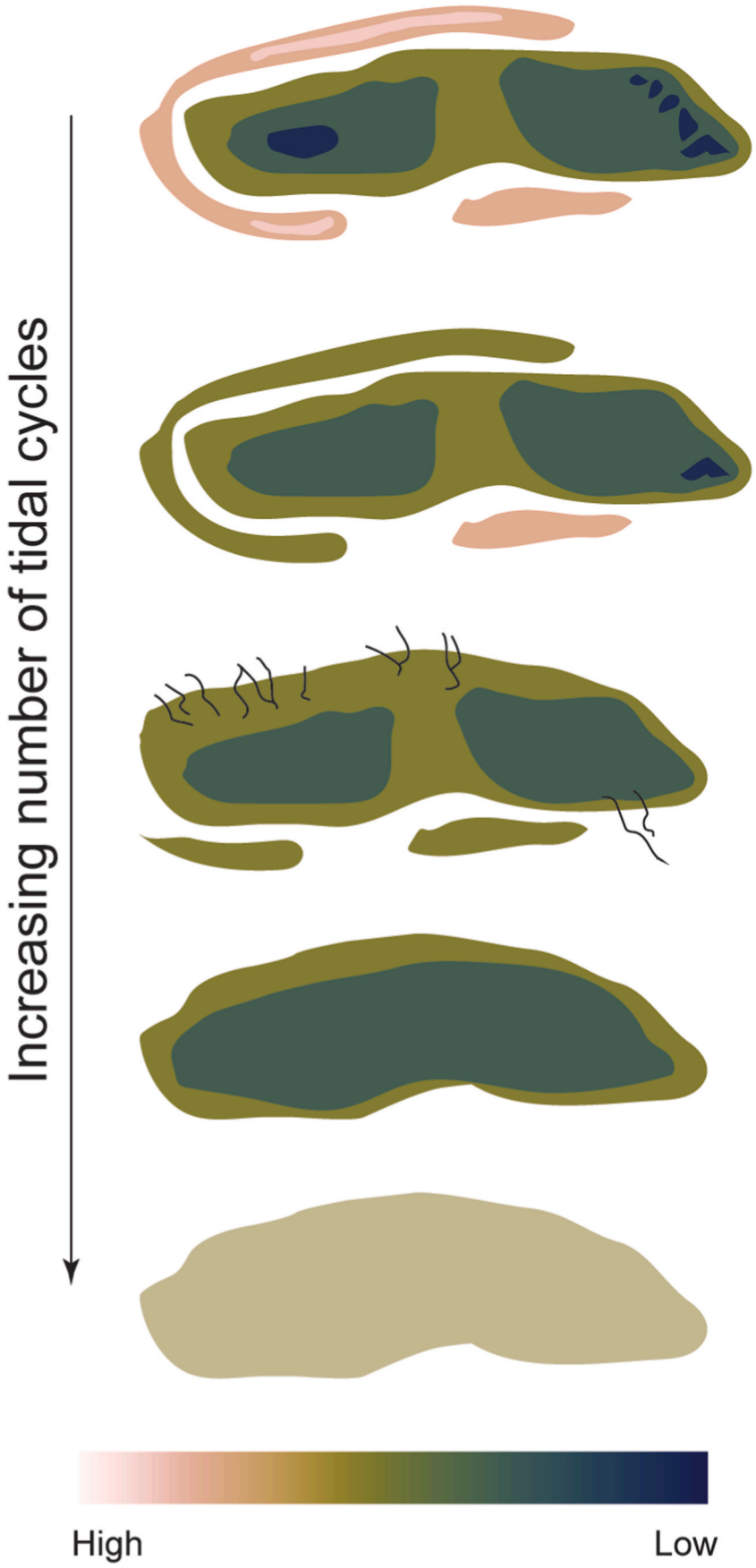

Fig. 14. Schematic illustration of the morphological decay pattern of a human track made in an estuarine setting.

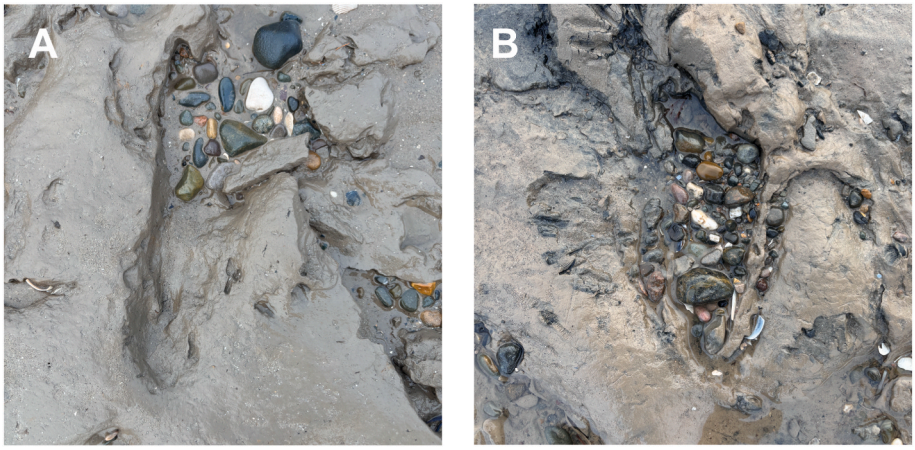

Fig. 15. Two previously unreported tracks from Talacre on the North Wales coast.

local sedimentary conditions play a significant role in shaping this decay trajectory. Remarkably, the footprints remain identifiable as human throughout the degradation process, based on factors such as location and track succession. Biometric inferences made across tidal cycles express consistency, with standard errors comparable to intra-trackway variance, supporting the reliability of such interpretations even after partial degradation. Although some of our observations are necessarily tied to the specific environmental and temporal context of our study, the implications are broadly relevant to footprint preservation in other tidal settings. We emphasize once more the importance of the four fundamental steps in footprint preservation: the presence of a clean, imprintable surface; the activity of a track maker; a hiatus for surface stabilization; and subsequent sedimentation and burial. Finally, we draw attention to the diverse range of analytical tools employed in this study and encourage future research to adopt and expand upon these approaches to further the quantitative analysis of ichnological data.

CRediT authorship contribution statement

Hannah Strehlau: Writing – original draft, Conceptualization. **Sarah Maryon:** Formal analysis. **Michael Everett:** Visualization. **Abigail Hunt:** Writing – review & editing. **Sally Reynolds:** Writing – review & editing. **Matthew R. Bennett:** Writing – original draft, Supervision, Conceptualization.

Data availability statement

The python scripts used for this study are available on GitHub (https://github.com/ahrc-footprints/Conwy-taphonomy-paper.git), and videos that explain the analytical workflow are available on Youtube (https://www.youtube.com/playlist?list=PLXuk-TGy50XQ0GbJ9stlJ8Q-ZLnnuwF1t).

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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