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The pressure record underfoot: Using ground penetrating radar to obtain pressure patterns of buried footprints

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ABSTRACT

Fossilised trackways are a key source of evidence for reconstructing how ancient humans and animals moved across the landscape. The morphology of tracks is of particular importance because it allows inferences to be made about plantar pressure and therefore mechanics of motion of the track maker. However, the typical methods of excavation and photogrammetry used to document these tracks can be time consuming and may not be ideal at sensitive sites. This paper explores the use of ground penetrating radar to record the morphology of human tracks buried in soft sediment at White Sands National Park, New Mexico. The results demonstrate that a record of plantar pressure is preserved in the radar data and that this record might be a more direct measure of pressure than the typical proxy of footprint depth. This suggests that ground penetrating radar is a strong choice of method in ichnological studies.

1. Introduction

Over the last decade there has been a rapid rise in the discovery of fossilised footprints, especially those of humans (e.g. Bennett et al. 2009, 2021; Duveau et al. 2019; Helm et al. 2019; Sedrati et al. 2024). Geophysical prospection has played an important part in this work; for example, in dinosaur palaeontology (Aucoin and Hasbargen 2010; Capineri et al. 2013; Vohra et al. 2015), in the study of Pleistocene megafauna and humans (Urban et al. 2018, 2019; Westaway et al. 2013), and on the Australopithecine tracks at Laetoli in Tanzania (Conyers 2025). Some experimental work has also been done to investigate appropriate parameters and methods (Wiewel et al. 2021). This work has largely focused on footprint recognition rather than developing the potential for biomechanical inferences first identified by Urban et al. (2019). In this body of work, it is not always explicit whether the radar anomalies are recording track morphology or something else. Given that a central tenant of footprint studies is the substitution of pressure for depth (Bates et al., 2013) determining what these anomalies record is important and consequently forms the focus of the current paper. Before proceeding we draw the reader's attention to several key definitions. Firstly, a "true track" refers to the base of a footprint that was once in contact with the plantar surface of the track maker. Secondly, an "under track" refers to the consolidation and transmission of strain below the base of a footprint (Lallensack et al. 2025). Finally, a "ghost track" is something common to playa sites and refers to the surface expression of an unexcavated track that comes and goes with ambient weather and soil moisture conditions (Bustos et al., 2018).

2. Study site

The footprints examined in this paper come from two different localities at White Sands National Park, New Mexico, USA. WHSA Locality 1 lies on the western margin of Alkali Flat to the west of the gypsum dune field (Fig. 1). A range of tracks made by Xenarthra, Proboscidean, Canid, Camelid and humans appear on the playa floor as "ghost tracks" which appear and disappear with changing ground moisture conditions. Tracks in the vicinity of the study site have been excavated and reported by Bustos et al. (2018) and Bennett et al. (2019). The age of these tracks is unknown, but they date from at least the terminal Pleistocene based on the co-existence, recognised by cross-cutting patterns, between extinct megafauna and human tracks (Bustos et al., 2018). In keeping with the policy of the National Park Service, precise locational information is not presented but can be requested from the National Park

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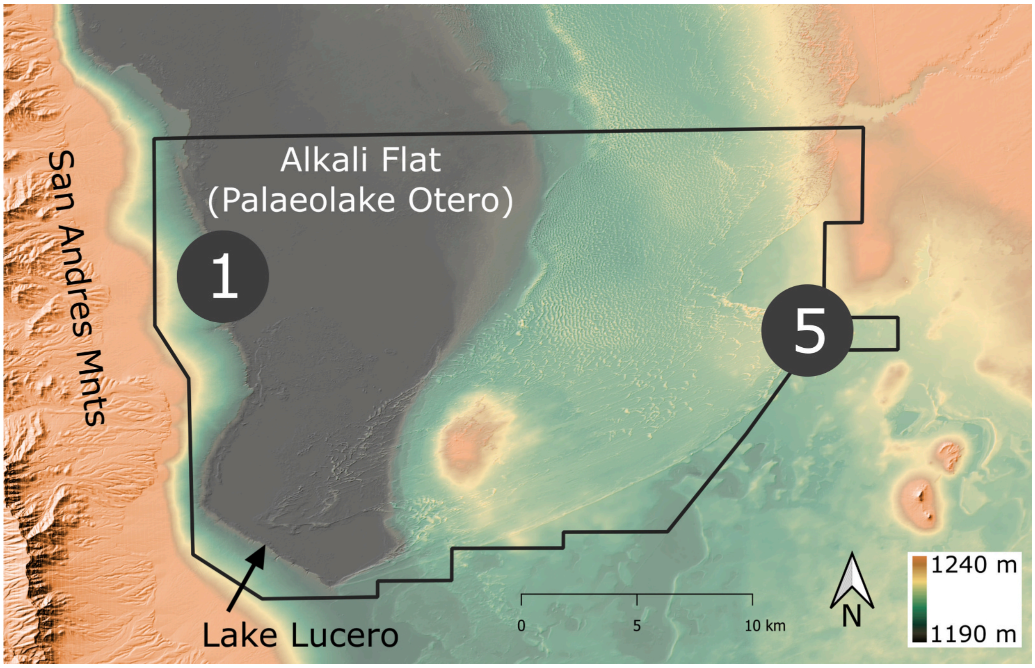

Fig. 1. Map of White Sands National Park (outlined in black) showing the approximate locations of Localities 1 and 5 in the dark circles. Elevation data used to create the basemap comes from the 3D Elevation Program provided by U.S. Geological Survey.

Service if required for scientific purposes.

At WHSA Locality 1, a large number of human tracks appear to represent the movement of a human group both in an east–west and west-east direction. In some cases, the track-makers appear to be running based on the length of the strides. A small sub-set of these tracks were identified for this study based on their surface expression and visibility at the time the data was collected (Fig. 2A). The uppermost sediments on the western margin of the playa where these footprints were found consists of approximately half a metre of interbedded gypsiferous sands and muds potentially forming large lenses within shallow troughs. These sediments are cut in places by deeper channels infilled with organic material, silty fine sand and thin gypsum layers which have been highly trampled. They appear to represent deposition by flood events from the adjacent San Andres Mountains both in the past and as a process that continues today. The tracks studied here are located just east of the zone of alluvial deposition but west of a complex of evaporative basins. The footprints lie at a depth of approximately 50 mm below the surface and are themselves up to 50 mm deep. At the time of fieldwork (early October 2024), many of them were clearly marked by a surface expression of slightly increased moisture which made them visible and easy to select for study.

The footprints at WHSA Locality 5 were surveyed in June 2025 after severe winds had removed much of the overlying sediment. WHSA Locality 5 lies on the southern side of the park (Fig. 1) and contains clay-rich sediments with some salts. Ghost tracks from this location have not previously been published. Surveys were done in two separate areas here. The first area (Fig. 2B) contains dozens of isolated human footprints that did not form clear trackways. These footprints remained buried beneath approximately 50 mm of sediment and were marked by similar moisture discolouration at the surface as at WHSA Locality 1. The second area (Fig. 2C) contained clear human trackways but the overlying sediment had been completely stripped leaving the footprints exposed.

3. Methods

In October of 2024, ten small scale GPR surveys were taken over identified human "ghost tracks" at WHSA Locality 1, White Sands National Park. The intent of these surveys was to take a very close look at the "GPR features" and morphology of buried tracks or pairs of tracks. The dimensions of each survey were 0.45 m x 0.45 m with profiles at 10 mm spacing and with 10 mm trace increment. In each instance, a 10 mm thick foam mat that had been marked with lines 10 mm apart was placed over the track to make a smooth surface and guide the survey lines. A Quantum Mini handheld antenna by USRadar was used to collect each transect. In June of 2025, twenty similar GPR surveys were taken at WHSA Locality 5, White Sands National Park. These surveys were taken in the same manner.

The collected survey data files were then processed with a Butterworth bandpass filter, an energy decay gain function and a background removal filter. The antenna used produced a broad spectrum response from very low (100 MHz) up to 2 GHz from which a narrow range of frequencies were extracted using the bandpass filter. The frequencies allowed through differed based on the site. At WHSA Locality 1, this was set to 1200–1500 MHz while at WHSA Locality 5 it was set to 1000–1300 MHz. It was found that these ranges produced the clearest results at the respective locations. These frequency ranges are relatively high to capture detail at a shallow depth while still having strong amplitude to ensure robust results. The profiles were then collated into a cube of amplitude envelope data and sliced at 0.1 ns intervals. Contrast enhancement and normalisation was, in most cases, necessary to visualise the tracks. Time slices of each track were exported at the depths where the size of the "amplitude footprint" was greatest. Profile cuts across the tracks were also exported. Finally, contour maps were made of the tracks where each contour represents the extent of the track feature in successive slices to understand how the shape of the features change in the time dimension.

4. Results

Thirty-seven tracks were identified across both sites but not all of these were initially visible at the surface (i.e., as identified targets). Ghost track surface expressions often represented composites of two or even three separate human footprints and additional tracks not visible at the surface were detected in the GPR surveys. The depths of the tracks varied in each case and probably represent more than one travelling

Fig. 2. Orthophotos of the human tracks surveyed at locality 1 (A) and locality 5 (B, C) created using photogrammetry. The tracks surveyed are enclosed in black squares.

episode although some variation in depth within a trackway is expected due to variation in sediment penetration by the foot.

The tracks were visible in the GPR slices as subtle, but distinctly higher amplitude, "footprint-shaped" reflections in plan view. It was assumed that the slice where the feature attained maximum area would represent the true area of the track at the two-way travel time when the centre of the reflected wavelets reached the receiver antenna. This was not always easy to determine. Surveys were placed on visible ghost tracks, but in practice multiple overlapping tracks were often visible in the GPR data. Additionally, various indeterminate reflection features partially obscured the footprints. As individual reflections were subtle, it was often necessary to use the normalisation filters available in the GPR processing software because of the unrelated reflections which were sometimes of much greater amplitude than those corresponding to human tracks and overpowered them. This resulted in features with crisp boundaries but often at the expense of erasing any detailed amplitude patterns within footprints. By cropping out these extraneous reflections, it was possible to see detailed patterns in amplitude inside the track outline (Fig. 3). The GPR tracks show a range of different morphologies with some preserving more "foot-like" detail than others. Most of the GPR tracks show a rounded heel impression distinct from a more angular and wider distal end of the foot. Individual toes are not seen. Some tracks preserve a clear longitudinal arch (Fig. 3B, E) although most show either muted or no width reduction in the midfoot. All of the tracks show clear asymmetry around the longitudinal axis with the toes being angled to create clearly identifiable medial and lateral sides to each track.

The change in radar amplitude across the foot has three general variations. Some tracks show separate regions of higher amplitude at both the proximal and distal ends of the foot (Fig. 3B, E). The second variation showed only a single region of higher amplitude at either end (Fig. 3A, D, F) while the third had relatively uniform amplitude across the entire foot (Fig. 3C, G).

The GPR profiles along the longitudinal axis of each footprint reveal consistent patterns in the shape and amplitude of the envelope of the response waveform (Fig. 4). In most cases, the profiles show a high amplitude zone at one end with a moderate amplitude "tail" extending out from it. The high amplitude response is often slightly thickened in the time direction so that the whole GPR track is "tadpole-shaped" with the "head" of the tadpole pointing in the direction of travel. This matches the pattern of a single high amplitude region seen in plan view (Fig. A, D, F). Some tracks (Fig. 4B) show a second high amplitude response so that both the heel and ball of the foot are distinguished. The profiles also generally show low to medium amplitude reflections beneath the tracks and extending to the bottom of the recorded profiles. These extend several times deeper than the tracks themselves and it is unclear if they are related. In some cases (e.g., Fig. 4D) they appear to be closely associated although it is more likely the case that this represents an older track that has been stepped on.

The slight thickening of the envelope of the reflections suggests that there may be information about changes in depth within the true track available in the data. To test this idea, the footprints from consecutive time slices were amalgamated into contour maps which show how they change with time-depth. Each contour here represents an amplitude-thresholded footprint silhouette taken from successive time slices. The threshold was kept the same for each slice. Only in a few cases was this approach possible because of the interference of unrelated reflections and difficulty with defining the boundary of a footprint in each slice. The results are seen in Fig. 5. The contour maps are similar to the amplitude patterns captured in single time slices which suggests that the two data representations are related. The slices wherein the high amplitude track reflections reached their greatest area likely represent the true size and shape of the preserved footprint. In the slices immediately below, the high amplitude reflections gradually reduced in area before disappearing. Our explanation for this phenomenon is that individual GPR trace reflections will have greatest amplitude at locations within the footprint where there is maximum contrast in dielectric permittivity (e.g., Fig. 3). This results in the reflected pulse maintaining a sufficient amplitude to be detected over a longer time period and hence the reflections in those traces will be visible in slices at greater time-depth (Fig. 6). In other words, the deeper slices are in fact below the true track and show lingering amplitude in the traces where more energy was reflected. It is possible there may be some influence from changes in depth of the plantar surface (i.e. low regions below the true track base) but it is important to stress that these contours are not of depth but of two-way time. The most parsimonious explanation is that the slight changes in the profiles are not primarily indicative of depth but relate to the compaction of sediments at or just below the true track surface.

5. Discussion

The results reported here demonstrate the potential of GPR to image buried footprints in sediments as reported by Urban et al. (2019) but also highlight some of the challenges of doing so. As with all geophysical investigations, it is critical to have a clear idea of exactly what is shown in the data. We have interpreted the identified reflections as being

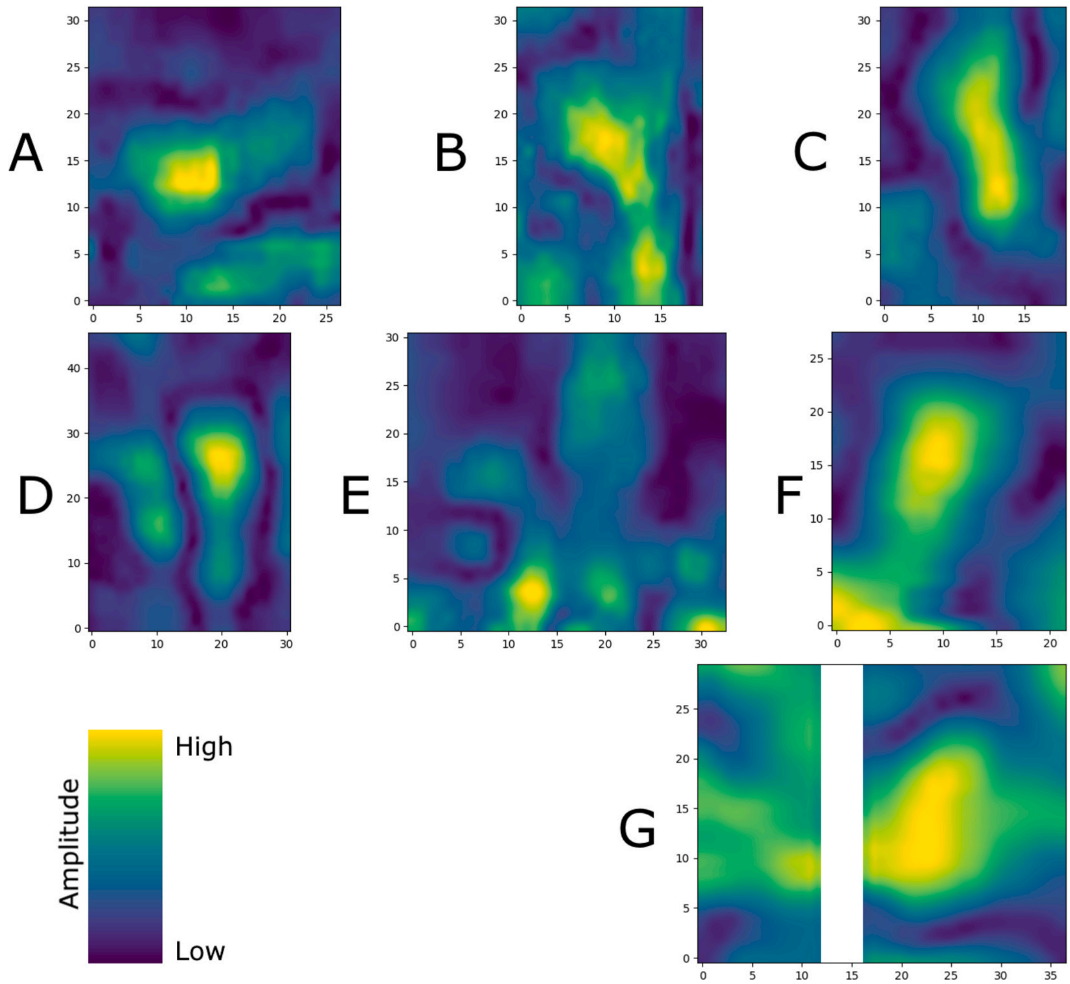

Fig. 3. A sample of GPR time slices showing the intra-track variations in amplitude. The tracks are not to a common numerical scale but are individually scaled to maximise contrast. Tracks A-C are from locality 1. Tracks D-G are from locality 5.

reflections off the base of the true track (i.e., surface once in contact with the plantar surface track-maker). These are caused by compression of the sediments beneath the foot leading to differential porosity between substrate and track fill. This is particularly important to emphasise since the fill may not always have a different dielectric permittivity to the surrounding sediment. It is this difference in porosity and water retention capacity that causes the ghost tracks at White Sands to have variable visibility. The difference in dielectric permittivity is slight and most tracks were not immediately visible in the GPR data without image contrast or normalisation filters being applied. Images obtained from GPR do not solely represent the morphology of a track but a combination of pressure signals (i.e. pressure compaction plus depth). Therefore, in interpreting morphology from GPR signals, one needs to be circumspect. An objection might be raised that changes in the coupling of GPR energy into the ground over visible ghost tracks is what results in tracks being visible in the data and that these results are merely showing surface changes already visible to the eye. We would argue against this on the grounds that the tracks visible in the GPR data were only seen over a select range of slices so it does not seem that this is a case of greater transmitted energy from increased surface coupling resulting in spurious track-shaped high amplitude reflections. Furthermore, there were multiple cases of tracks being visible in the GPR data where there were no visible tracks on the surface.

Although this data set was obtained at two different times of the year (October and June) and in two different sedimentary environments (gypsum playa and clay-rich sediment), the same general data collection and processing flow with minor alterations was successful in identifying human footprints and producing interpretable pressure patterns. There is no reason to suppose that it would not be similarly successful for a broad range of archaeological and palaeontological sites if the targeted tracks were sufficiently close to the surface to be imaged in detail. This opens new possibilities at soft sediment trackway sites where excavation may be too difficult or time consuming due to the subtle contrast between substrate and fill, or too destructive towards sites with cultural significance.

It is not likely that the frequency ranges used (1000–1500 MHz) are sufficient to accurately resolve the relief of the plantar surface: a conclusion experimentally supported by Wiewel et al. (2021). Therefore, the reflections probably represent a mostly flattened view of the track. Contrary to the aforementioned paper, we were not able to use the GPR reflections in profile to mark out the base of the track. This is probably because of the subtlety of the contrast in dielectric properties and because the sediments at White Sands do not form clear, well defined layers but lenses of sediment that produced complex and noisy reflection profiles. In the experimental study presented by Wiewel et al. (2021), the footprints were made on a cohesive clay surface which produced a clear and uninterupted GPR reflection. Footprints were easily visible as modifications to this surface. This was not the case for our data. Despite this setback, it was still possible to discern some internal variation within the tracks. In fact, there is substantial variation in amplitude within each track which is interpreted here as representing varying degrees of sediment compactions and, therefore, of plantar pressure during track formation. This is consistently present across all tracks identified by GPR at White Sands National Park. The apparent

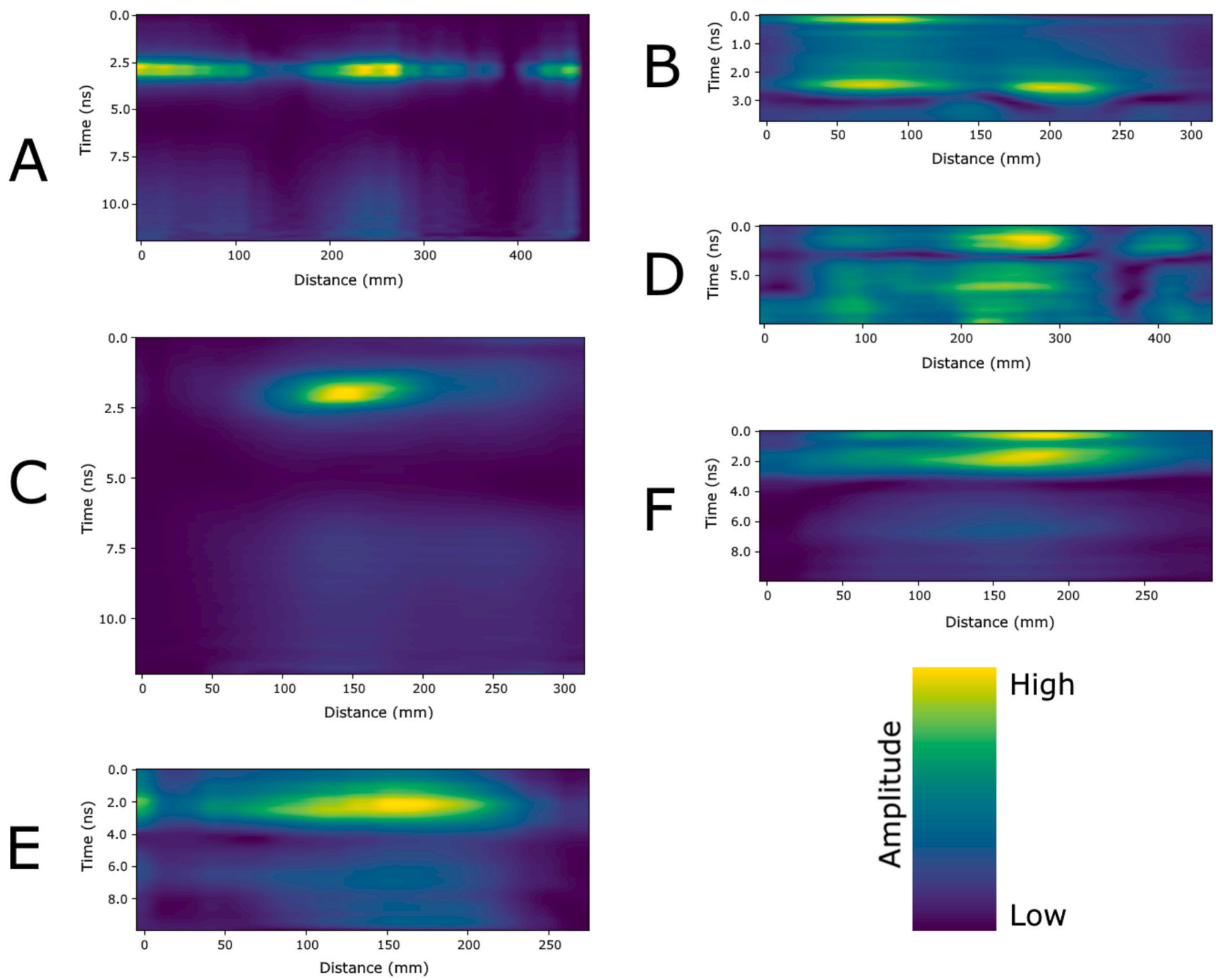

Fig. 4. Envelopes of GPR profiles showing the amplitudes of the radar reflections. The profiles are not to a common scale. Individual footprints are enclosed in white boxes.

changes in time duration of the reflections seen in the profiles and contour maps are likely to be a product of the amplitude of the GPR reflections rather than of any variation in sediment penetration across the plantar surface of the foot.

Alternatively, the variation seen in the time duration of the GPR response may be due to separate reflections from the top and bottom of the track fill which have combined into one response because of the low vertical resolution. In this case, there is the possibility that some plantar depth information could be derived from GPR data. However, it would require much higher frequencies to delineate between these two hypothetical reflections if they are present. On the other hand, this study has shown that even a relatively low frequency antenna can reveal useful information about buried human footprints and that the highest frequency antennas are not strictly necessary for ichno-geophysical research. Alternative explanations for the high amplitude responses seen within tracks include the focusing of GPR energy due to concave depressions from the ball and heel of the foot. This would enhance the amplitude in those parts of the track. Another possibility is that these depressions may have been filled with clay which would strongly reflect GPR energy. We would note the shallow relief of most footprints would mean there would need to be a very thin deposit of clay within the freshly made track to produce the amplitude patterns in question while not covering the entire plantar surface. This is unlikely to be true in the general case.

The results here suggest that the potential for the intra-track depth variation usually taken as a proxy for plantar pressure is difficult to access and would probably require more specialised equipment operating at higher frequencies. However, the amplitude variations found in time slices represent an alternative method of deriving pressure records which may prove to be a more direct relationship given questions over the robustness of the relationship between depth variation and pressure (Bates et al. 2013).

Sub-track GPR reflections were previously reported by Urban et al. (2019) but in that case they were interpreted as direct reflections off the compacted sediment beneath the plantar surface. Given that these were proboscidean tracks rather than human, it is likely that they would be associated with larger compressional and listric fault zones as well as greater variation in sediment compaction and, therefore, the radar might be able to distinguish this undertrack feature directly. We do not believe this is likely to be possible with human footprints except, perhaps, at very high frequencies and in ideal conditions where the subtle changes in sub-track compression would be distinguishable. While this study did find that there were deeper reflections underneath the footprint, it is hard to interpret these as being compressed zones

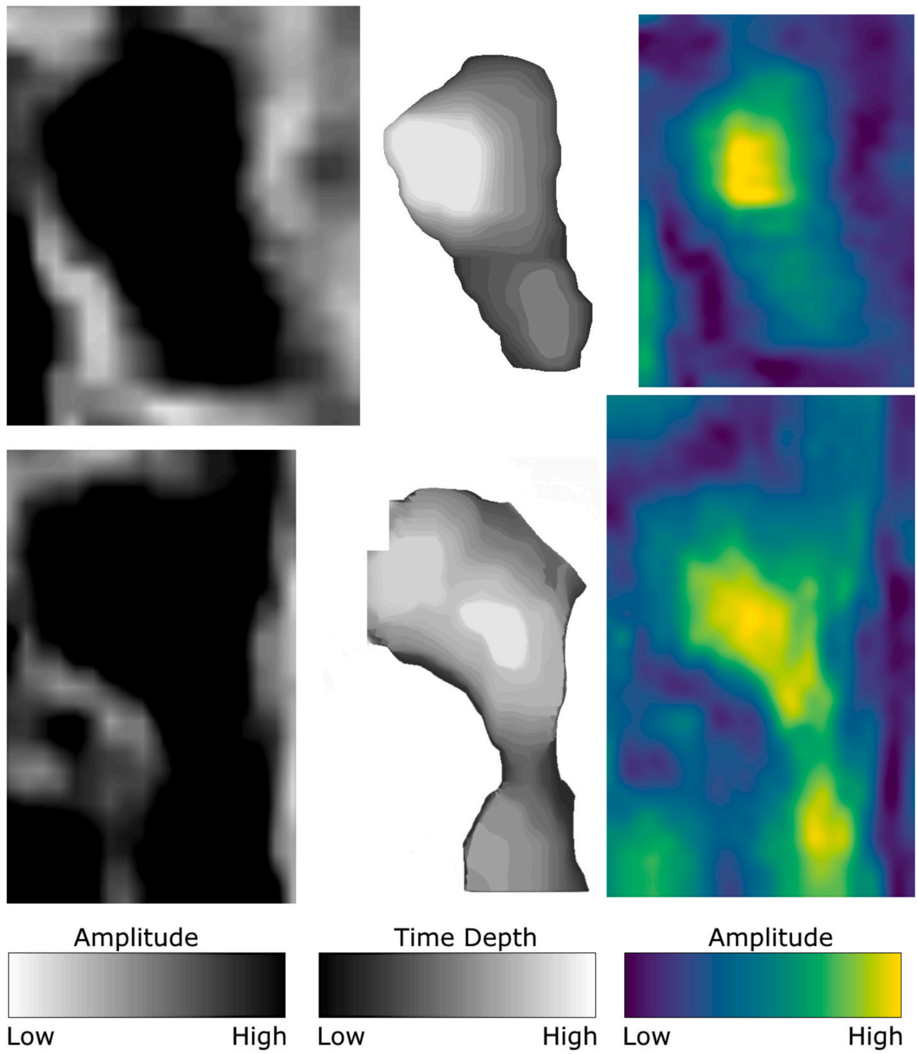

Fig. 5. Comparison between visualisations of two footprints. Left: amplitude-thresholded time slices at maximum track area. Middle: time-depth contour maps. Lighter shades represent later (deeper) time slices. Right: non-thresholded time slices.

beneath the plantar surface as they are substantially deeper than the footprints themselves (potentially tens of centimetres). It is unclear whether these features are related to the footprints or a result of natural geology or even the data processing.

6. Conclusion

These results have shown that GPR has the potential to extract information from tracks preserved in soft sediment across sedimentary contexts and seasons. Pressure patterns are typically recorded although they can be obscured by other reflections in the data. The main difficulty with this approach is disentangling the target footprint reflections from other features in the ground. Plantar depth records are unlikely to be resolved without more specialised equipment. This is an important result because it adds another technique to what archaeologists and palaeontologists working on footprint records have available. Fossil trackways are time consuming to excavate over a large area and are frequently culturally significant. A non-destructive and non-invasive method like GPR is an ideal choice in such situations but it is important to understand what information can be obtained from it. Future work in this area could focus on gathering more GPR-derived pressure records so that their inter- and intra-trackway variability as well as their relation to other biomechanical evidence such as stride length can be understood. The use of higher frequency antennas could be recommended to explore the feasibility of measuring variations in track thickness from plantar and track fill reflections at sites where there is substantial contrast between the fill and substrate. Finally, morphometric analyses could be applied to GPR derived track outlines in order to provide more robust identification of human footprints where they are not visible on the surface.

CRediT authorship contribution statement

Michael Everett: Writing – original draft, Methodology, Investigation, Conceptualization. **Sarah Maryon:** Writing – review & editing. **Abigail Hunt:** Writing – review & editing. **Hannah Strehlau:** Writing – review & editing. **Sally Reynolds:** Project administration, Writing – review & editing. **Matthew Bennett:** Writing – review & editing, Funding acquisition, Methodology, Project administration.

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.

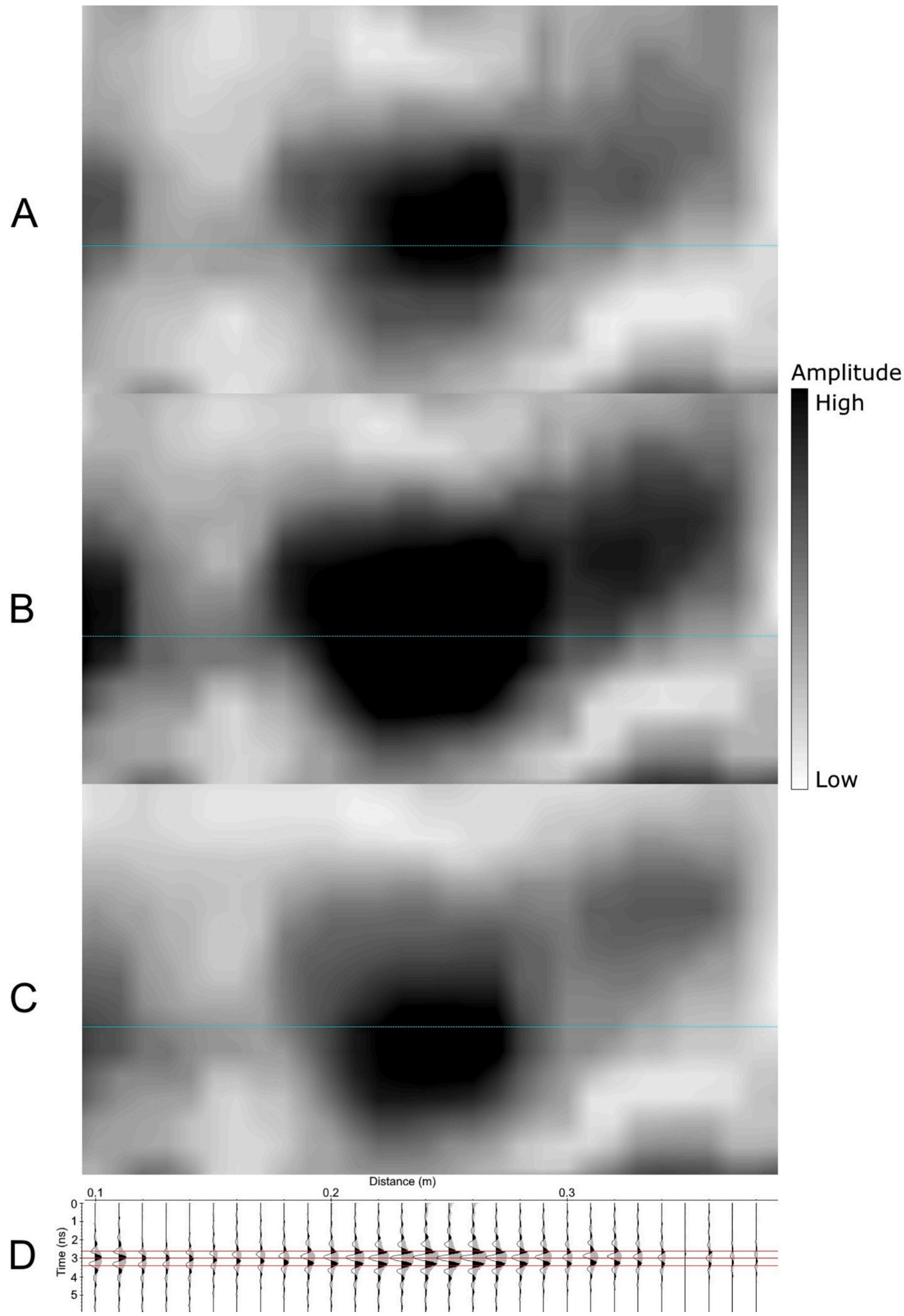

Fig. 6. Showing the relationship between changes in amplitude across time slices (A-C) with a profile over the same footprint (D). Slices A-C are to a common scale. The location of the profile is shown in cyan while the three slices are shown by the red lines. The envelope of each trace (D) is shown in grey.

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